COMPARATIVE ANALYSIS OF NTPEP PAVEMENT MARKING PERFORMANCE EVALUATION RESULTS

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COMPARATIVE ANALYSIS OF NTPEP PAVEMENT MARKING

PERFORMANCE EVALUATION RESULTS

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Thesis

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ABSTRACT

Pavement markings are used on roadways to provide guidance and information to drivers and pedestrians. They include 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). They come in different configurations and designs, making it possible for drivers and pedestrians to instantly recognize the meaning of the markings and quickly react to them so that they can travel safely and efficiently along the roadway.

A wide range of marking materials are available, including traffic paints (solvent-base and water-base), polyester, thermoplastic, epoxy, modified urethane, polyurea, methyl methacrylate, preformed thermoplastic, and preformed tape. These materials vary in cost, effectiveness in providing a contrast in color from that of the underlying surface, visibility under adverse weather condition such as rain and fog, adherence to different pavement surfaces, and durability under different traffic and environmental conditions.

This research presents a comparative and statistical analysis study of pavement marking materials from the National Transportation Product Evaluation Program (NTPEP).The performance of seven types of pavement markings (thermoplastic, preformed thermoplastic, epoxy, polyurea, modified urethane, durable tapes, and methyl methacrylate) was compared based on retroreflectivity, durability, and color. These materials were selected from four different NTPEP test decks (Mississippi, Pennsylvania, Wisconsin, and Utah). The performance evaluation results were compared to preselected milestone performance criteria. In addition, their service life was predicted using four mathematical models (exponential, linear, power and natural logarithmic model). Pavement marking service life is defined as 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 outcome of this study can assist state highway agencies in selecting appropriate pavement marking materials for different needs.

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CHAPTER I

INTRODUCTION

1.1 Background

Pavement markings are used on roadways to provide guidance and information to drivers and pedestrians. They include 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). They come in different configurations and designs as defined in the Manual for Uniform Traffic Control Devices (MUTCD), making it possible for drivers and pedestrians to instantly recognize the meaning of the markings and quickly react to them so that they can travel safely and efficiently along the roadway (FHWA 2003).

A wide range of marking materials are available, including traffic paints (solvent-base and water-base), polyester, thermoplastic, epoxy, modified urethane, polyurea, methyl methacrylate, preformed thermoplastic, and preformed tape (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 condition such as rain and fog, adherence to different pavement surfaces, and durability under different traffic and environmental conditions.

1.2 Problem Statement

Significant progress has taken place over the last two decades in producing high quality marking materials. As a result, several research studies were initiated by various states to determine the suitable of different materials to prevailing traffic and environmental conditions. Example studies on this subject that ended within the last two decades include Lu (1995) in Alaska, Thomas and Scholtz (2001) in Iowa, Lee at al. (1999) in Michigan, Abbas et al. (2009) in Ohio, Lynde (2006) in Oregon, Henry et al. (1990) in Pennsylvania, Swygert (2002) in South Carolina, Becker and Marks (1993) in South Dakota, and Lagergren et al. (2005) in Washington.

Aside from the previous research studies that had limited research focus, the most comprehensive pavement marking performance evaluation program is the National Transportation Product Evaluation Program (NTPEP). The 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 such as pavement markings, which are the focus of this thesis. Its main objective is to assist state highway agencies in making informed decisions regarding the prequalification of these products; and thus improve the quality of available products and raise awareness of their availability. Additional information about the NTPEP program is available at www.ntpep.org.

A large amount of pavement marking performance evaluation data has been collected by the NTPEP program. This data is available on the web at http://data.ntpep.org. It can be explored using the NTPEP DataMine web tool or downloaded and viewed in Microsoft Excel or Microsoft Access. Several states have used this data in pavement marking prequalification (NTPEP Oversight Committee 2004). However, a very limited number of research studies have utilized this data to compare the performance of pavement markings. Furthermore, the NTPEP uses several test decks widely distributed within the US for the field evaluations. The location of these tests decks was chosen to cover different environmental and traffic conditions. Nevertheless, the literature is silent regarding the performance of the same marking material on different NTPEP test decks. This study attempts to fill this gap in the state of knowledge by comparing the performance of pavement markings within the same test deck and on different test decks to determine their suitability for use in different geographic locations.

1.3 Objectives of the Study

The main objectives of this study are:

- Develop a comprehensive evaluation plan for the performance of pavement markings;
- Choose most common pavement markings and develop a pavement markings database from NTPEP;
- Summarizes the performance evaluation results of the pavement marking materials.
- Evaluate retroreflectivity, durability and color performance of pavement markings between different material groups;

- Evaluate retroreflectivity, durability and color performance of pavement markings between different test decks;
- Estimate the service life of the evaluated materials;

1.4 Thesis Organization

This thesis is organized into eight chapters. Chapter II introduces past research studies that are related to pavement markings. Chapter III gives a brief overview of the NTPEP program. Chapter IV focuses on the summary of NTPEP performance evaluation results. Chapter V offers the comparison study between material groups and Chapter VI Chapter focuses on the comparison study between test decks. Chapter VII estimates the service life of the various pavement markings evaluated in this study and Chapter VIII summarizes the research conclusions.

CHAPTER II

LITERATURE REVIEW

2.1 Introduction

Pavement markings are classified into two broad categories by service purposes, namely removable and non-removable. The former has a relatively short service life (less than a year); and is used with temporary traffic patterns; while the latter has a longer service life (greater than one year), and is used with permanent traffic patterns. The focus of this study is on non-removable (permanent) pavement markings. Therefore, the discussion in this thesis will be limited to this type of marking materials.

2.2 Pavement Marking Materials

Pavement markings consist of three main components: binder (glue), reflective media (reflectors), and pigment (color). The binder provides the material with its ability to withstand abrasion from traffic and snow plowing. The reflective media allow the material to be visible at night by reflecting the light from the vehicle headlight back to the driver's eyes. The most common type of reflective media is glass beads, which can be either intermixed or surface applied. The pigment determines the daytime and nighttime color of the pavement marking, and contributes to the retroreflectivity of the marking material at night.

Common marking materials include traffic paint, thermoplastic, epoxy, modified urethane, polyurea, methyl methacrylate, preformed thermoplastic, and preformed tapes. These materials are discussed in detail in the following subsections.

2.2.1 Traffic Paint

Traffic paints are the least expensive and the most widely used pavement marking material in the US, although its use has recently declined as thermoplastic has become more popular. Traffic paints consist of binder for base material, pigment for color and reflectivity, and solvents/additives. Traffic paints are classified into two types: solvent-based paints (alkyd) and waterborne paints (latex). In solvent-based paints, the polymeric binder provides the integrity and the film-forming material. Fillers such as calcium carbonate are used to extend the paint composition. Optimum pigment volume concentration in the range of 42 to 59 percent is common. Numerous other additives such as anti-settling agents, anti-skinning agents, stabilizers and biocides may also be included in the formulation. To enable the paint to be brushed, sprayed, or rolled onto a surface, its viscosity must be suitably adjusted with a solvent. In water-based paints, the binder resin is a mixed acrylate-methacrylate copolymer available in the form of a 50 percent solid latex. The solvent is replaced for the most part by water, and additives are included in the formulation. These are different from those in solvent-borne paints and include non-ionic or ionic detergents to stabilize the latex, a dispersant such as polymethacrylate with acid functionalities, a coalescent to ensure rapid film formation and a thickener to maintain consistency (Yu 2004).

2.2.2 Thermoplastic

Thermoplastic has been used in the United States since the late 1950s, and is increasingly becoming more popular due to its excellent durability on asphalt surfaces. Thermoplastic is composed of four main ingredients: binder, glass beads, titanium dioxide, and calcium carbonate (or filler). The binder is used to hold the mixture together as a rigid mass, the glass beads are used to provide reflectivity, the titanium dioxide is used for reflectivity enhancement, and calcium carbonate or sand is used as an inert filler material. Typical thermoplastic markings are 15 to 33 percent binder, 14 to 33 percent glass beads, 8 to 12 percent titanium dioxide, and 48 to 50 percent filler (Migletz et al. 1994).

Thermoplastics are classified into two types: 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). Both types require strict quality control during application as they are very sensitive to the variables governing the application procedure (Lopez 2004).

As mentioned earlier, thermoplastics have excellent durability on asphalt surfaces, which can be attributed to the thermal bonding mechanism between the heated thermoplastic and the asphalt surface upon installation, resulting in bond strengths equivalent to that of the cohesive strength within the asphalt. On the other hand, thermoplastics have poor durability on concrete surfaces due to the inferior mechanical bond between these two materials during installation, leading to premature failure on concrete surfaces (Gates et al. 2003).

2.2.3 Epoxy

Researchers first introduced two-component epoxy-resin paints as a pavement marking material in the 1970s. Since then, this material has developed into a common pavement marking material used by many agencies. Epoxy paints are durable, sprayable materials that provide exceptional adhesion to both asphalt and concrete surfaces with good abrasion resistance. Epoxies are more expensive than traffic paints and are about the same cost or slightly more expensive than most thermoplastics (Lopez 2004).

Epoxy paints consist of two main materials: binder and pigment. The binder consists of two components: resin and catalyst. When combined, these components chemically react to form a hard material that adheres to the roadway surface (Migletz et al., 1994). Typically, glass beads are added as part of the application procedure.

Epoxy paints have been recognized for their exceptional durability on asphalt and concrete surfaces. This exceptional durability is a result of tight bonding to the pavement surface that results from the chemical reaction that occurs when the two components are mixed. Epoxies can be applied at surface temperatures as low as 35°F and when pavement surfaces are slightly wet. On roadways subjected to low to medium traffic volumes, epoxies have been reported to provide service lives in excess of four years. Epoxies require proper cleaning of the pavement surface to achieve the best bond. One drawback associated with epoxies, particularly slow cure epoxies, is that they often take much longer to dry than other materials. Some formulations take over 40 minutes to dry. If a two-component marking material, like epoxy, does not dry within the manufacturer's recommended drying time, the components likely did not react properly and will not cure. In this case, the two component products must be removed and the road must be restriped (Lopez 2004).

2.2.4 Modified Urethane

Modified urethanes are two-component durable marking materials with similar performance characteristics to those of epoxies. Modified urethanes are currently produced by one manufacture, namely Innovative Performance Systems (IPS). This product is marketed as being slightly more durable than epoxy, but with much quicker cure times and better ultraviolet color stability (Gates et al 2003). Another advantage of this material is that it can be applied using a standard epoxy equipment, which helps minimize the installation cost of this material.

2.2.5 Polyurea

Polyurea markings are two-component durable pavement marking material that is relatively new to the pavement marking market. Limited but rapidly increasing experience has been recently reported for polyurea pavement markings. Manufacturers producing this product market it as a durable marking material with the following attributes: maintains good color stability when exposed to ultraviolet light, dries to no-track in three to eight minutes at all temperatures, may be applied at ambient pavement surface temperatures as low as 40º, is not affected by humidity, and provides excellent adhesion on both asphalt and concrete surfaces (Lopez 2004).

One of the major drawbacks of polyurea is that special equipment is necessary to apply this material. As a result, contracted costs are higher than most other liquid materials, ranging from $0.92 to $1.00 per linear foot (Gates et al. 2003).

2.2.6 Methyl Methacrylate (MMA)

Methyl methacrylate pavement markings are another two-component pavement marking materials. The first component consists of a methyl methacrylate monomer, pigments, fillers, glass beads, and silica. The second component consists of benzoyl peroxide dissolved in a plasticizer. The two components are mixed immediately before application to form the methyl methacrylate pavement marking, which can be applied by spray or extrusion.

This material 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). Besides, it does not need heat to cure. Therefore, it is an attractive material in cold-weather climates (Lopez 2004). Furthermore, it is resistant to oils, antifreeze, and other common chemicals found on the roadway (Migletz et al. 1994). Its main disadvantages include slow curing time of thirty minutes, high initial cost, and the need for special installation equipment (Lopez 2004).

2.2.7 Preformed Thermoplastic

Preformed thermoplastic markings are composed of pigments, reflective glass beads, fillers, binders, and additives. They are commonly used for transverse markings and symbols. They are typically supplied in large pieces, which are put together as a giant puzzle. These materials do not have any pre-applied adhesive, and bonding to the pavement is achieved by placing the material in the desired location and heating the material with a propane torch. There are two basic types of preformed thermoplastic markings. The first type does not require preheating the road surface prior to installation, while the second type requires preheating the road surface to a prescribed temperature prior to installation [7]. A primer/sealer is usually required on concrete or old asphalt surfaces. The pavement surface must be dry before applying the preformed thermoplastic or the primer/sealer. The pavement surface must also be free of dirt, dust, chemicals, and oily substances. Most preformed thermoplastic materials may be applied at air temperatures down to 35ºF. However, surface temperature is critical and must conform to manufacturer recommendations [7].

2.2.8 Durable Tapes

Durable tapes are cold-applied, preformed pavement marking materials that are supplied in continuous rolls of various lengths and widths (Lopez 2004). They are manufactured by melting and extruding plastic into the desired shape in the factory and are cold-applied in the field using either an overlay or an inlay installation procedure. Most tapes come with pre-applied adhesive protected by paper backing and are applied by removing the paper backing and pressing the tape to the pavement with either a roller or a truck tire (Migletz et al. 1994).

Durable tapes generally have good durability and abrasion resistance. In general, they exhibit better performance on asphalt surfaces than on concrete surfaces because of the adhesive characteristics. Inlaid tapes almost always outperform overlaid tapes. Tapes are known to distort in areas that have a high amount of turning movements or weaving over the markings. A clean surface is more important for tapes than for any other material. Therefore, tapes must be applied in areas where good bonding can be ensured. If applied properly, tapes can provide durability and visibility for many years. Durable tapes are most commonly used for short line markings including crosswalks, stop bars, words, and symbols. However, their use as a long line application is increasing nationwide. Preformed tapes require no drying or curing time. They can be open to traffic almost immediately after installation (Lopez 2004). Their main disadvantages include high initial cost, slow application procedures, and the added cost of removal at the end of their service life since they are not compatible with other marking materials commonly used for restriping.

2.3 Performance Evaluation of Pavement Markings

Pavement marking performance has been judged using three main criteria, namely durability, color, and retroreflectivity. Durability refers to the resistance of the marking material to abrasion from traffic and snow removal activities; color refers to vividness of white markings and richness of yellow markings as viewed from a distance; and retroreflectivity relates to the contrast in color between the marking material and the underlying pavement surface. These criteria are discussed next in detail.

2.3.1 Durability

The durability of a pavement marking is typically measured by assessing the amount of material remaining on the roadway 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**.** Figure (2.1) depicts the durability rating procedure used by the Ohio Department of Transportation (ODOT). As can be noticed in this figure, different durability ratings can be assigned for the marking material depending on the amount of material remaining on the surface. Several factors affect the durability of the pavement marking including material type, traffic volume, surface type, and environmental conditions.

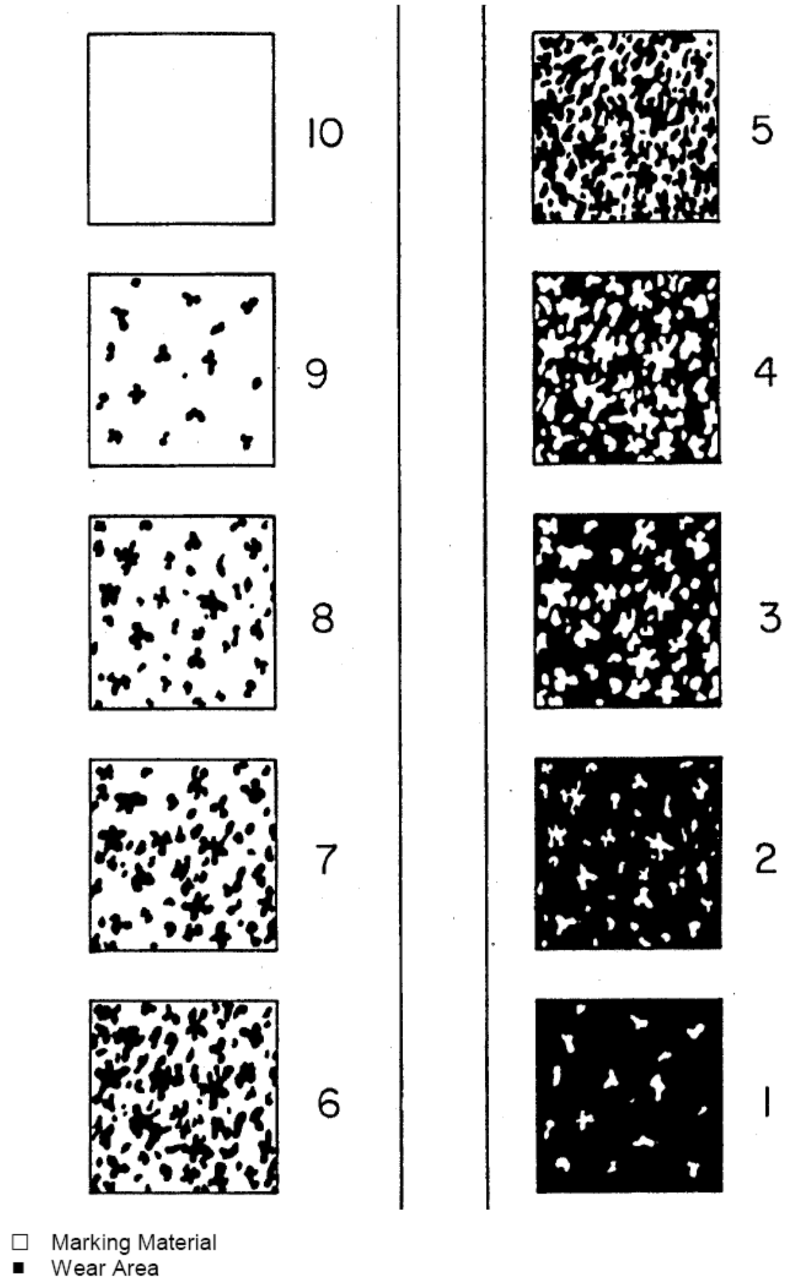


Figure 2.1- Pavement Marking Durability (ODOT TEM 2002).

Pavement markings are generally classified into durable and non-durable products depending on the service life of the marking material. For example, the typical service life of traffic paint is less than two years and hence it is considered non-durable, while the typical service life of thermoplastic, epoxy, modified urethane, polyurea, methyl methacrylate, preformed thermoplastic, and durable tape is greater than three years and hence they are considered durable marking materials.

2.3.2 Color

Pavement markings come in different colors making it possible for drivers to recognize the meaning of the markings and quickly react to them so that they can travel safely and efficiently along the roadway. For longitudinal marking applications, yellow color markings are utilized between opposite traffic for separating purpose and white color markings are used to isolate traffic in the same direction.

Pavement marking color has been evaluated using subjective and objective evaluation techniques. Subjective evaluation techniques are made by experienced evaluators who use their judgment in rating the vividness of yellow markings and the richness in white markings according to a set of predefined guidelines. Meanwhile, objective evaluation techniques are conducted using an instrument such as a colorimeter, which describe color using two coordinates, x and y, as suggested by the Commission Internationale de l'Eclairage (CIE). These coordinates can be plotted on a CIE chromaticity diagram, as shown in Figure (2.2), to determine the color of the pavement marking. In addition, these devices provide one additional reading, Y, which describes how light or dark the object is.

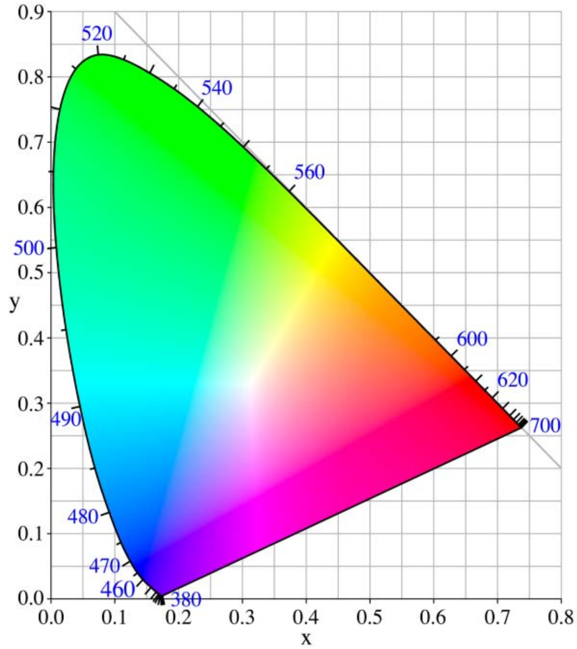


Figure 2.2- CIE Chromaticity Diagram.

Color specifications are typically defined as ranges for white and yellow markings based on the CIE chromaticity diagram. Table (2.1) presents example color specifications used by the Federal Highway Administration (FHWA) for white and yellow markings. Figure (2.3) depicts the location of these coordinates on the CIE color chromaticity diagram. For the color reading to meet the FHWA color specifications, it has to fall within the corresponding color box. This approach will be used in this study to determine whether pavement marking color meets the FHWA color specifications or not.

Table 2.1- FHWA 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

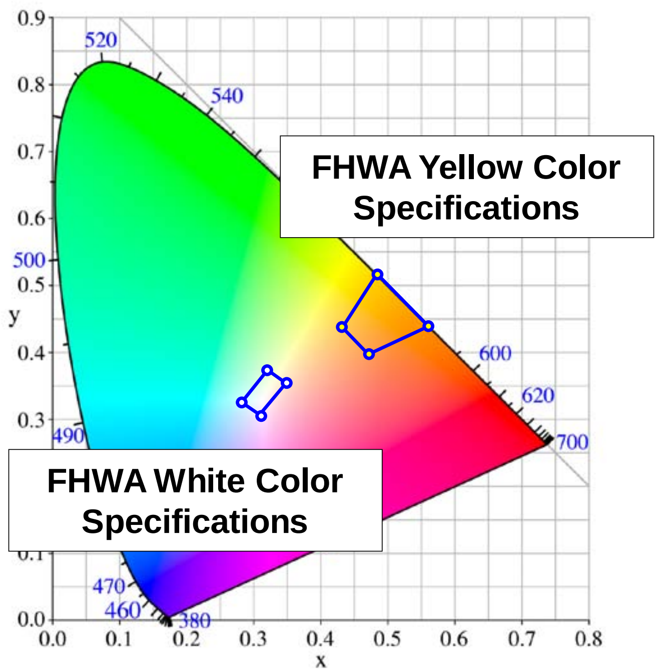


Figure 2.3- FHWA Color Requirements for White and Yellow Markings.

2.3.3 Retroreflectivity

Nighttime visibility of pavement markings is generally described using the marking retroreflectivity, which is defined as the portion of incident light from the vehicle headlight beams reflected to the driver after striking the marking material (Migletz et al. 1999). As shown in Figure (2.4), the pavement marking retroreflectivity is typically provided through the use of round transparent glass beads that are partially embedded in the marking material (Migletz et al. 1999). To insure that the retroreflection will happen effectively, the embedment depth of glass beads is critical. For optimum retroreflectivity performance 50 to 60% of the glass beads diameter must be embedded in the marking material.

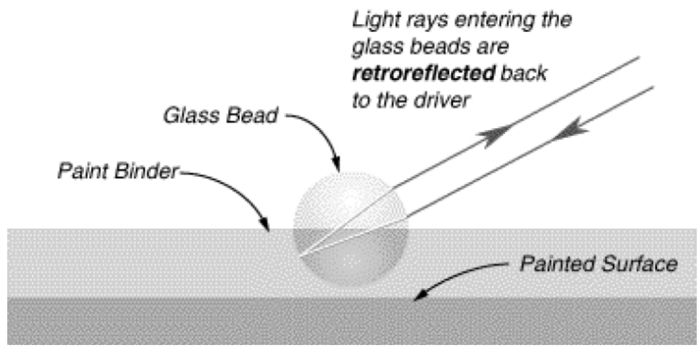


Figure 2.4- Glass Bead Retroreflection (after Thomas and Scholz 2001).

Pavement marking retroreflectivity is quantified using the coefficient of retroreflected luminance, R_L, represented in millicandelas per square meter per flux ($mcd/m^2/lux$); (ASTM 2009). 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 Scholz 2001). It is commonly measured using hand-held 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; ASTM 2009; Migletz et al. 1999). Figure (2.5) presents the standard 30-m geometry (entrance angle of 88.76^o and observation angle of 1.05^o) used for measuring nighttime retroreflectivity (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).

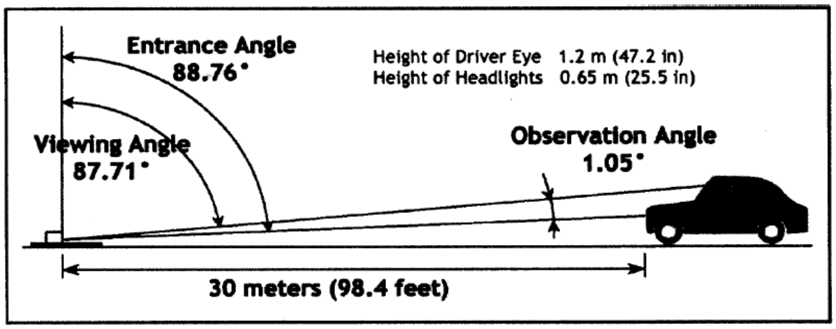


Figure 2.5- Standard 30-m Measurement Geometry for Pavement Marking Retroreflectivity (after Migletz and Graham 2002; source Hawkins et al. 2000).

The American Standard for Testing and Materials (ASTM) specifies a minimum retro-reflectivity value of 250 mcd/m^2/lux for new white markings and 175 mcd/m^2/lux for new yellow markings (Migletz and Graham 2002). Some States have different requirements, while others do not have any requirements (Migletz and Graham 2002).

The loss in retro-reflectivity could be resulted from loss of glass beads, wearing of marking material, color change of the marking material, loss of contrast between the marking material and the underlying pavement surface, or simply due to accumulation of dirt and dried salt on the highway (Thomas and Schloz 2001; Shay 2004). Environmental conditions such as recurrent changes in moisture and temperature and intense exposure to ultraviolet light can further expedite the wearing of the marking material (TranSafety, Inc. 1998).

Based on the previous, the retroreflectivity of a pavement marking is one of the most important aspects among safety features on highways and rural roads, and it explains the reason why retroreflectivity is increasingly becoming a vital technical specification corresponding to pavement marking materials.

2.4 Pavement Marking Selection

The most common factors used in the selection of the pavement marking material are the type of the line to be striped (centerline, lane line, edge line, transverse line, or auxiliary such as message, arrow, railroad, etc.), pavement surface (asphalt or concrete), highway classification (interstate highway, multilane highway, two-lane highway, or two-way highway), and average daily traffic (ADT); (Migletz and Graham 2002). Other factors include highway lighting, number of skilled workers, installation equipment, environmental effects, pavement maintenance schedule, and whether the marking material manufacturer offers any warranties on their products or not (Thomas and Schloz 2001).

In selecting which marking material to use, highways with higher traffic volumes and pavements in new or good condition are more likely to receive durable markings than highways with low to medium traffic volumes and pavements in old or bad condition. Interstate highways are more likely to receive durable markings than two-lane and two-way highways. Centerlines and lane lines are more likely to receive durable markings than edge lines (Migletz and Graham 2002).

CHAPTER III

OVERVIEW OF THE NTPEP PROGRAM

3.1 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 (permanent) 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 (permanent) pavement markings since they are the focus of this study.

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. The Ohio Department of Transportation (ODOT), for example, has been revised over the last decade to allow using NTPEP data from Pennsylvania and

Wisconsin Test Decks for product prequalification. For completeness, an overview of the NTPEP pavement marking performance evaluation procedure is presented next. Performance evaluation measures collected during the field evaluations are discussed in detail.

3.2 NTPEP Test Decks

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 evaluations, the NTPEP uses several test decks that are widely distributed within the United States to cover different environmental and traffic conditions (Figure 3.1). 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.

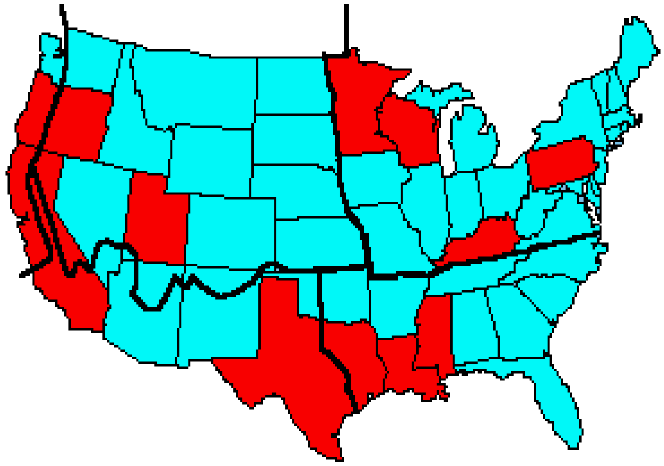


Figure 3.1- NTPEP Pavement Marking Test Decks (http://www.ntpep.org).

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)

Over the last ten years, the quality of pavement marking materials has significantly improved. As such, results from the Pennsylvania ('00,'02,'05,'08), Wisconsin ('04,'07), Utah ('01,'05), and Mississippi ('02,'04,'06) experiments will be analyzed in this study. Therefore, these test decks are covered next in detail.

3.2.1 Pennsylvania Test Deck

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. The test deck consists of two sites within 3 miles of each other, a Portland cement concrete site along the eastbound and a bituminous asphalt site along the westbound. The Portland cement concrete site (I-80 eastbound) has an average daily traffic (ADT) of 10,000. The surface is 8 years old with no resurfacing. It has transverse tines that are worn and exhibits aggregate polishing along the wheel tracks. The bituminous asphalt site (I-80 westbound) also carries an ADT of 10,000. The bituminous asphalt surface is nine years old. It is made of heavy duty mix. Exposed aggregate is present in both “skip” and “wheel” locations. Both sites are subjected to moderate to heavy truck traffic.

3.2.2 Wisconsin Test Deck

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 bituminous asphalt is conducted near the north end of the test deck, while testing on Portland cement concrete is conducted near the south end. The Portland cement concrete surface is not tined. The bituminous asphalt surface is four years old. It 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.

3.2.3 Utah Test Deck

The NTPEP Utah (UT) test deck is located along the eastbound direction of interstate I-84, west of Morgan, Utah. The Portland cement concrete test site is located to the east of mile marker 102.25, and the bituminous asphalt test site is located to the west of the same mile marker. Both test sites are located in a flat area where the interstate has two-lanes per direction. The average daily traffic (ADT) is more than 5,000.

3.2.4 Mississippi Test Deck

The NTPEP Mississippi (MS) test deck is located along U.S. Highway 78. It consists of two sites, a Portland cement concrete site and a bituminous asphalt site. The Portland cement concrete site is located along the westbound of U.S. Highway 78, east of New Albany, Mississippi. The ADT on this site is 20,000. The project to place the concrete pavement was completed in 1971 with no resurfacing and represents standard MDOT design. The Portland cement concrete surface is not tined and exhibits polishing of aggregate/concrete surface in both “skip” and “wheel” locations. The bituminous asphalt site is located along the eastbound of U.S. Highway 78, east of Tupelo, Mississippi. This site has an ADT of 15,000 (i.e., less than the Portland cement concrete site). The project to place the asphalt pavement was completed in 1995 with no resurfacing and represents standard MDOT design. The bituminous asphalt surface exhibits aggregate polishing in both “skip” and “wheel” locations. Both Portland cement concrete and bituminous asphalt test sites are located in a flat area. Both sites meet the criteria for ASTM-713 for site location.

3.3 Performance Evaluation Plan

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 2009).

As can be seen in Figure (3.2), 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 material are evaluated. These lines are placed in pairs in two different test deck sections to minimize the effects of adverse surface conditions and possible accidental loss of evaluation lines during the course of the evaluation. The test strips are applied at a width of 4 inches (100 mm). All of the striping materials are placed by the manufacturers who are responsible for supplying all necessary installation equipment. Meanwhile, the installation is supervised by the host agency that provides traffic control. 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 3.2). 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 (Bahar et al. 2006).

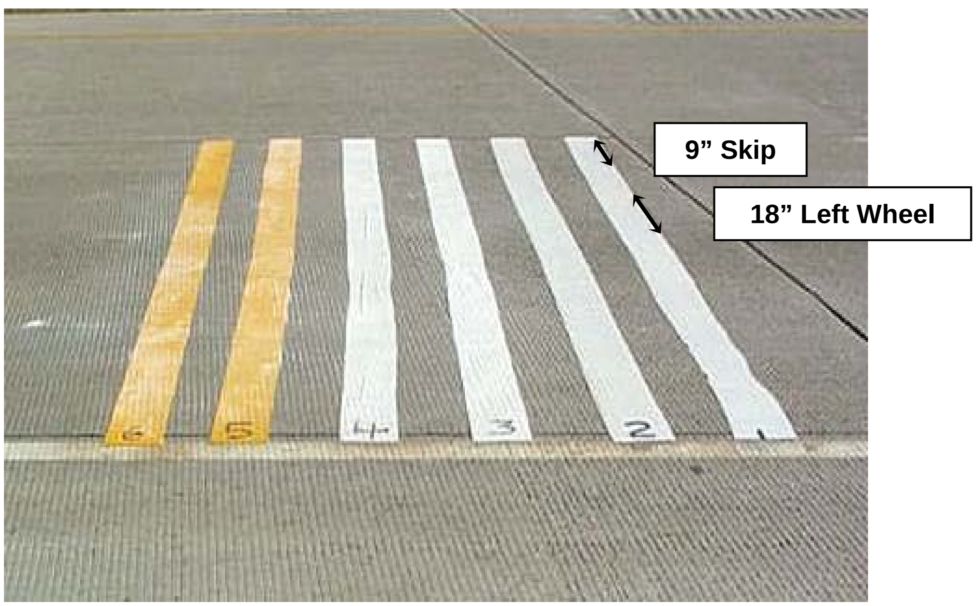


Figure 3.2- Transverse Placement of Pavement Markings on NTPEP Test Decks

(after http://www.ntpep.org/).

The NTPEP field evaluation is conducted in three phases: 1) Project organization, material installation, and initial product evaluation; 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. It is worth noting that due to winter weather conditions and residual deicing/antiskid materials commonly found in northern areas, evaluations are suspended between the months of December through April for these areas.

In each field evaluation, durability is subjectively rated by experienced evaluators; daytime color is measured using a Gardner color-guide spectrophotometer; retroreflectivity is measured using a Delta LTL 2000 or Delta LTL-X handheld retroreflectometers or other acceptable device; 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, air and pavement temperatures, relative humidity, wind velocity, wind direction, barometric pressure, no-track time, and type and rate of application of beads), and information regarding snowfall and snowplow damage (where applicable).

3.3.1 Durability

Subjective durability ratings are made by a team of experienced evaluators, whereby durability is rated by visually assessing the percentage of material remaining on the surface on a scale of 0 to 10. A durability rating of 0 indicates that the material has been completely lost and a durability rating of 10 means that 100% of the material is remaining. Durability is evaluated and reported, in the NTPEP program, for both “skip” and “wheel” locations.

3.3.2 Color

Color measurements in the NTPEP program are collected using a Gardner color spectrophotometer. They are performed in an un-beaded area of the test line (within three feet of the test line on the right edge line side) to minimize the affect of dirt collection. Figure (3.3) presents a picture of the Gardner color spectrophotometer. 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.

Figure 3.3- Gardner Color Spectrophotometer (after NTPEP Manual).

3.3.3 Retroreflectivity

Pavement marking retroreflectivity is measured in the NTPEP program using LTL 2000 or LTL-X handheld retroreflectometers or other acceptable devices. Figure (3.4) presents a picture of the LTL-X handheld retroreflectometer. This device measures nighttime retroreflectivity in accordance with CEN and ASTM standards. It uses the standard 30-m geometry (entrance angle of 88.76^o and observation angle of 1.05^o) in simulating the roadway being illuminated, which exemplifies the driver's ability to view the marking at a location that is 30-m ahead of the vehicle. 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.

Figure 3.4- LTL-X Handheld Retroreflectometer (http://www.flinttrading.com).

As shown in Figure (3.5), retroreflectivity measurements are collected in both “skip” and “wheel” locations of the test lines.

Figure 3.5- Measuring Retroreflectivity in “Skip” and “Wheel” Locations along the Transverse Test Lines (after http://ntpep.usu.edu/index.html).

CHAPTER IV

SUMMARY OF NTPEP PERFORMANCE EVALUATION RESULTS

4.1 Introduction

Pavement marking materials evaluated in the NTPEP program are classified into five main categories:

1- Waterborne traffic paint:

- 1A: 2-year Waterborne
- 1B: 3-year Waterborne
- 1C: 1-year Waterborne

2- Solvent borne traffic paint:

- 2A: 2-year Solvent Borne
- 2B: 3-year Solvent Borne

3- Durable marking materials:

- 3A: Thermoplastic
- 3B: Preformed Thermoplastic
- 3C: Epoxy
- 3D: Polyester
- 3E: Durable Tapes

- 3F: Polymeric Films
- 3G: Methyl Methacrylate
- 3H: Durable Other Temporary Tape

4- Experimental marking materials

- 5A: 2-year Experimental
- 5B: 3-year Experimental
- 5C: 1-year Experimental

This study focuses on the performance of durable marking materials, especially those that have received greater attention and use by various departments of transportations in recent years, such as thermoplastic (3A), preformed thermoplastic (3B), epoxy (3C), durable tapes (3E), methyl methacrylate (3G), and durable other such as polyurea and modified urethane (3H).

In each experiment, the NTPEP tests a very large number of marking materials. To simplify the analysis, the performance of selected marking materials was analyzed in this study. These materials were chosen by reviewing the pavement marking qualified product lists of all 50 states (if available online), and selecting those materials that have been tested on several NTPEP test decks.

Table (4.1) provides a brief description of the selected marking materials for further analysis. This table includes the trade name of the product, the name of the product producer, the NTPEP test decks where the product was tested and the beginning year of the field evaluation. As can be seen in this table, the performance of seven (7) marking materials was analyzed in this study using data from the Wisconsin ('04), Pennsylvania ('02,'05), Mississippi ('02,'04), and Utah ('01) experiments.

Table 4.1- List of Products Analyzed in this Study

	Producer	Product Name	NTPEP Test Decks And Year	Product Description
1	Innovative Performance Systems	HPS-4	Mississippi 2004	Modified Urethane
			Wisconsin 2004	
			Pennsylvania 2005	
2	Crown Technology II, LLC	Tuffline Alkyd	Mississippi 2002	Thermoplastic
			Pennsylvania 2002	
3	POLY-CARB, Inc.	MARK - 55.3	Utah 2001	Epoxy
			Pennsylvania 2002	
4	Innovative Performance Systems	HPS-5	Mississippi 2004	Polyurea
			Wisconsin 2004	
			Pennsylvania 2005	
5	3M Corporation	Tape Series 380	Mississippi 2002	Durable Tape
			Pennsylvania 2002	
			Wisconsin 2004	
6	Flint Trading, Inc.	Premark Plus	Mississippi 2002	Preformed Thermoplastic
			Pennsylvania 2002	
			Wisconsin 2004	
7	TMT Pathway LLC	Dura-Stripe	Mississippi 2002	Methyl Methacrylate
			Pennsylvania 2002	

4.2 Performance Evaluation Results

This section summarizes the performance evaluation results of the pavement marking materials depicted in Table (4.1). Only results for initial, 1-yr, 2-yr, and 3-yr (if available) performance are presented.

4.2.1 Retroreflectivity

Tables (4.2) through (4.8) present initial, 1-yr, 2-yr, and 3-yr (if available) retroreflectivity data for the seven (7) marking materials presented in Table (4.1) and the corresponding NTPEP test decks on which each material was tested. Each table consists of four sub-tables representing white skip retroreflectivity, white wheel retroreflectivity, yellow skip retroreflectivity, and yellow wheel retroreflectivity.

Retroreflectivity values not meeting preselected milestone criteria are highlighted. The milestone criteria for initial retroreflectivity is 300 mcd/m^2/lux for Yellow and 250 mcd/m^2/lux for White, one-year retroreflectivity is 250 mcd/m^2/lux for Yellow and 200 mcd/ m^2/lux for White, two-year retroreflectivity is 200 mcd/m^2/lux for Yellow and 150 mcd/m^2/lux for White, and three-year retroreflectivity is 150 mcd/m^2/lux for Yellow and 100 mcd/m^2/lux for White. These criteria were selected base on threshold retroreflectivity values of 150 mcd/m^2/lux for yellow markings and 100 mcd/m^2/lux for white markings. It is assumed that most of the evaluated materials will last more than 3 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.

By reviewing the data presented in Tables (4.2) through (4.8), the following observations can be made pertaining to retroreflectivity variations between white and yellow markings, skip and wheel locations, asphalt and concrete surfaces, and general trends in data from one year to another:

- White markings have higher retroreflectivity than yellow markings.
- For most cases, yellow markings deteriorated at almost the same rate as white markings. The deterioration rate was quantified by dividing 2-year retroreflectivity since this value is available for all materials by initial retroreflectivity.

- For the same pavement marking and on the same test deck, initial skip and wheel retroreflectivity was very close. This can be rationally explained by the same installation conditions in both locations.
- The wheel deterioration rate, however, was higher than that of the skip since the former comes more frequently in contact with traffic.
- In general, comparable initial retroreflectivity values were obtained for asphalt and concrete surfaces.
- Furthermore, there was no obvious difference in pavement marking performance on asphalt and concrete surfaces.
- For most materials, the highest deterioration took place in the first year. This trend was more obvious for wheel retroreflectivity than skip retroreflectivity.
- Based on skip retroreflectivity, most materials did not reach the end of their service life (150 mcd/m^2/lux for white and 100 mcd/m^2/lux for yellow) before the end of the NTPEP evaluation.
- Based on wheel retroreflectivity, most materials reached the end of their service life (150 mcd/m^2/lux for white and 100 mcd/m^2/lux for yellow) in less than 2 years.

Additional comments based retroreflectivity variations between materials and between test decks are presented in the following chapters.

Table 4.2- Initial, 1-year, 2-year, and 3-year Average Retroreflectivity Measurements for HPS-4 (Modified Urethane).

White Skip Retroreflectivity						
Age	MS-056 (Asphalt)	MS-056 (Concrete)	WI-043 (Asphalt)	WI-043 (Concrete)	PA-047 (Asphalt)	PA-047 (Concrete)
Initial	560	513.5	410	**297.5**	469.75	473.25
1-year	333.75	311.5	**216.33**	528	360.25	414.75
2-year	233	228.5	**124.67**	390.5	293	398.25
3-year	179.75	170.25	--	--	196	290.5

White Wheel Retroreflectivity						
Age	MS-056 (Asphalt)	MS-056 (Concrete)	WI-043 (Asphalt)	WI-043 (Concrete)	PA-047 (Asphalt)	PA-047 (Concrete)
Initial	520.5	548.5	449.67	406	562.25	529
1-year	**214**	**178.75**	**173.33**	**179.5**	**168.5**	**161.25**
2-year	**132.5**	**123**	**102**	**140**	**124.25**	**94.75**
3-year	**128.75**	**101**	**--**	**--**	**86.25**	**73.5**

Yellow Skip Retroreflectivity						
Age	MS-057 (Asphalt)	MS-057 (Concrete)	WI-044 (Asphalt)	WI-044 (Concrete)	PA-048 (Asphalt)	PA-048 (Concrete)
Initial	374.25	**231**	351.75	316	293.75	328.5
1-year	**183**	256.25	**151**	338	**167.5**	222.5
2-year	**136.25**	177.75	**106.75**	212	**146**	215.25
3-year	121	128.75	--	--	123.5	169.75

Yellow Wheel Retroreflectivity						
Age	MS-057 (Asphalt)	MS-057 (Concrete)	WI-044 (Asphalt)	WI-044 (Concrete)	PA-048 (Asphalt)	PA-048 (Concrete)
Initial	386.5	260.75	379.75	367	296.5	323.5
1-year	**114**	**136**	**116**	**132**	**113.25**	**111.75**
2-year	**84.25**	**95.5**	**69**	**86**	**83.5**	**86.5**
3-year	**89.75**	**80**	**--**	**--**	**75.25**	**67.5**

Table 4.3- Initial, 1-year, 2-year, and 3-year Average Retroreflectivity Measurements for Tuffline Alkyd (Thermoplastic).

White Skip Retroreflectivity				
Age	MS-029 (Asphalt)	MS-029 (Concrete)	PA-024 (Asphalt)	PA-024 (Concrete)
Initial	472.25	418	481.25	483.75
1-year	411.25	280.5	413.25	342.5
2-year	**191.25**	202.25	363.25	353
3-year	--	--	247.75	219.75

White Wheel Retroreflectivity				
Age	MS-029 (Asphalt)	MS-029 (Concrete)	PA-024 (Asphalt)	PA-024 (Concrete)
Initial	499.25	442.75	486	433.25
1-year	**137.25**	**135.5**	**142.5**	**120.75**
2-year	**126.5**	**124.25**	**135.75**	**122.75**
3-year	**--**	**--**	**118**	**106.25**

Yellow Skip Retroreflectivity				
Age	MS-030 (Asphalt)	MS-030 (Concrete)	PA-025 (Asphalt)	PA-025 (Concrete)
Initial	**233.75**	**191**	**218**	**248**
1-year	**114.25**	**109.25**	**168**	**141.75**
2-year	**93.75**	**112**	213.5	**141.25**
3-year	--	--	167	115.75

Yellow Wheel Retroreflectivity				
Age	MS-030 (Asphalt)	MS-030 (Concrete)	PA-025 (Asphalt)	PA-025 (Concrete)
Initial	**245.75**	**177**	**222.75**	**216**
1-year	**57.5**	**60.25**	**75.75**	**62.5**
2-year	**57.5**	**59.75**	**77**	**49.75**
3-year	--	--	**57.5**	**30.25**

Table 4.4- Initial, 1-year, 2-year, and 3-year Average Retroreflectivity Measurements for Mark 55.3 (Epoxy).

White Skip Retroreflectivity				
Age	PA-145 (Asphalt)	PA-145 (Concrete)	UT-020 (Asphalt)	UT-020 (Concrete)
Initial	424	421.5	305	**211**
1-year	262.75	443.25	**101**	**192**
2-year	**187.75**	407.25	**92**	**168**
3-year	**104.5**	**145.25**	--	--

White Wheel Retroreflectivity				
Age	PA-145 (Asphalt)	PA-145 (Concrete)	UT-020 (Asphalt)	UT-020 (Concrete)
Initial	399	448	252	**224**
1-year	**120.25**	**140.75**	**10**	**92**
2-year	**61.5**	**67.75**	**5**	**52**
3-year	**38.5**	**25.25**	--	--

Yellow Skip Retroreflectivity				
Age	PA-147 (Asphalt)	PA-147 (Concrete)	UT-021 (Asphalt)	UT-021 (Concrete)
Initial	394.75	325.75	**191**	**146**
1-year	281.25	319.25	**75**	**130**
2-year	169	275.5	**70**	**98**
3-year	**80.5**	109	--	--

Yellow Wheel Retroreflectivity				
Age	PA-147 (Asphalt)	PA-147 (Concrete)	UT-021 (Asphalt)	UT-021 (Concrete)
Initial	396.5	348.5	**176**	**149**
1-year	**104.5**	**129.5**	**11**	**62**
2-year	**54.25**	**62**	**0**	**40**
3-year	**30.25**	**22.75**	--	--

Table 4.5- Initial, 1-year, 2-year, and 3-year Average Retroreflectivity Measurements for HPS-5 (Polyurea).

White Skip Retroreflectivity						
Age	MS-058 (Asphalt)	MS-058 (Concrete)	WI-045 (Asphalt)	WI-045 (Concrete)	PA-049 (Asphalt)	PA-049 (Concrete)
Initial	570.75	445.5	415.5	481.25	340	454.75
1-year	368.25	365.25	257.5	555.75	254.5	342.25
2-year	265.25	258.5	**196**	413.25	220.75	298
3-year	226	211.5	--	--	174	297.75

White Wheel Retroreflectivity						
Age	MS-058 (Asphalt)	MS-058 (Concrete)	WI-045 (Asphalt)	WI-045 (Concrete)	PA-049 (Asphalt)	PA-049 (Concrete)
Initial	525.75	480.75	443.25	468	307.25	531
1-year	**207**	**182.75**	**158.25**	**184**	**134**	**146.25**
2-year	**149.5**	**129.75**	**95.5**	**109**	**98**	**98.25**
3-year	167.25	**94.5**	--	--	**100.5**	**88**

Yellow Skip Retroreflectivity						
Age	MS-059 (Asphalt)	MS-059 (Concrete)	WI-046 (Asphalt)	WI-046 (Concrete)	PA-050 (Asphalt)	PA-050 (Concrete)
Initial	459.25	313.75	366.25	302.5	392	374
1-year	294.5	285.5	202	366.25	234	324.75
2-year	226.75	208.75	**140**	299	213.5	246.75
3-year	173.5	125	--	--	156.25	193

Yellow Wheel Retroreflectivity						
Age	MS-059 (Asphalt)	MS-059 (Concrete)	WI-046 (Asphalt)	WI-046 (Concrete)	PA-050 (Asphalt)	PA-050 (Concrete)
Initial	453	296.75	366.25	359.5	378.75	384
1-year	**164.25**	**168.25**	**99.75**	**188.5**	**132.25**	**146.75**
2-year	**116.25**	**120.25**	**82.5**	**122.25**	**85.75**	**79.5**
3-year	116.25	**76.75**	--	--	**79.75**	**56.5**

Table 4.6- Initial, 1-year, 2-year, and 3-year Average Retroreflectivity Measurements for 3M 380 (Durable Tape).

White Skip Retroreflectivity						
Age	MS-001 (Asphalt)	MS-001 (Concrete)	PA-003 (Asphalt)	PA-003 (Concrete)	WI-003 (Asphalt)	WI-003 (Concrete)
Initial	934.25	745.25	898.5	852.5	741.5	765.75
1-year	906.75	500	627.5	651.25	484.75	892
2-year	224.5	297.25	348.25	424.5	347	651
3-year	--	--	168	230.5	--	--

White Wheel Retroreflectivity						
Age	MS-001 (Asphalt)	MS-001 (Concrete)	PA-003 (Asphalt)	PA-003 (Concrete)	WI-003 (Asphalt)	WI-003 (Concrete)
Initial	915	702	776.75	740.5	815.75	733
1-year	**154.25**	**217**	**106**	**120.75**	374.75	451.5
2-year	**66.75**	**133.75**	**88**	**94.25**	**156.25**	**194.5**
3-year	**--**	**--**	**75.5**	**72.5**	**--**	**--**

Yellow Skip Retroreflectivity						
Age	MS-002 (Asphalt)	MS-002 (Concrete)	PA-004 (Asphalt)	PA-004 (Concrete)	WI-004 (Asphalt)	WI-004 (Concrete)
Initial	517	436.5	489.5	456.75	398.75	411.5
1-year	537	353	323.75	343.25	299.25	517
2-year	337	258	195.75	255.25	229	380.25
3-year	--	**--**	**99.5**	153.5	--	**--**

Yellow Wheel Retroreflectivity						
Age	MS-002 (Asphalt)	MS-002 (Concrete)	PA-004 (Asphalt)	PA-004 (Concrete)	WI-004 (Asphalt)	WI-004 (Concrete)
Initial	486.75	429	407.25	384	423.75	403.25
1-year	259	**180**	**64.25**	**64.75**	**135.75**	261
2-year	**140.75**	**107**	**36.5**	**44.25**	**101.75**	**129**
3-year	**--**	**--**	**28.75**	**29**	**--**	**--**

Table 4.7- Initial, 1-year, 2-year, and 3-year Average Retroreflectivity Measurements for Premark Plus (Preformed Thermoplastic).

White Skip Retroreflectivity						
Age	MS-066 (Asphalt)	MS-066 (Concrete)	PA-064 (Asphalt)	PA-064 (Concrete)	WI-040 (Asphalt)	WI-040 (Concrete)
Initial	554.5	521.75	552	648	520.25	656.75
1-year	396.5	348	474	551.75	423.75	641.25
2-year	**104**	**190.75**	270.75	277.5	285.75	422.25
3-year	--	--	161.25	173.25	--	--

White Wheel Retroreflectivity						
Age	MS-066 (Asphalt)	MS-066 (Concrete)	PA-064 (Asphalt)	PA-064 (Concrete)	WI-040 (Asphalt)	WI-040 (Concrete)
Initial	598	590.25	638	685.5	531	581.5
1-year	**85.25**	**90.25**	**141.75**	**93.5**	**222.5**	395.5
2-year	**70**	**75**	**103.75**	**90.75**	**122.5**	**141**
3-year	**--**	**--**	**110**	**88.75**	**--**	**--**

Yellow Skip Retroreflectivity				
Age	MS-067 (Asphalt)	MS-067 (Concrete)	PA-065 (Asphalt)	PA-065 (Concrete)
Initial	464.25	317	265	346.25
1-year	219.25	**168.25**	240.75	267.5
2-year	**72**	**99.75**	151.5	153
3-year	--	--	123.5	138.25

Yellow Wheel Retroreflectivity				
Age	MS-067 (Asphalt)	MS-067 (Concrete)	PA-065 (Asphalt)	PA-065 (Concrete)
Initial	363.75	332	349.5	344.75
1-year	**63.25**	**76**	**86.75**	**74**
2-year	**55**	**55.75**	**99.5**	**89**
3-year	--	--	**89.5**	**69.75**

Table 4.8- Initial, 1-year, 2-year, and 3-year Average Retroreflectivity Measurements for Dura-Stripe (Methyl Methacrylate).

White Skip Retroreflectivity				
Age	MS-155 (Asphalt)	MS-155 (Concrete)	PA-208 (Asphalt)	PA-208 (Concrete)
Initial	**102.5**	**125.25**	284.5	368.75
1-year	**235.75**	**104.5**	279.75	401
2-year	**99**	**68**	261	359
3-year	--	--	219.25	262.75

White Wheel Retroreflectivity				
Age	MS-155 (Asphalt)	MS-155 (Concrete)	PA-208 (Asphalt)	PA-208 (Concrete)
Initial	**105.5**	**108.5**	412.25	355.75
1-year	**94.75**	**43.5**	**203**	**185.5**
2-year	**33.75**	**38**	**31.5**	**82.5**
3-year	**--**	**--**	**28.25**	**45.5**

Yellow Skip Retroreflectivity				
Age	MS-156 (Asphalt)	MS-156 (Concrete)	PA-209 (Asphalt)	PA-209 (Concrete)
Initial	**122**	**75.25**	**81.5**	**156.25**
1-year	**101**	**102**	**145.5**	**176.5**
2-year	168.25	**53.25**	**126.25**	**116**
3-year	--	--	**54.25**	**69.5**

Yellow Wheel Retroreflectivity				
Age	MS-156 (Asphalt)	MS-156 (Concrete)	PA-209 (Asphalt)	PA-209 (Concrete)
Initial	**121.5**	**81.25**	**107.5**	**149.5**
1-year	**46.75**	**26.75**	**64.25**	**45.75**
2-year	**40.75**	**23**	**36.25**	**29.5**
3-year	**--**	**--**	**20.25**	**16.75**

4.2.2 Durability

Tables (4.9) through (4.15) present initial, 1-yr, 2-yr, and 3-yr (if available) durability ratings for the seven (7) marking materials presented in Table (4.1) and the corresponding NTPEP test decks on which each material was tested. Each table consists of four sub-tables representing white skip durability, white wheel durability, yellow skip durability, and yellow wheel durability.

By reviewing the data presented in these tables, the following observations can be made:

- All materials investigated in this study are durable pavement markings. As such, the durability of most materials did not drop below a durability rating of five.
- In general, comparable durability performance was obtained for white and yellow pavement markings.
- As expected, lower durability ratings were obtained for wheel than skip.
- Comparable durability performance was obtained on asphalt and concrete surfaces.
- As compared to retroreflectivity, which had a higher deterioration rate in the first year compared to the following years, durability deterioration rate was the highest towards the end of the evaluation.

Additional comments based retroreflectivity variations between materials and between test decks are presented in the following chapters.

Table 4.9- Initial, 1-year, 2-year, and 3-year Durability Measurements for HPS-4 (Modified Urethane).

White Skip Durability				
Age	MS-056 (Asphalt)	MS-056 (Concrete)	PA-047 (Asphalt)	PA-047 (Concrete)
Initial	10	10	10	10
1-year	10	10	9	9
2-year	9	9	9	9
3-year	8	9	8	9

White Wheel Durability				
Age	MS-056 (Asphalt)	MS-056 (Concrete)	PA-047 (Asphalt)	PA-047 (Concrete)
Initial	10	10	10	10
1-year	10	9	8	9
2-year	7	6	8	7
3-year	7	7	7	6

Yellow Skip Durability				
Age	MS-057 (Asphalt)	MS-057 (Concrete)	PA-048 (Asphalt)	PA-048 (Concrete)
Initial	10	10	10	10
1-year	10	10	10	9
2-year	9	10	10	9
3-year	9	9	9	9

Yellow Wheel Durability				
Age	MS-057 (Asphalt)	MS-057 (Concrete)	PA-048 (Asphalt)	PA-048 (Concrete)
Initial	10	10	10	10
1-year	9	10	10	9
2-year	8	8	9	9
3-year	8	8	8	8

Table 4.10- Initial, 1-year, 2-year, and 3-year Durability Measurements for Tuffline Alkyd (Thermoplastic).

White Skip Durability				
Age	MS-029 (Asphalt)	MS-029 (Concrete)	PA-024 (Asphalt)	PA-024 (Concrete)
Initial	10	10	10	10
1-year	10	10	10	10
2-year	9	10	9	10
3-year	--	--	6	9

White Wheel Durability				
Age	MS-029 (Asphalt)	MS-029 (Concrete)	PA-024 (Asphalt)	PA-024 (Concrete)
Initial	10	10	10	10
1-year	10	10	9	9
2-year	8	10	9	9
3-year	--	--	5	8

Yellow Skip Durability				
Age	MS-030 (Asphalt)	MS-030 (Concrete)	PA-025 (Asphalt)	PA-025 (Concrete)
Initial	10	10	10	10
1-year	10	10	10	9
2-year	9	10	9	7
3-year	--	--	7	6

Yellow Wheel Durability				
Age	MS-030 (Asphalt)	MS-030 (Concrete)	PA-025 (Asphalt)	PA-025 (Concrete)
Initial	10	10	10	10
1-year	10	10	9	9
2-year	9	10	9	7
3-year	--	--	5	4

Table 4.11- Initial, 1-year, 2-year, and 3-year Durability Measurements for Mark 55.3 (Epoxy).

White Skip Durability				
Age	PA-145 (Asphalt)	PA-145 (Concrete)	UT-020 (Asphalt)	UT-020 (Concrete)
Initial	10	10	10	10
1-year	10	10	8	10
2-year	9	9	8	10
3-year	7	6	--	--

White Wheel Durability				
Age	PA-145 (Asphalt)	PA-145 (Concrete)	UT-020 (Asphalt)	UT-020 (Concrete)
Initial	10	10	10	10
1-year	9	9	1	10
2-year	9	7	0	10
3-year	4	2	--	--

Yellow Skip Durability				
Age	PA-147 (Asphalt)	PA-147 (Concrete)	UT-021 (Asphalt)	UT-021 (Concrete)
Initial	10	10	10	10
1-year	10	10	8	10
2-year	9	9	8	10
3-year	6	6	--	--

Yellow Wheel Durability				
Age	PA-147 (Asphalt)	PA-147 (Concrete)	UT-021 (Asphalt)	UT-021 (Concrete)
Initial	10	10	10	10
1-year	9	9	2	10
2-year	9	7	0	10
3-year	5	4	--	--

Table 4.12- Initial, 1-year, 2-year, and 3-year Durability Measurements for HPS-5 (Polyurea).

White Skip Durability				
Age	MS-058 (Asphalt)	MS-058 (Concrete)	PA-049 (Asphalt)	PA-049 (Concrete)
Initial	10	10	10	10
1-year	10	10	10	9
2-year	9	10	9	9
3-year	8	9	9	9

White Wheel Durability				
Age	MS-058 (Asphalt)	MS-058 (Concrete)	PA-049 (Asphalt)	PA-049 (Concrete)
Initial	10	10	10	10
1-year	10	10	9	9
2-year	8	8	9	8
3-year	6	8	8	8

Yellow Skip Durability				
Age	MS-059 (Asphalt)	MS-059 (Concrete)	PA-050 (Asphalt)	PA-050 (Concrete)
Initial	10	10	10	10
1-year	10	10	10	9
2-year	9	10	9	9
3-year	8	9	9	8

Yellow Wheel Durability				
Age	MS-059 (Asphalt)	MS-059 (Concrete)	PA-050 (Asphalt)	PA-050 (Concrete)
Initial	10	10	10	10
1-year	10	10	9	8
2-year	8	10	9	7
3-year	7	8	8	6

Table 4.13- Initial, 1-year, 2-year, and 3-year Durability Measurements for 3M 380 (Durable Tape).

White Skip Durability				
Age	MS-001 (Asphalt)	MS-001 (Concrete)	PA-003 (Asphalt)	PA-003 (Concrete)
Initial	10	10	10	10
1-year	10	10	10	10
2-year	10	10	10	10
3-year	--	--	9	10

White Wheel Durability				
Age	MS-001 (Asphalt)	MS-001 (Concrete)	PA-003 (Asphalt)	PA-003 (Concrete)
Initial	10	10	10	10
1-year	10	10	10	10
2-year	10	9	10	10
3-year	--	--	8	9

Yellow Skip Durability				
Age	MS-002 (Asphalt)	MS-002 (Concrete)	PA-004 (Asphalt)	PA-004 (Concrete)
Initial	10	10	10	10
1-year	10	10	10	10
2-year	10	10	10	10
3-year	--	--	9	10

Yellow Wheel Durability				
Age	MS-002 (Asphalt)	MS-002 (Concrete)	PA-004 (Asphalt)	PA-004 (Concrete)
Initial	10	10	10	10
1-year	10	10	10	10
2-year	10	10	9	9
3-year	--	--	8	9

Table 4.14- Initial, 1-year, 2-year, and 3-year Durability Measurements for Premark Plus (Preformed Thermoplastic).

White Skip Durability				
Age	MS-066 (Asphalt)	MS-066 (Concrete)	PA-064 (Asphalt)	PA-064 (Concrete)
Initial	10	10	10	10
1-year	10	10	10	10
2-year	10	10	10	10
3-year	--	--	8	9

White Wheel Durability				
Age	MS-066 (Asphalt)	MS-066 (Concrete)	PA-064 (Asphalt)	PA-064 (Concrete)
Initial	10	10	10	10
1-year	10	10	10	10
2-year	10	10	10	10
3-year	--	--	7	8

Yellow Skip Durability				
Age	MS-067 (Asphalt)	MS-067 (Concrete)	PA-065 (Asphalt)	PA-065 (Concrete)
Initial	10	10	10	10
1-year	10	10	10	10
2-year	10	10	9	9
3-year	--	--	8	8

Yellow Wheel Durability				
Age	MS-067 (Asphalt)	MS-067 (Concrete)	PA-065 (Asphalt)	PA-065 (Concrete)
Initial	10	10	10	10
1-year	10	10	10	9
2-year	10	10	9	8
3-year	--	--	7	7

Table 4.15- Initial, 1-year, 2-year, and 3-year Durability Measurements for Dura-Stripe (Methyl Methacrylate).

White Skip Durability				
Age	MS-155 (Asphalt)	MS-155 (Concrete)	PA-208 (Asphalt)	PA-208 (Concrete)
Initial	10	10	10	10
1-year	10	10	8	10
2-year	9	10	8	10
3-year	--	--	6	9

White Wheel Durability				
Age	MS-155 (Asphalt)	MS-155 (Concrete)	PA-208 (Asphalt)	PA-208 (Concrete)
Initial	10	10	10	10
1-year	10	10	9	10
2-year	9	10	8	9
3-year	--	--	4	8

Yellow Skip Durability				
Age	MS-156 (Asphalt)	MS-156 (Concrete)	PA-209 (Asphalt)	PA-209 (Concrete)
Initial	10	10	10	10
1-year	10	10	9	10
2-year	9	10	9	10
3-year	--	--	6	8

Yellow Wheel Durability				
Age	MS-156 (Asphalt)	MS-156 (Concrete)	PA-209 (Asphalt)	PA-209 (Concrete)
Initial	10	10	10	10
1-year	10	10	9	9
2-year	9	9	9	8
3-year	--	--	6	5

4.2.3 Color

Figures (4.1) through (4.18) present a comparison between NTPEP color measurements and the FHWA MUTCD color specification limits. Color performance of HPS-4 is presented in Figures (4.1) through (4.3); color performance of Tuffline Alkyd is presented in Figures (4.4) through (4.5); color performance of Mark 55.3 is presented in Figures (4.6) through (4.7); color performance of HPS-5 is presented in Figures (4.8) through (4.10); color performance of 3M 380 Tape is presented in Figures (4.11) through (4.13); color performance of Premark Plus is presented in Figures (4.14) through (4.16); and color performance of Dura-Strip is presented in Figures (4.17) through (4.18). Each figure consists of four sub-figures representing white color on asphalt, white color on concrete, yellow color on asphalt, and yellow color on concrete.

As mentioned earlier, the NTPEP program measures color in an un-beaded area of the line (within three feet of the test line on the right edge line side) to minimize the affect of dirt collection. As a result, the comparison in this section will be limited to the performance of white markings versus yellow markings on asphalt and concrete surfaces.

By reviewing the data presented in these figures, the following observations can be made:

- White pavement markings continued to receive white color readings well within specifications. This could be the result of: 1- the color of these materials continue to be acceptable throughout the performance evaluation duration, 2- white color specifications are not strict enough to identify the materials that have poor white color performance, or that 3- existing color measuring devices are incapable of measuring changes in white color. Given the wide range of materials examined in this study, some of the materials are expected to fail to meet specifications and hence it is believed that either the current white color specifications are not strict enough or that existing color measuring devices are not sensitive enough to measure changes in white color.

- Similar observation was reported by Abbas et al. (2009), who compared white color readings of sixteen pavement markings materials with subjective color ratings and noticed that color readings were well within the specification box even for the materials that continued to receive low subjective color ratings. According, it was suggested that the current white color specification limits are not necessarily capable of identifying the materials with poor color performance.
- In rare occasions, some marking materials had color readings outside the color specification box. These color readings, however, were inconsistent with the rest of the color readings obtained for that material. Therefore, it is believed that these color readings are probably outliers and should be excluded from the analysis.
- Even though white color readings were well within the white color specification box, it was noticed that initial white color readings were close to the center of the white color specification box and over time color readings moved towards the upper right side of the specification box.
- As for yellow markings, initial yellow color readings were close to the bottom left side of the yellow color specification box and over time color readings moved towards the lower left side of the specification box.

- In several instances, the color of the yellow markings continued to change beyond the lower left side of the specification box leading to the materials failing to meet specifications, which took place after about two years.
- As for the performance of pavement markings on asphalt and concrete surfaces, comparable color readings were obtained on these surfaces.

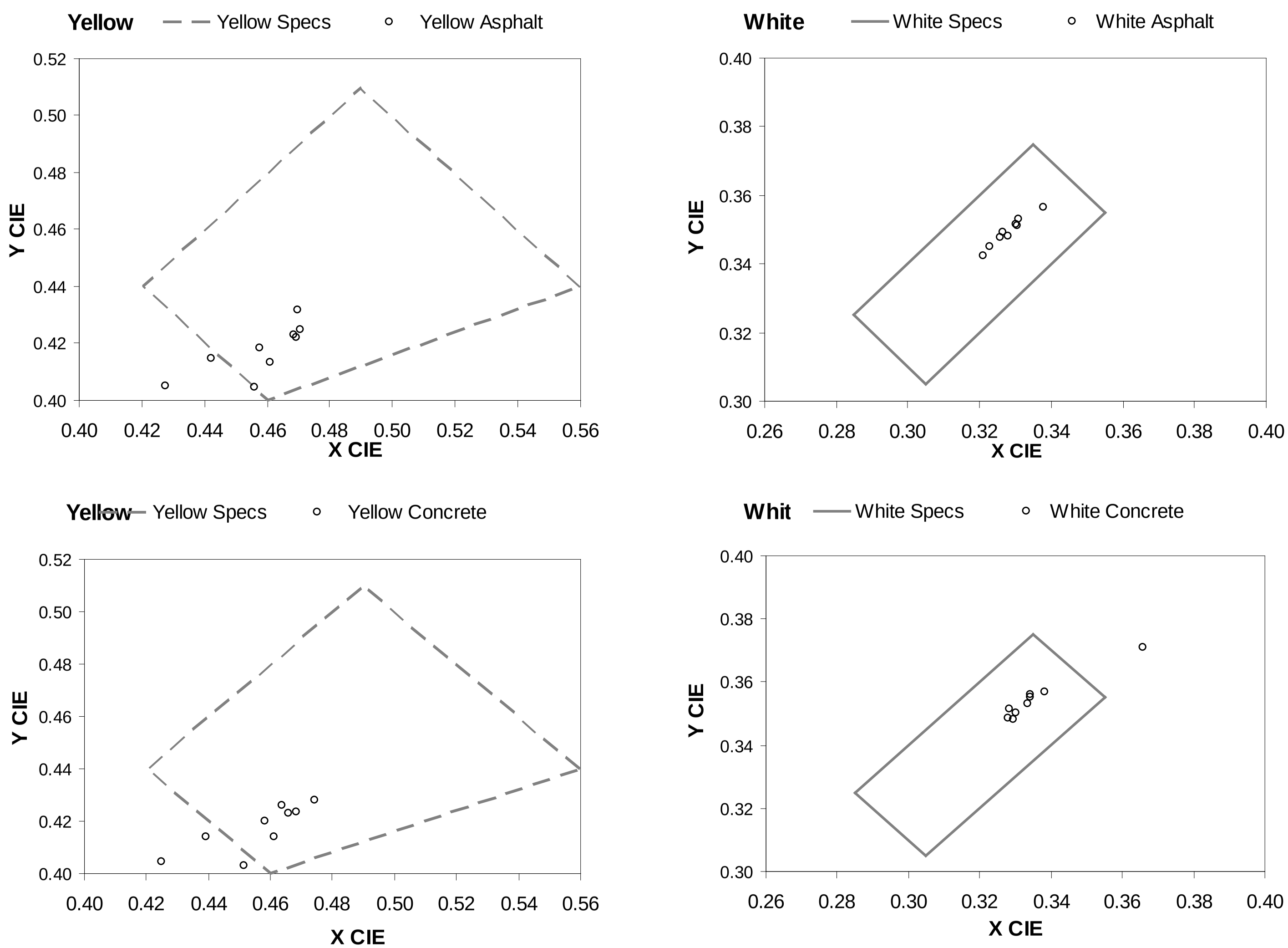


Figure 4.1- Color of HPS-4 in Mississippi.

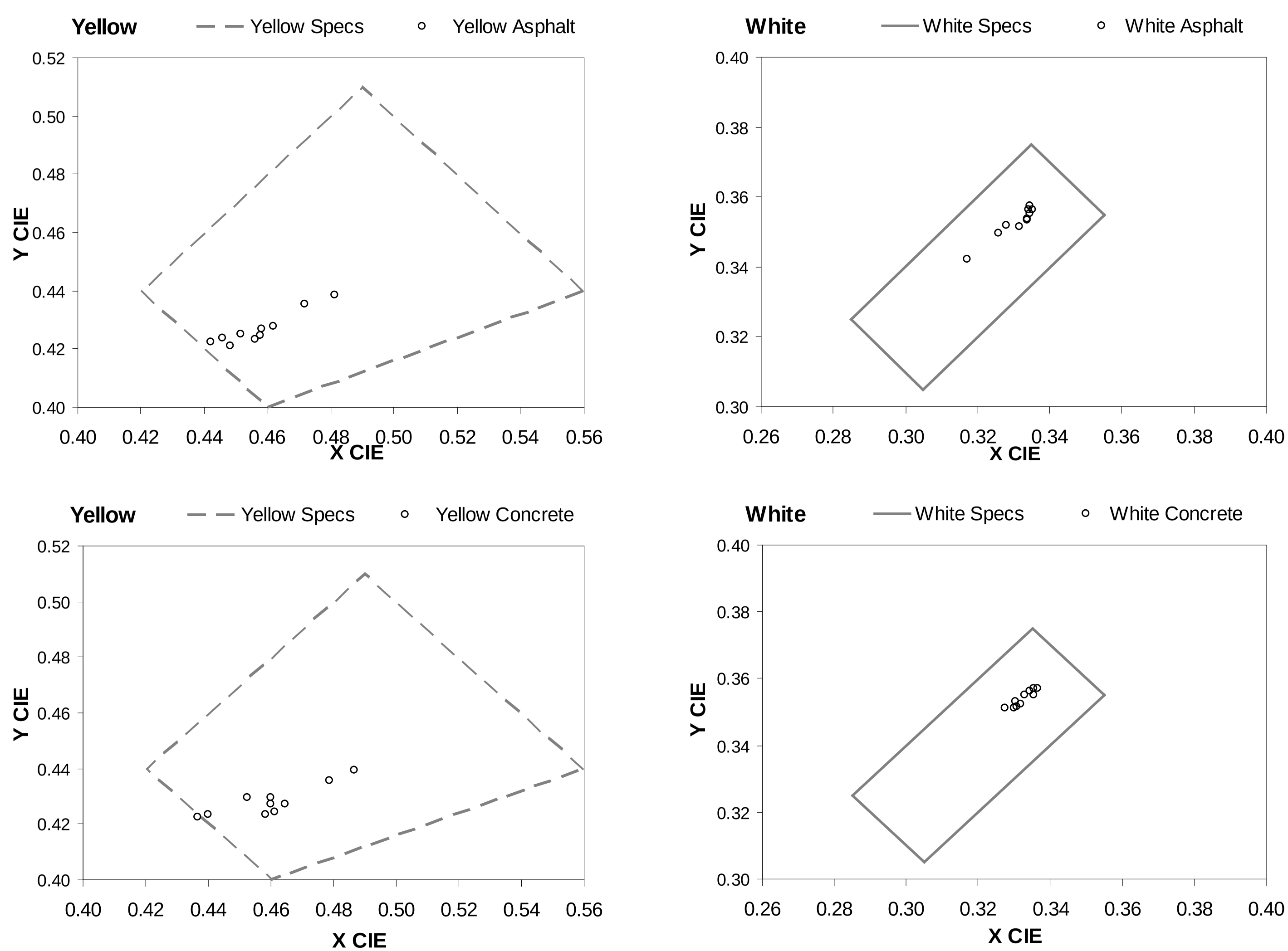


Figure 4.2- Color Performance of HPS-4 in Pennsylvania.

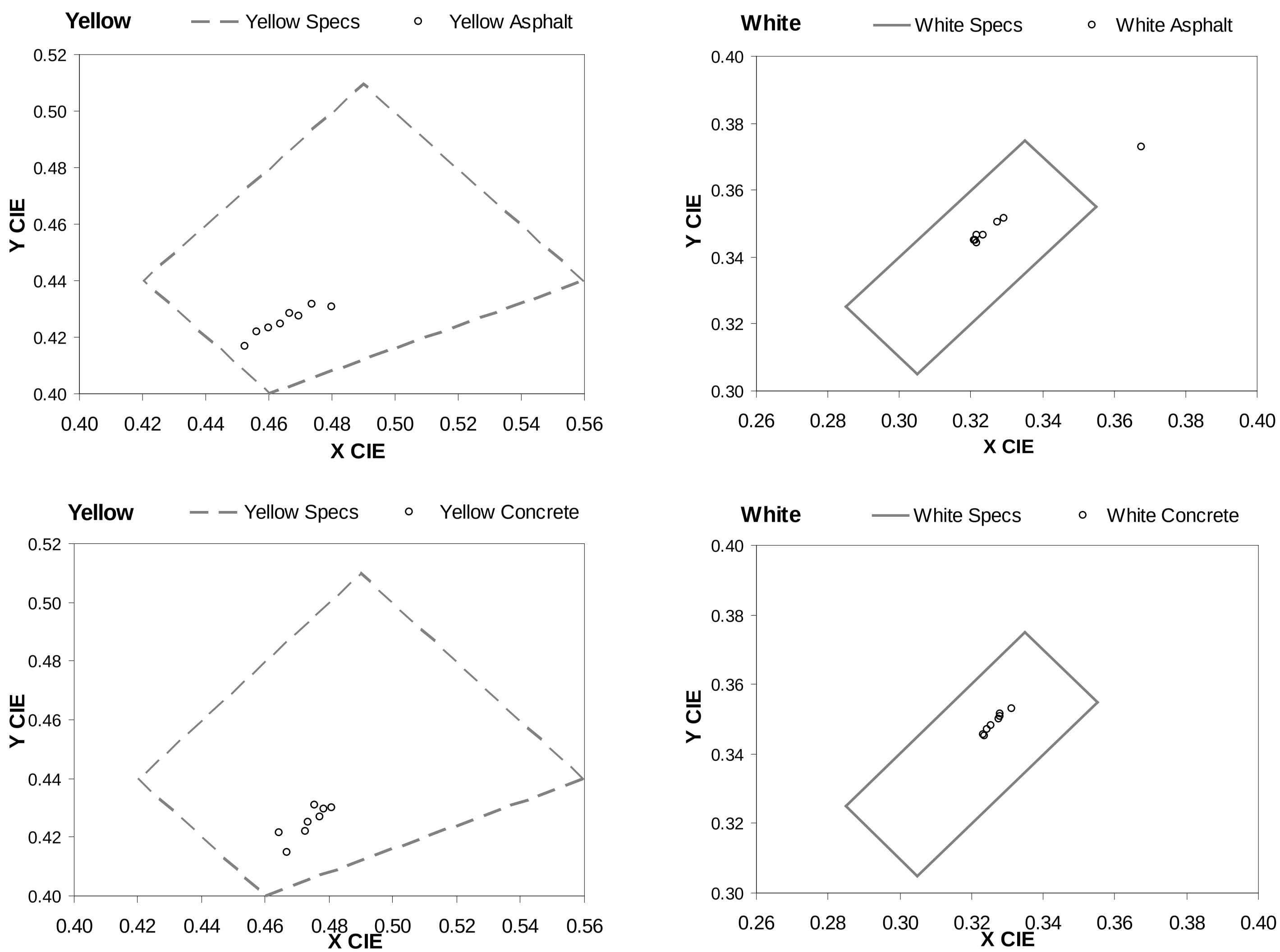


Figure 4.3- Color Performance of HPS-4 in Wisconsin.

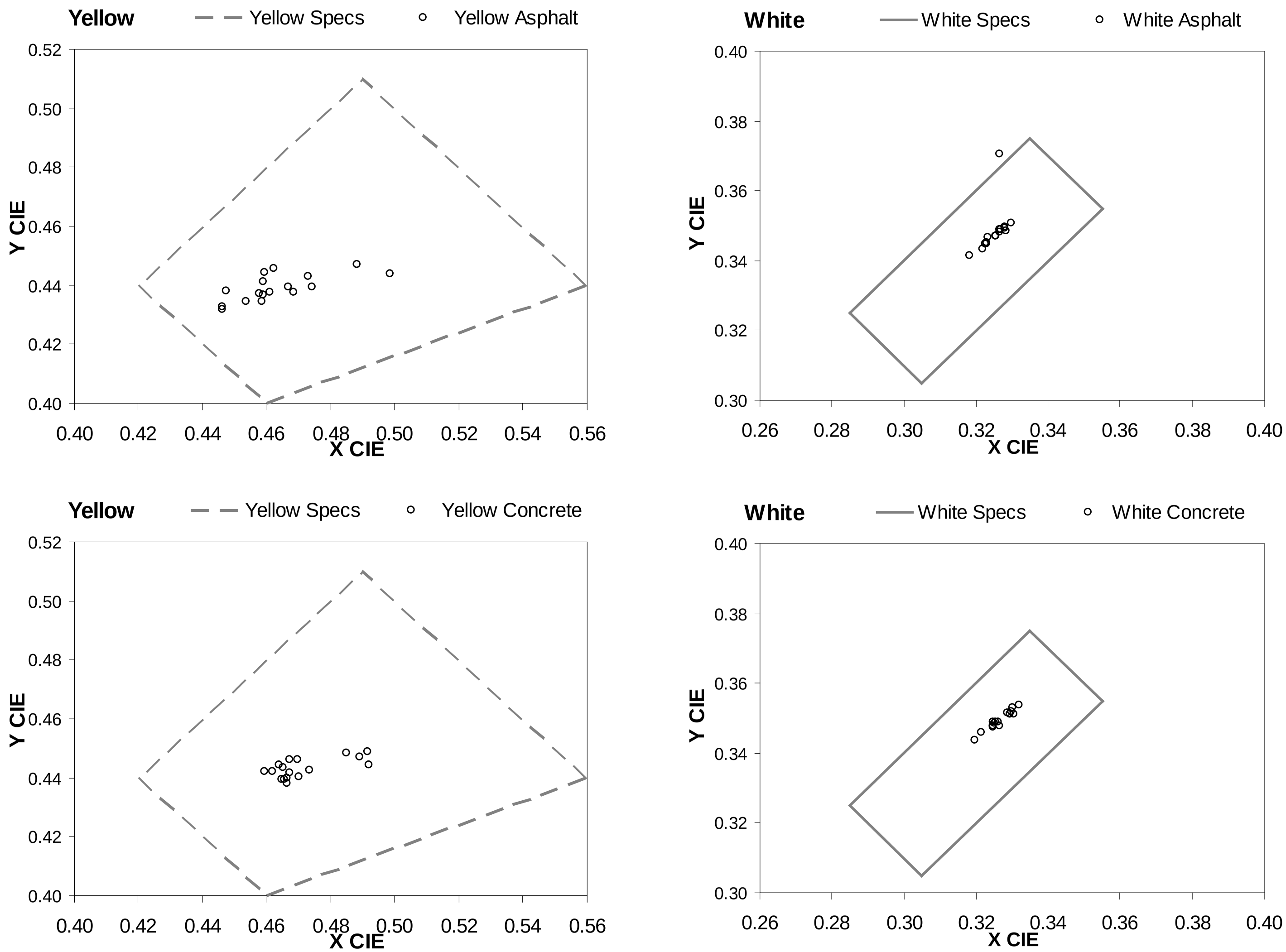


Figure 4.4- Color Performance of Tuffline Alkyd in Mississippi.

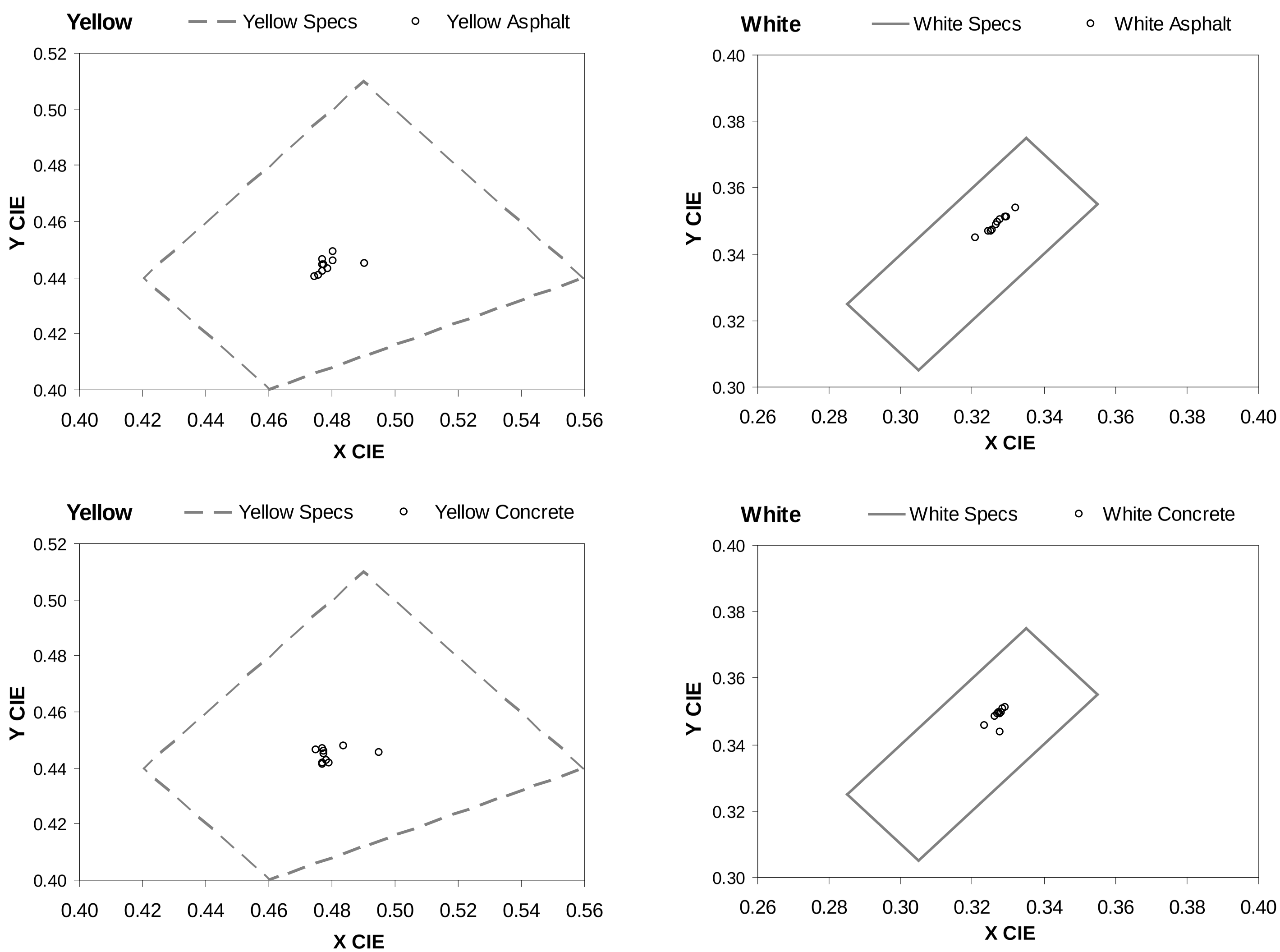


Figure 4.5- Color Performance of Tuffline Alkyd in Pennsylvania.

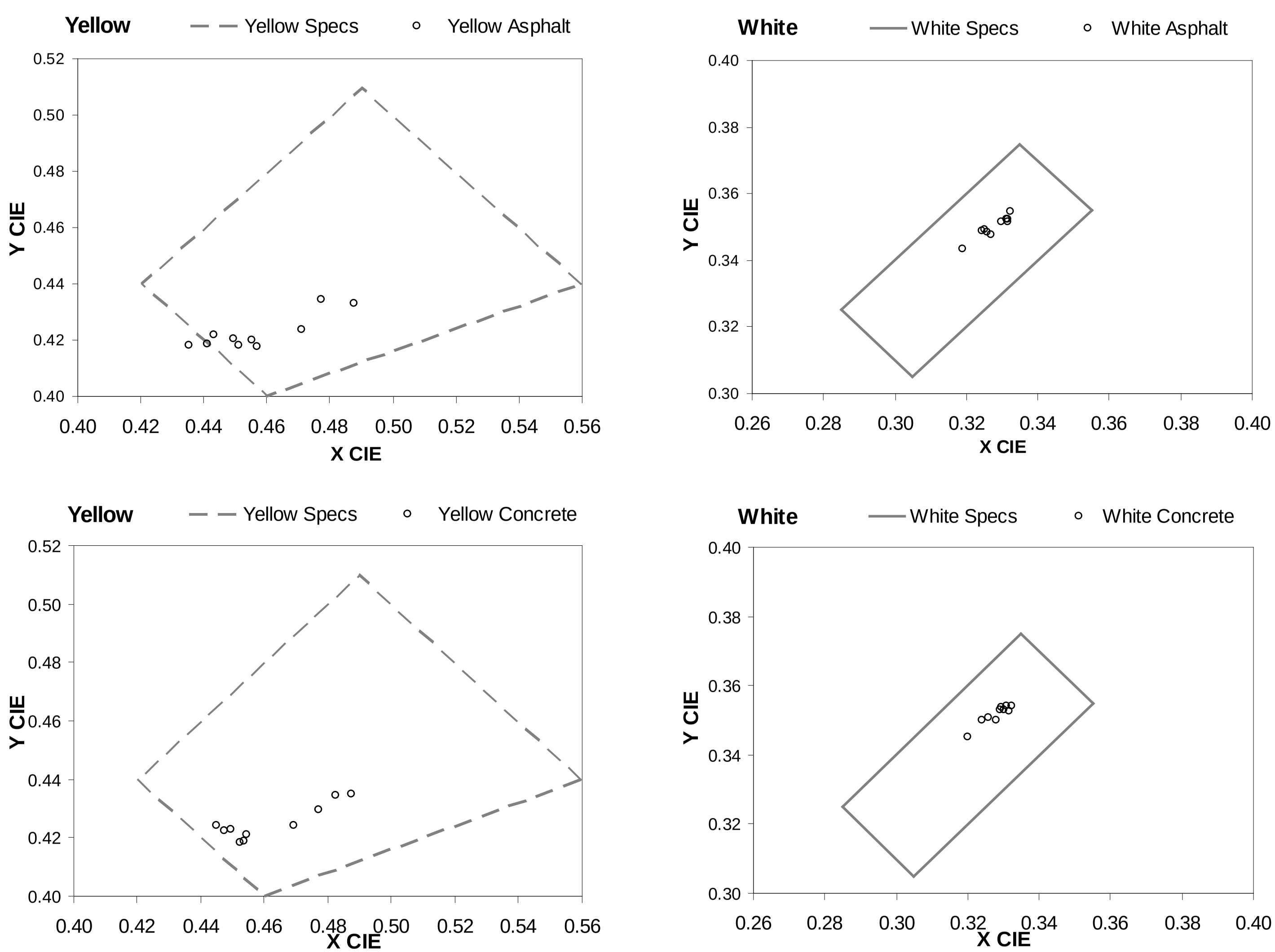


Figure 4.6- Color Performance of MARK 55.3 in Pennsylvania.

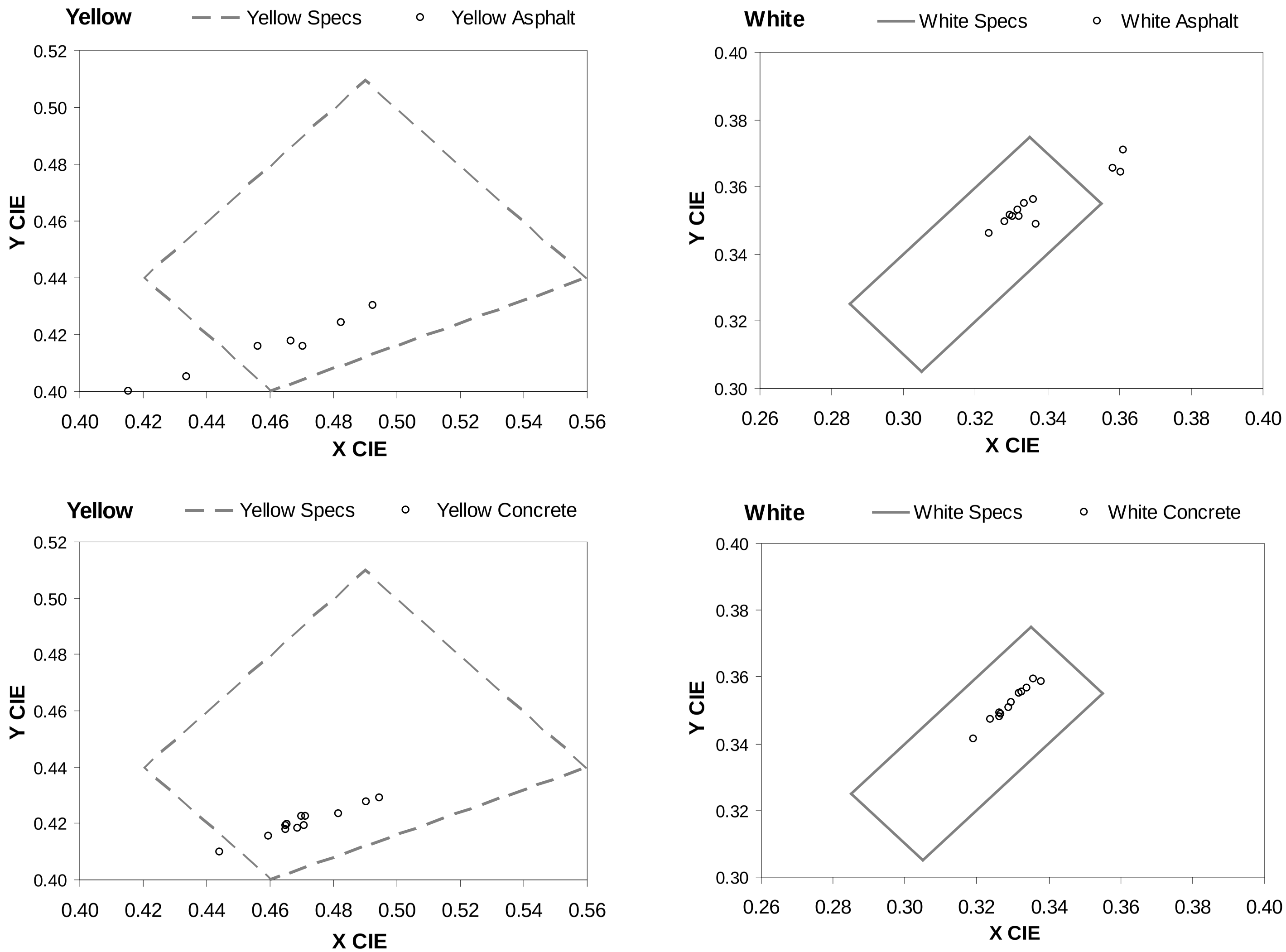


Figure 4.7- Color Performance of MARK 55.3 in Utah.

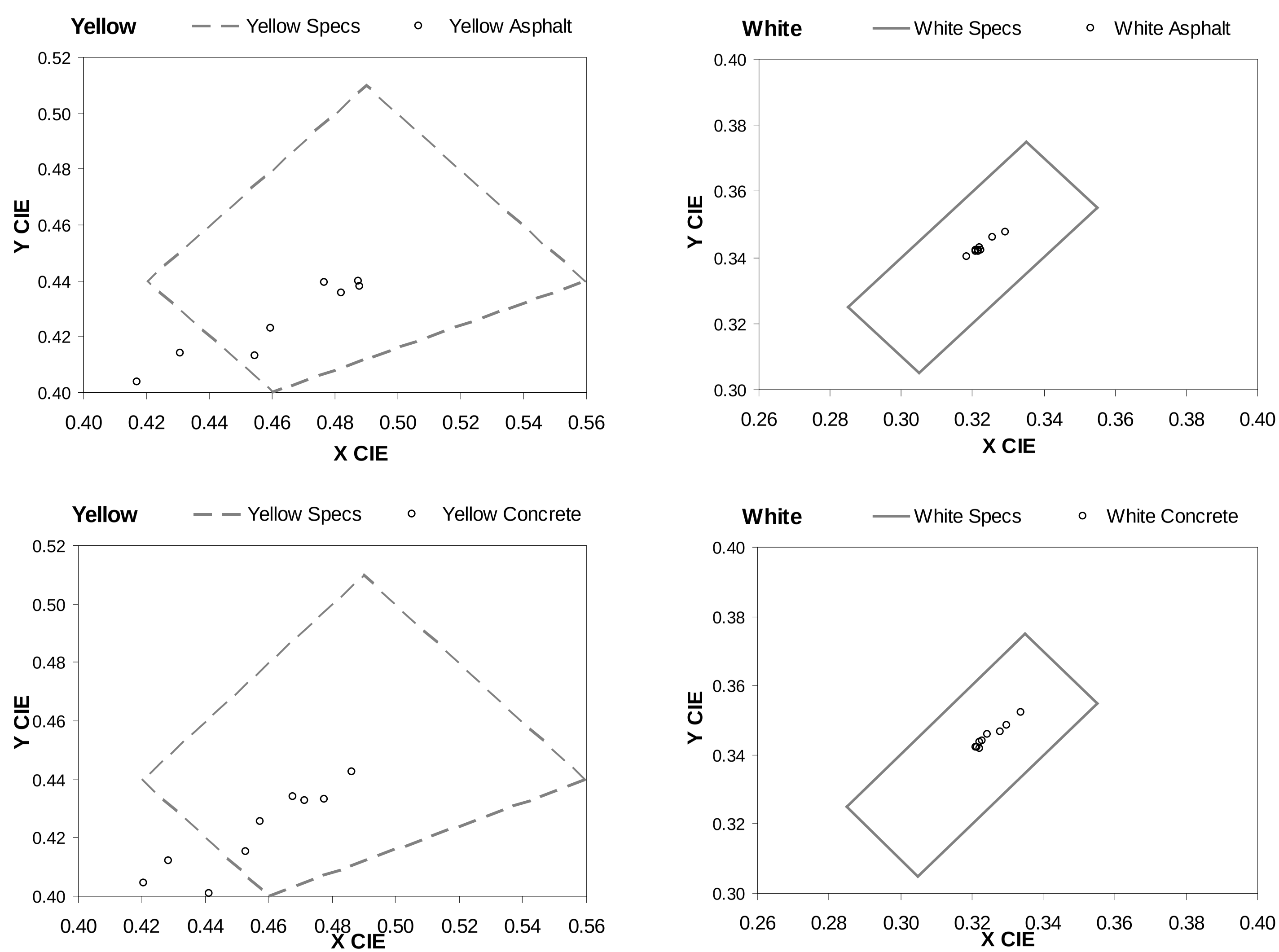


Figure 4.8- Color Performance of HPS-5 in Mississippi.

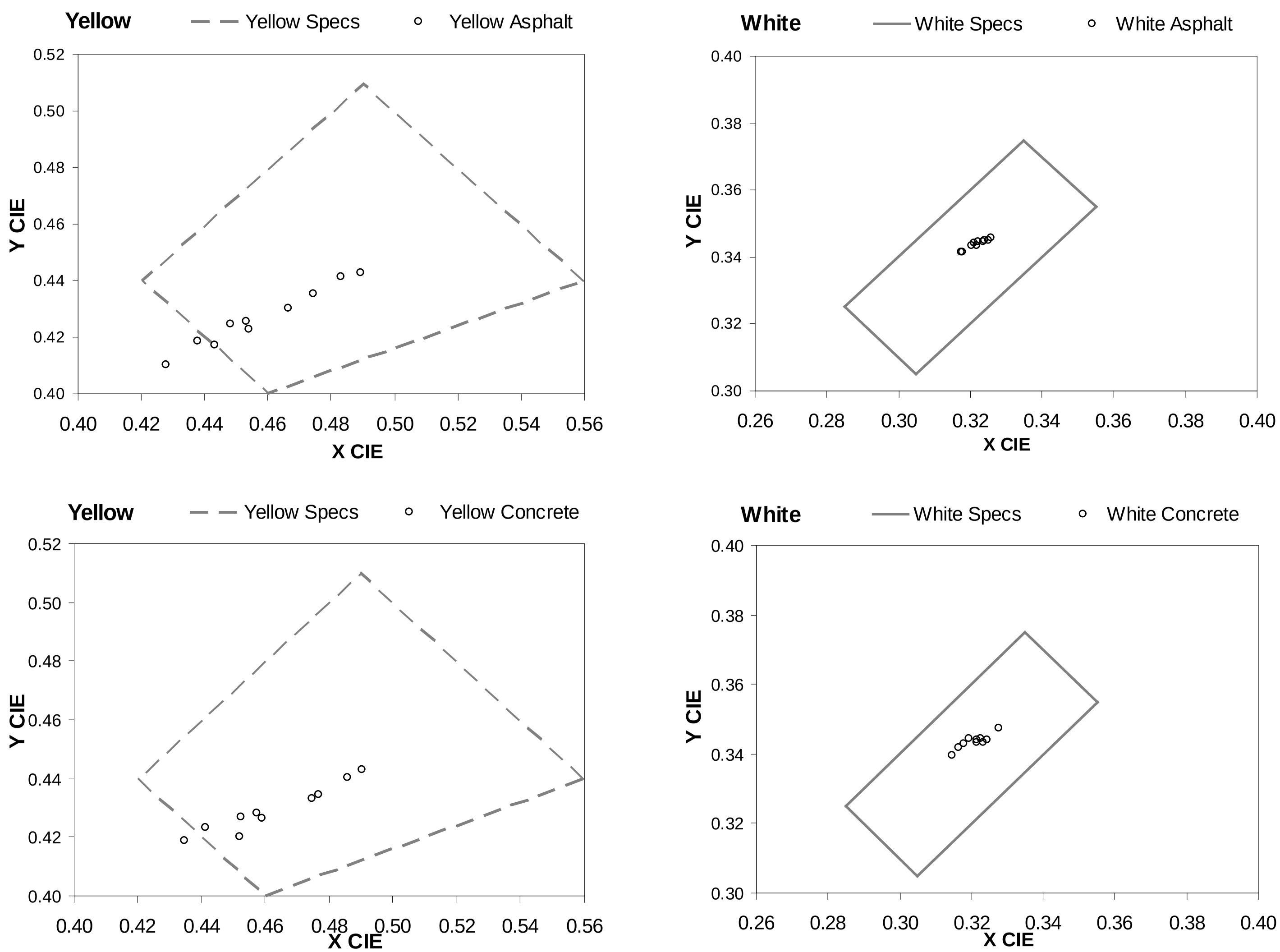


Figure 4.9- Color Performance of HPS-5 in Pennsylvania.

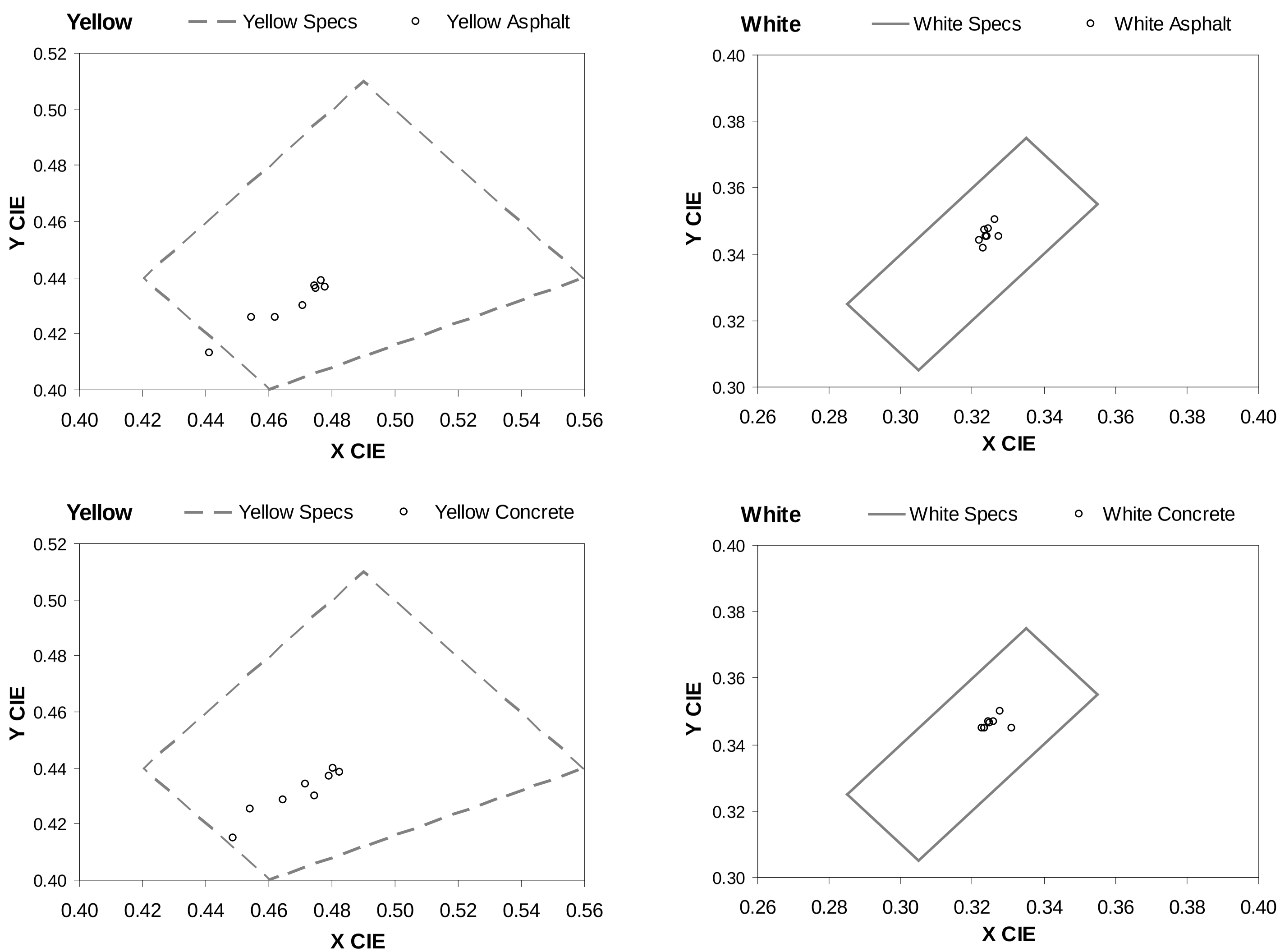


Figure 4.10- Color Performance of HPS-5 in Wisconsin.

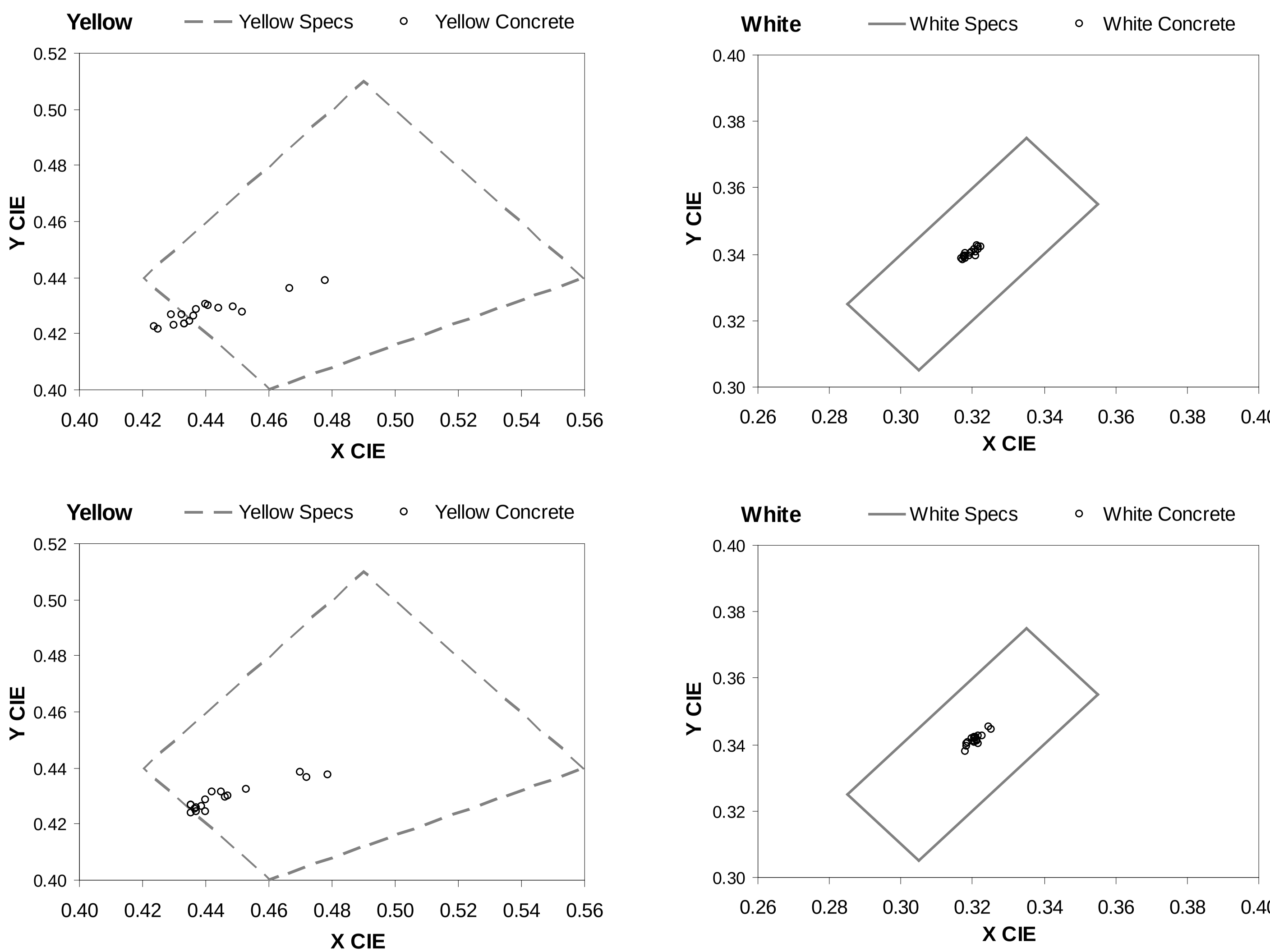


Figure 4.11- Color Performance of 3M 380 Tape in Mississippi.

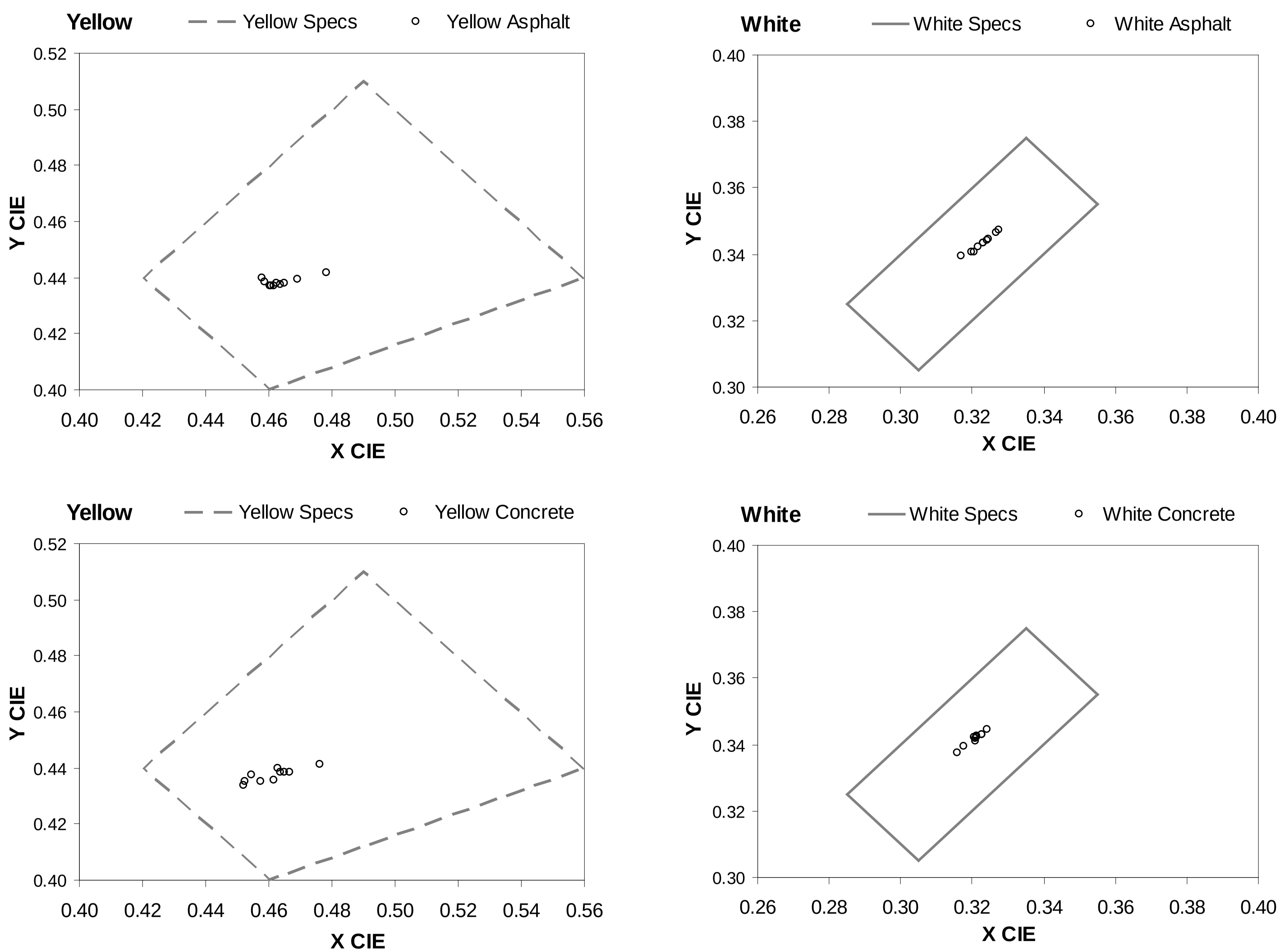


Figure 4.12- Color Performance of 3M 380 Tape in Pennsylvania.

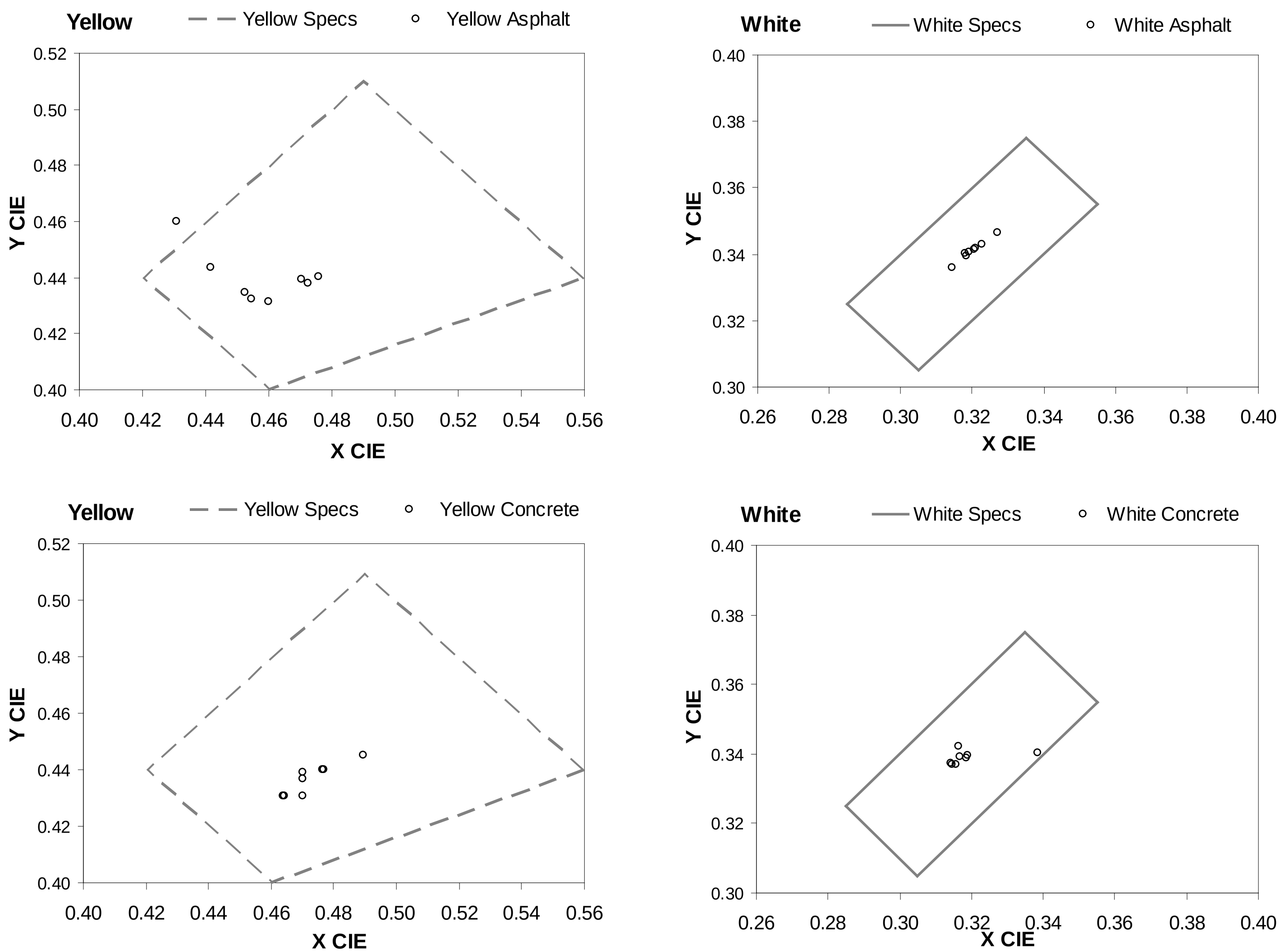


Figure 4.13- Color Performance of 3M 380 Tape in Wisconsin.

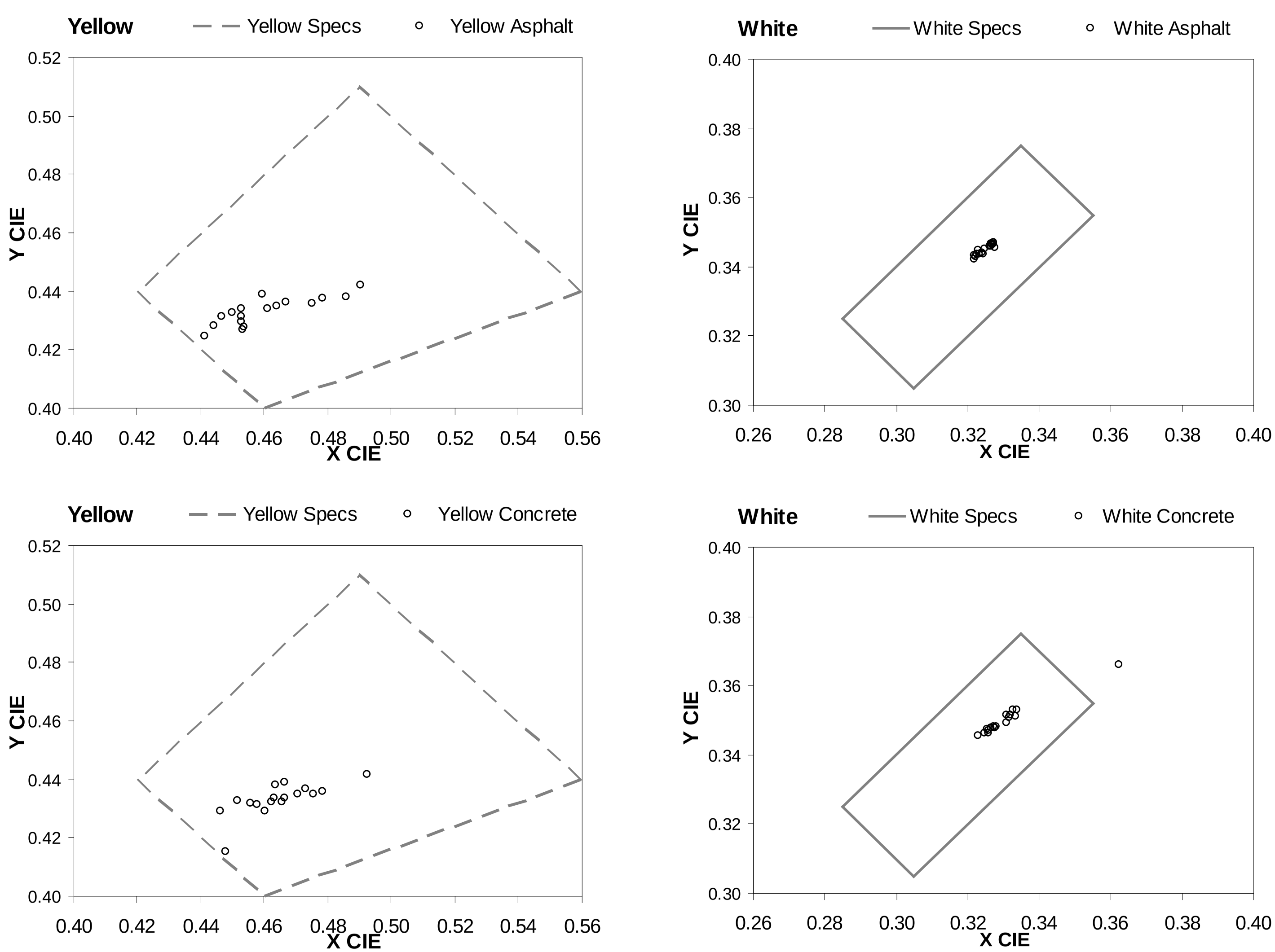


Figure 4.14- Color Performance of Premark Plus in Mississippi.

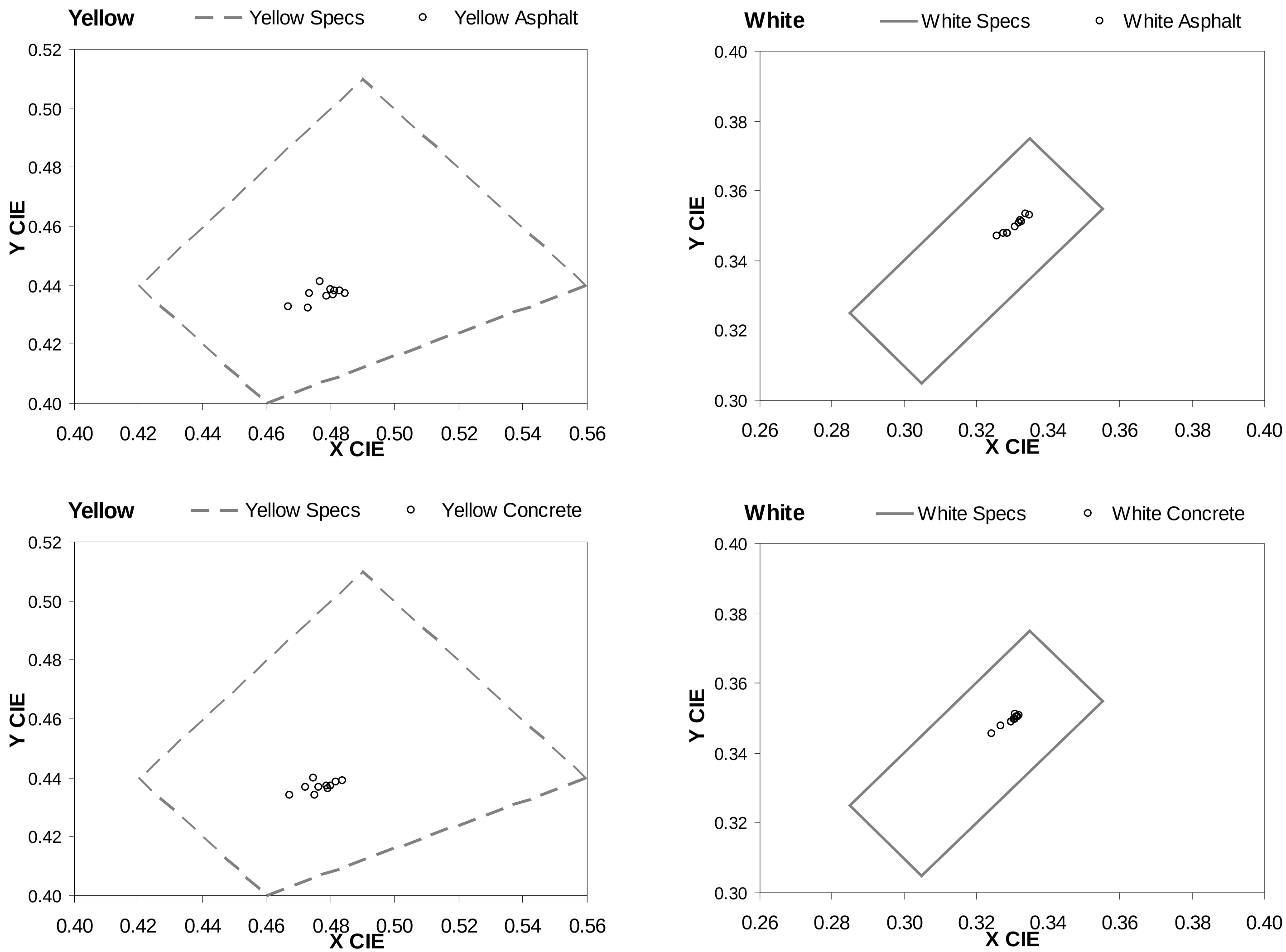


Figure 4.15- Color Performance of Premark Plus in Pennsylvania.

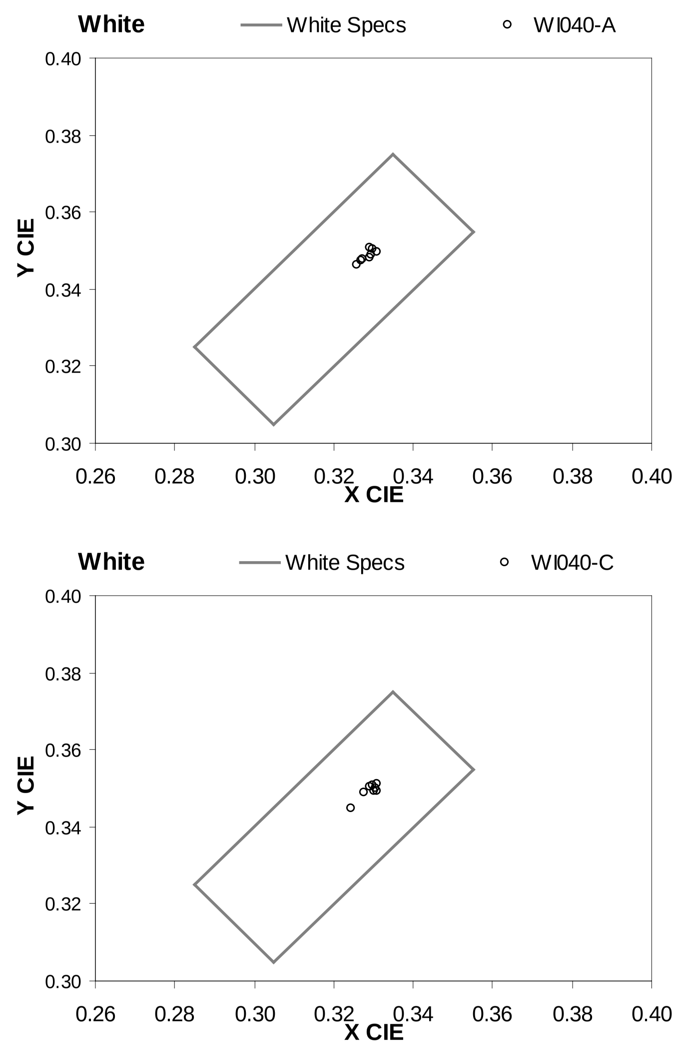


Figure 4.16- Color Performance of Premark Plus in Wisconsin.

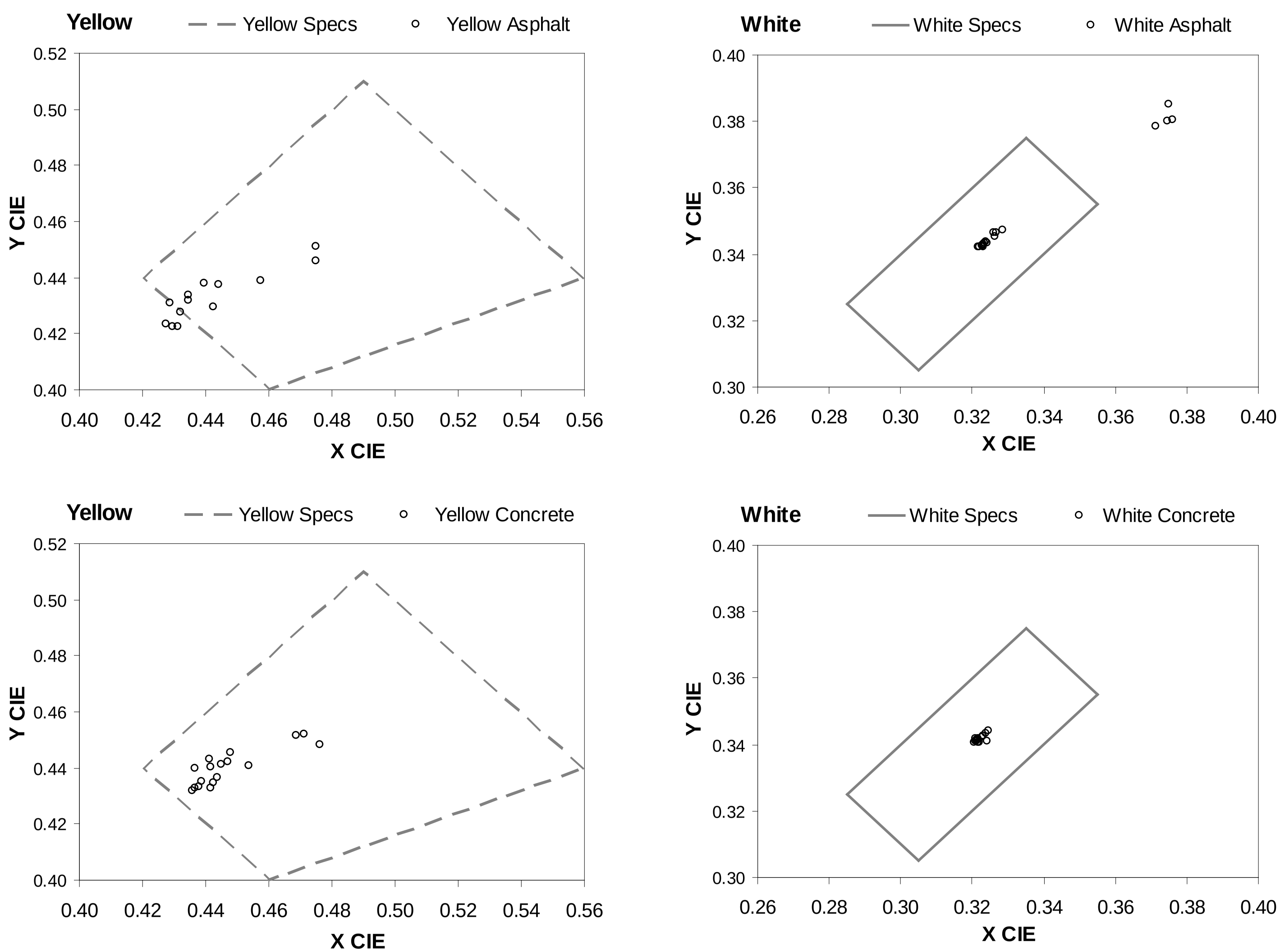


Figure 4.17- Color Performance of Dura-Stripe in Mississippi.

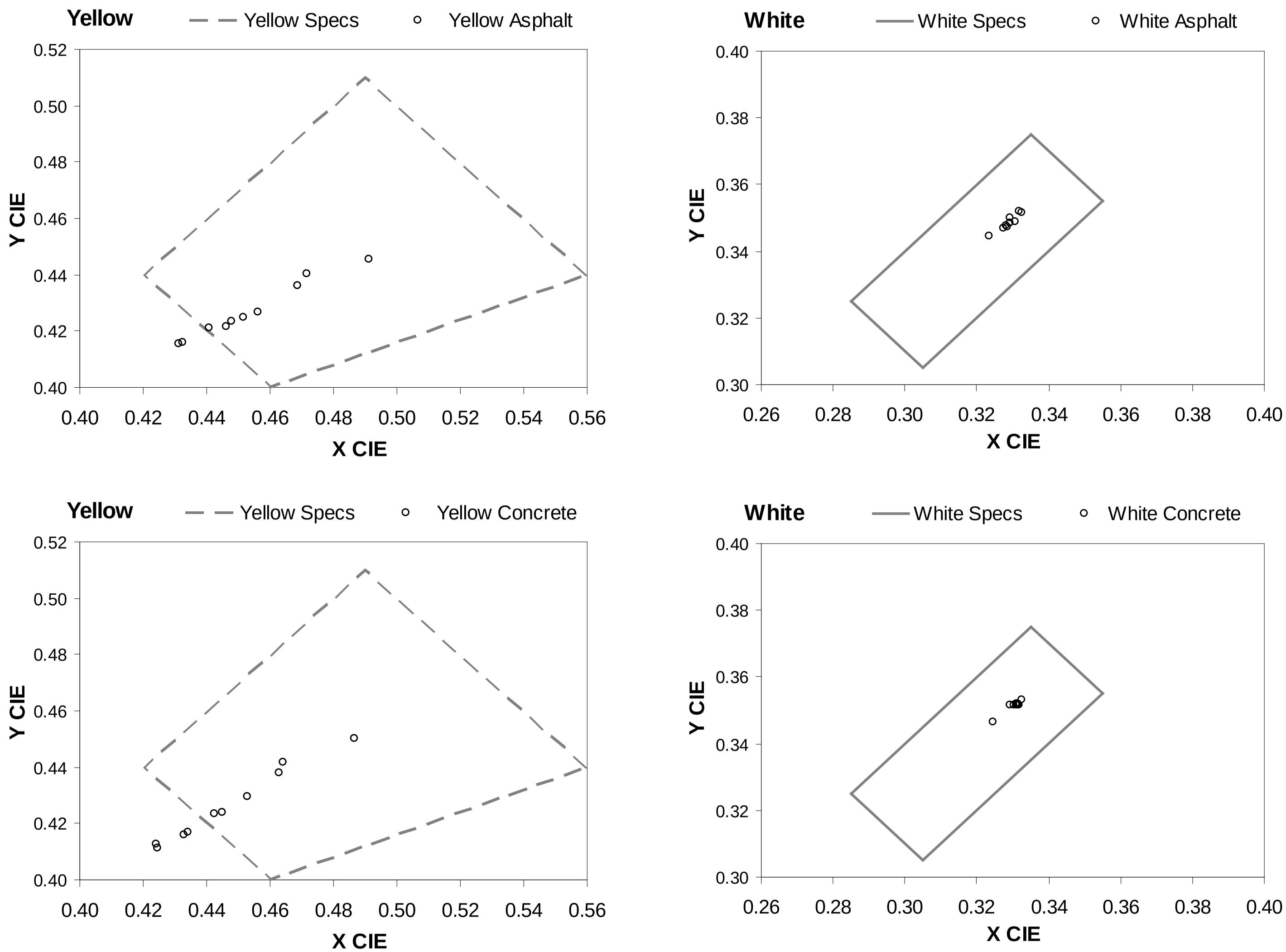


Figure 4.18- Color Performance of Dura-Stripe in Pennsylvania.

CHAPTER V

COMPARISON BETWEEN MATERIAL GROUPS

5.1 Introduction

In the previous chapter, general observations were made pertaining to performance variations between white and yellow markings, skip and wheel locations, asphalt and concrete surfaces, and general trends in data from one year to another.

In this chapter, comparisons are made between the retroreflectivity performance of the seven material groups (modified urethane, thermoplastic, epoxy, polyurea, durable tape, preformed thermoplastic and methyl methacrylate) studied in this research.

5.2 Summary of Results

Similar to the previous chapter, the comparison is based on retroreflectivity, durability, and color. The discussion is limited to the retroreflectivity performance of these materials since retroreflectivity is the most importance performance measure for pavement marking materials.

5.2.1 Retroreflectivity

A comparison between the retroreflectivity performance of the seven material groups is presented in Figures (5.1) through (5.8). Figures (5.1) and (5.2) present the pavement marking performance on the Mississippi test deck for white and yellow pavement markings, respectively. Figures (5.3) and (5.4) present the pavement marking performance on the Pennsylvania test deck for white and yellow pavement markings, respectively. Figures (5.5) and (5.6) present the pavement marking performance on the Wisconsin test deck for white and yellow pavement markings, respectively. Figures (5.7) and (5.8) present the pavement marking performance on the Utah test deck for white and yellow pavement markings, respectively. Each figure consists of four subfigures for retroreflectivity in skip and wheel locations, and on asphalt and concrete surfaces.

By reviewing the data presented in these figures, the following observations can be made:

- More material types were evaluated in Pennsylvania than in Mississippi than in Wisconsin than in Utah.
- Due to weather constraints, more field evaluations are conducted in the Mississippi test deck than the rest of the test decks.
- Some periodic evaluations lasted for three years (MS 04-06, PA 02-04, and PA 05-07), while others lasted for two years (MS 02-03, WI 04-05, and UT 01-02).
- A significant drop in retroreflectivity is noticed during the winter in Pennsylvania, Wisconsin, and Utah, especially the first winter, which is probably due to snow plowing. This is not the case in Mississippi where snow plowing is not used.
- Higher retroreflectivity values were obtained for 3M 380 durable tape than the rest of the materials especially during the first two years. After the first two years, however, the performance of 3M 380 was comparable to the rest of the materials.
- The lowest retroreflectivity performance was obtained for Dura Stripe methyl methacrylate. This material had relatively low retroreflectivity even after installation.

- The performance of HPS-4 modified urethane, HPS-5 polyurea, and Premark Plus preformed thermoplastic is comparable.
- The performance of Tuffline Alkyd thermoplastic was slightly lower than HPS-4, HPS-5, and Premark Plus; and better than Dura Stripe.
- The previous order was consistent among the test decks. However, the relative difference in retroreflectivity varied from one test deck to another.
- The previous order was also consistent for white and yellow colors.
- There are some irregular peaks and troughs in the retroreflectivity curves. Interestingly, these irregularities took place at exactly the same time. Therefore, they are probably due to: dirt accumulation or calibration variations of retroreflectometers from one field evaluation to another.
- Sometimes, retroreflectivity increased over time. This maybe can be justified as follows: (1) retroreflectivity measurements were not taken at exactly the same location within the line; (2) some 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 due to traffic, these glass beads got exposed, resulting in an increase in retroreflectivity; or (3) more glass beads than necessary were used during the installation, which resulted in so called shadowing effect that lowers the initial material retroreflectivity.
- By comparing the initial, 2-year and 3-year retroreflectivity values, it can be seen that high initial retroreflectivity is not always indicative of good retained retroreflectivity.

5.2.2 Durability

By reviewing the data presented in Tables (4.9) through (4.15), the following observations can be made:

- 3M 380 durable ape has the best performance among all seven material groups. t
- The lowest durability performance was obtained for Mark 55.3 epoxy on asphalt surface in Utah. This material had almost worn out after 1 year of installation.
- Comparable performance was obtained for HPS-4 modified urethane, HPS-5 polyurea, and Premark Plus preformed thermoplastic, average durability reading at end of test is between 7 and 8.
- Dura Stripe methyl methacrylate, Tuffline Alkyd thermoplastic had comparable performance; average reading at the end of test is between 5 and 6.
- The ranking of seven test material groups is: 3M 380 durable tape, followed by HPS-4 modified urethane, HPS-5 polyurea, and Premark Plus preformed thermoplastic; followed by Dura Stripe methyl methacrylate, Tuffline Alkyd thermoplastic; Mark 55.3 epoxy was the lowest.

5.2.3 Color

By reviewing the data presented in Figures (4.1) through (4.18), the following observations can be made:

- In general, for all seven test material groups, white initial color readings were close to the center of the white color specification box and yellow initial color reading were close to the bottom left of the yellow color specification box.

- In general, for all seven test material groups, with time going, white color reading move up towards the upper right side of the specification box and yellow move down towards the lower left side of the specification box.
- Tuffline Alkyd thermoplastic had more stable color performance comparing with other six test material groups.

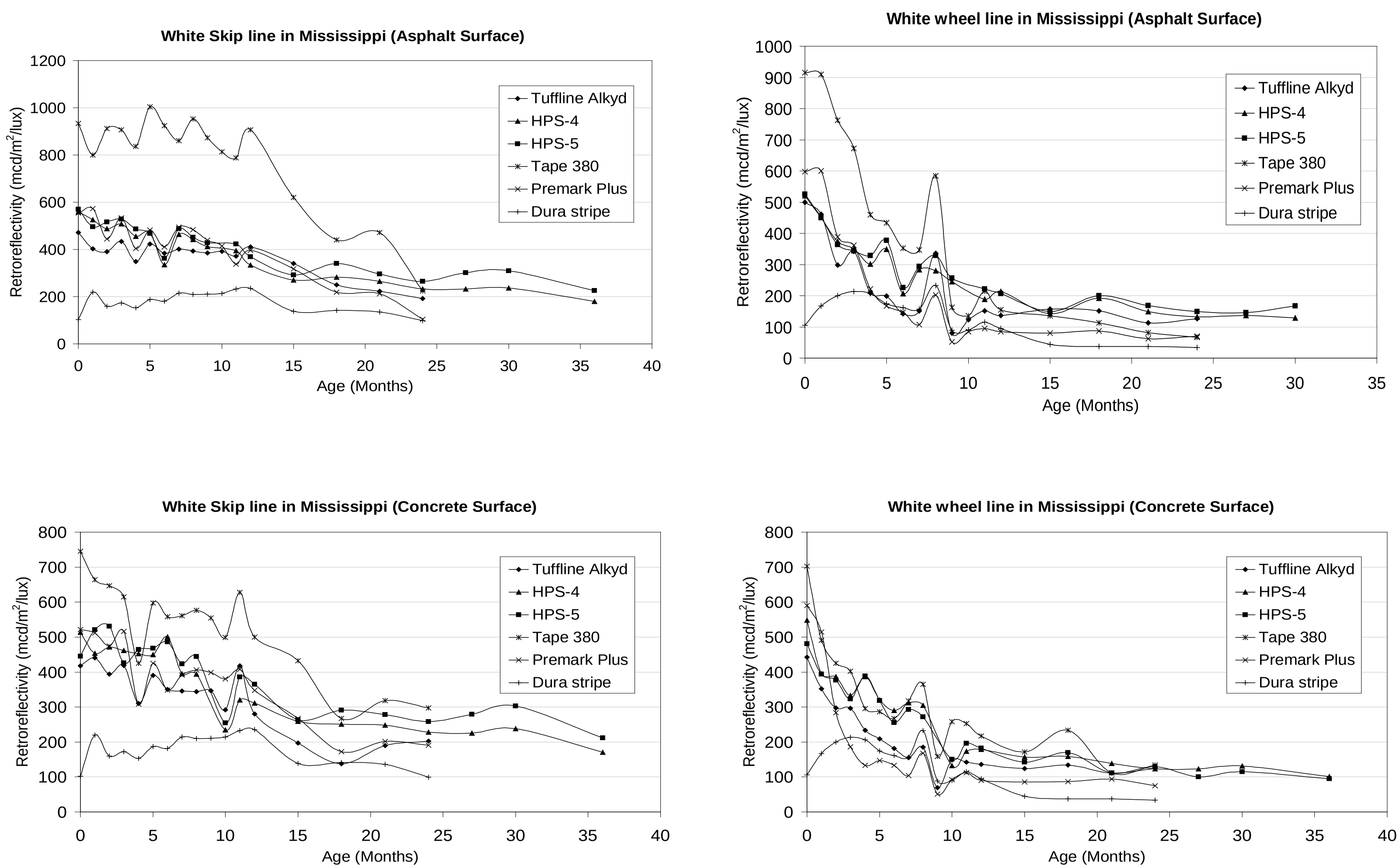


Figure 5.1- Retroreflectivity Comparison between Material Groups for White Color in Mississippi.

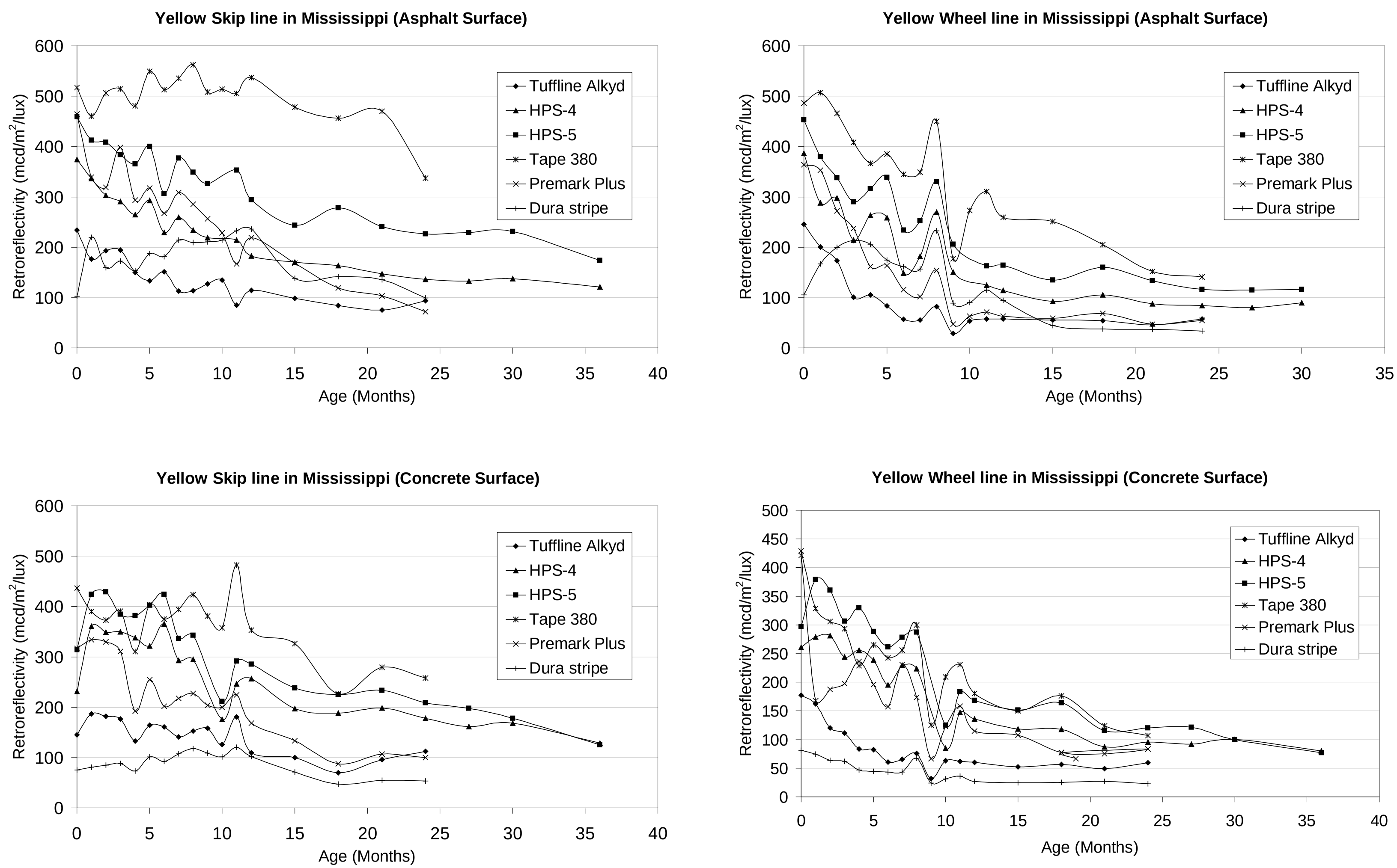
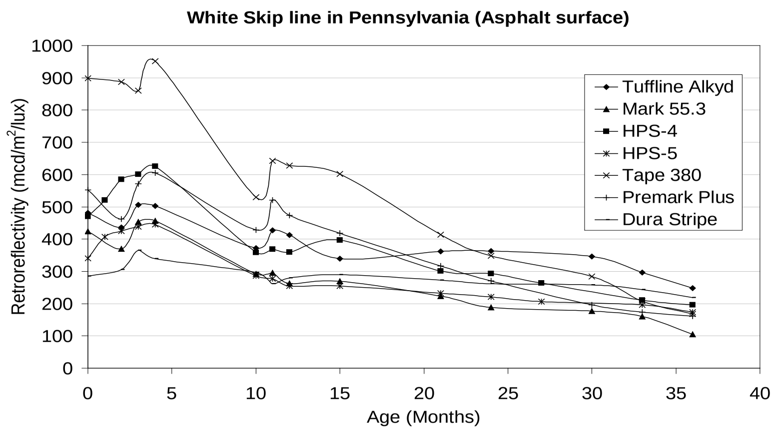
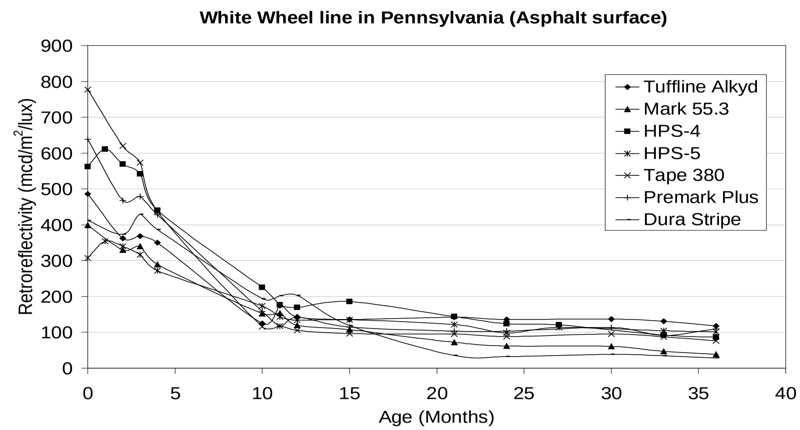
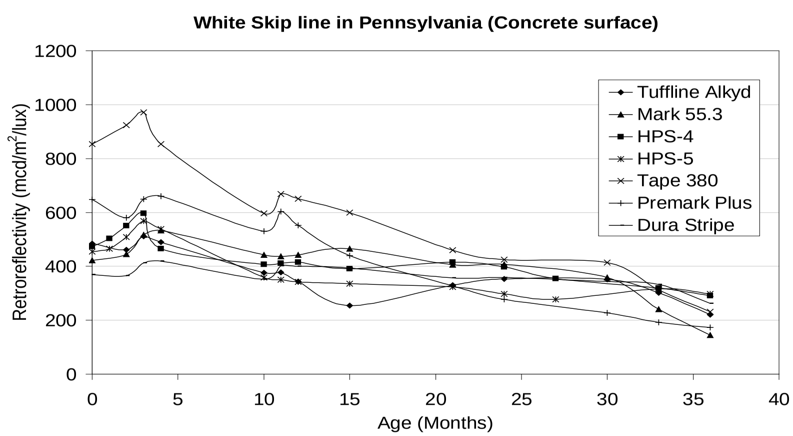


Figure 5.2- Retroreflectivity Comparison between Material Groups for Yellow Color in Mississippi.







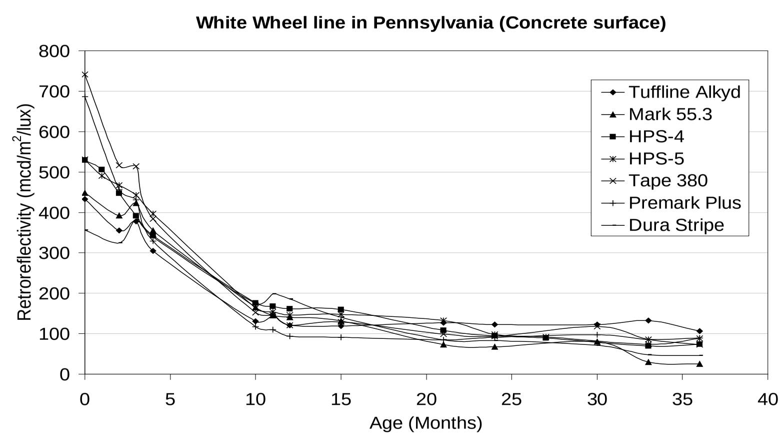


Figure 5.3- Retroreflectivity Comparison between Material Groups for White Color in Pennsylvania.

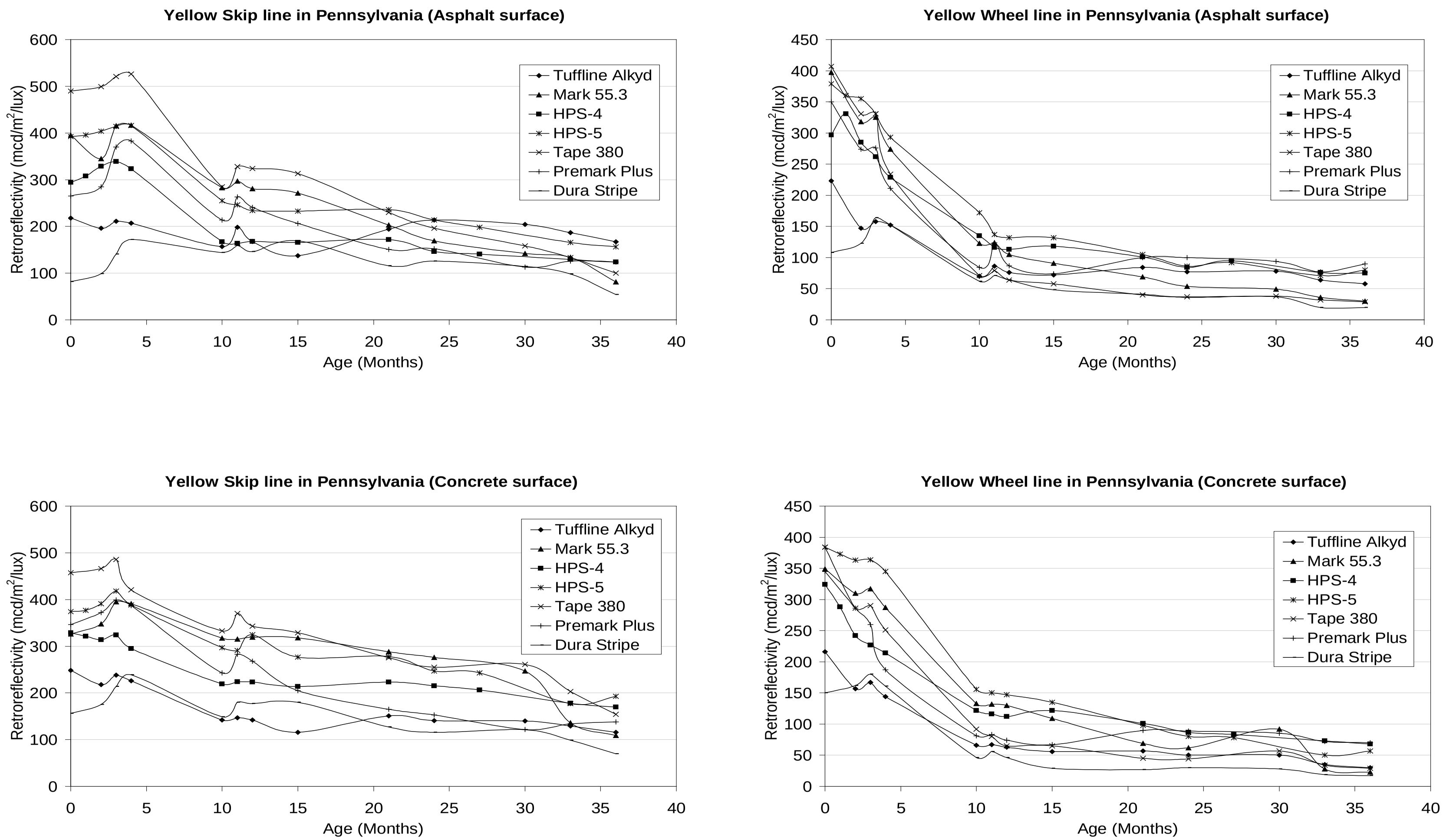


Figure 5.4- Retroreflectivity Comparison between Material Groups for Yellow Color in Pennsylvania.

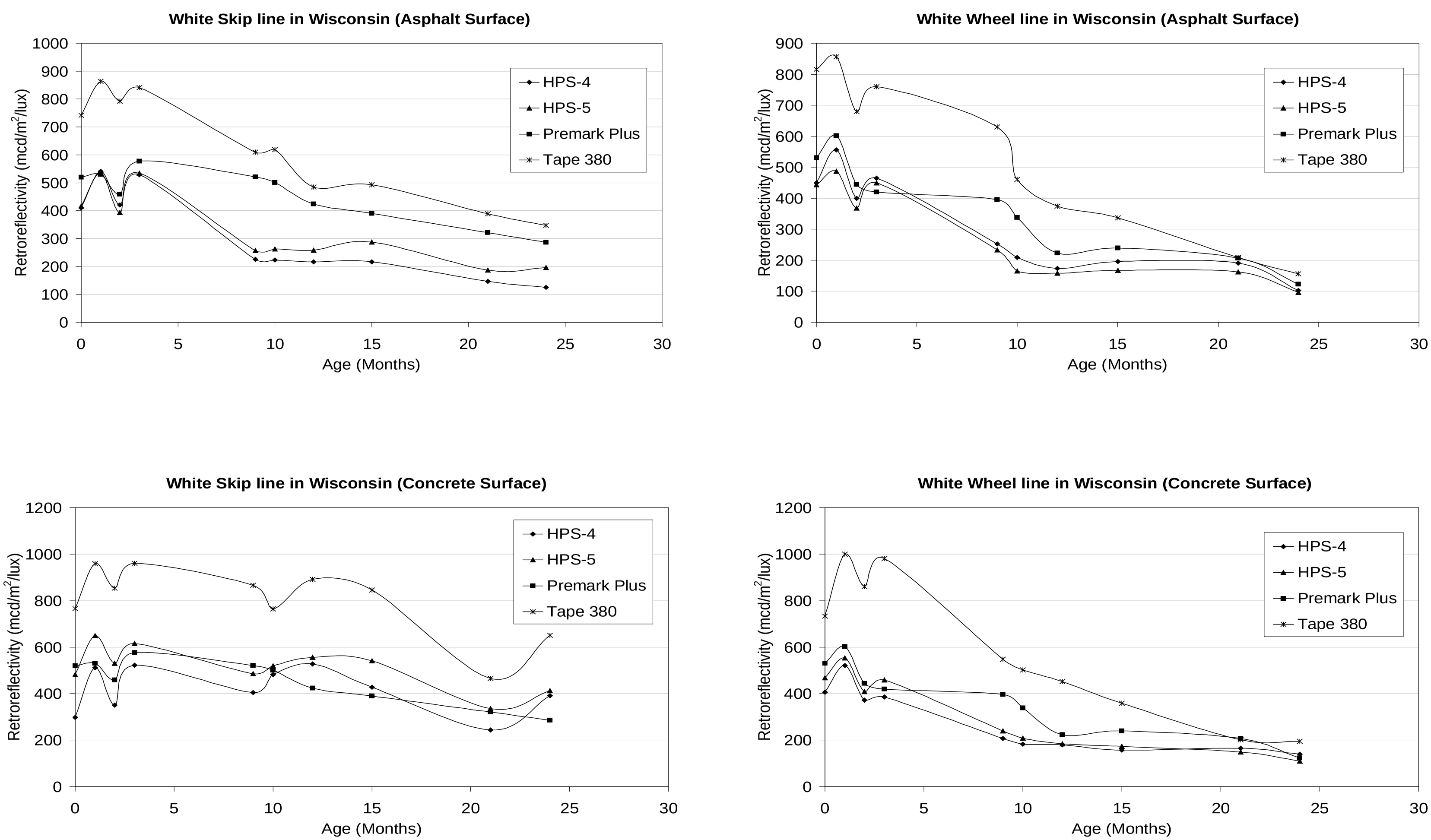


Figure 5.5- Retroreflectivity Comparison between Material Groups for White Color in Wisconsin.

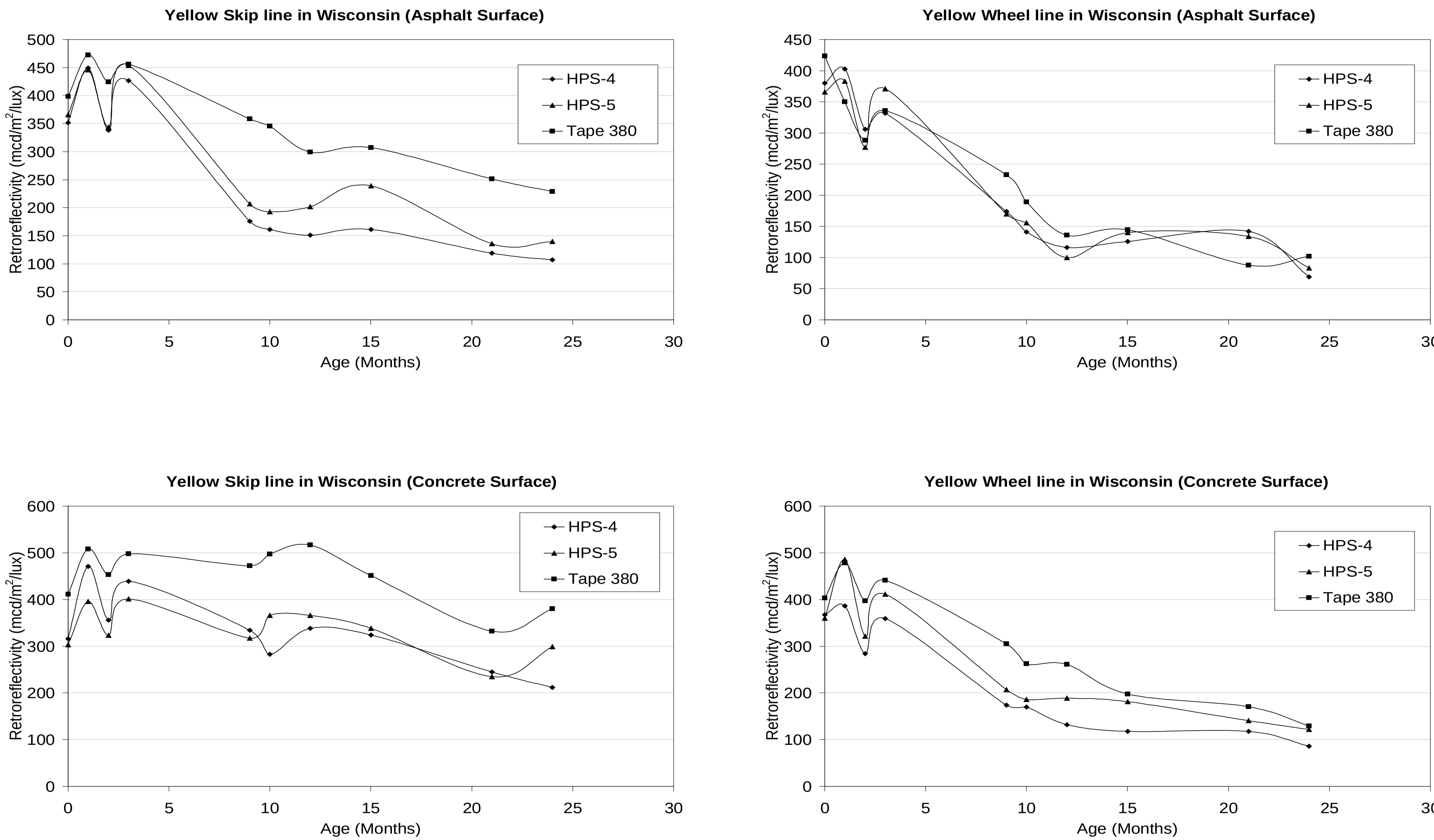


Figure 5.6- Retroreflectivity Comparison between Material Groups for Yellow Color in Wisconsin.

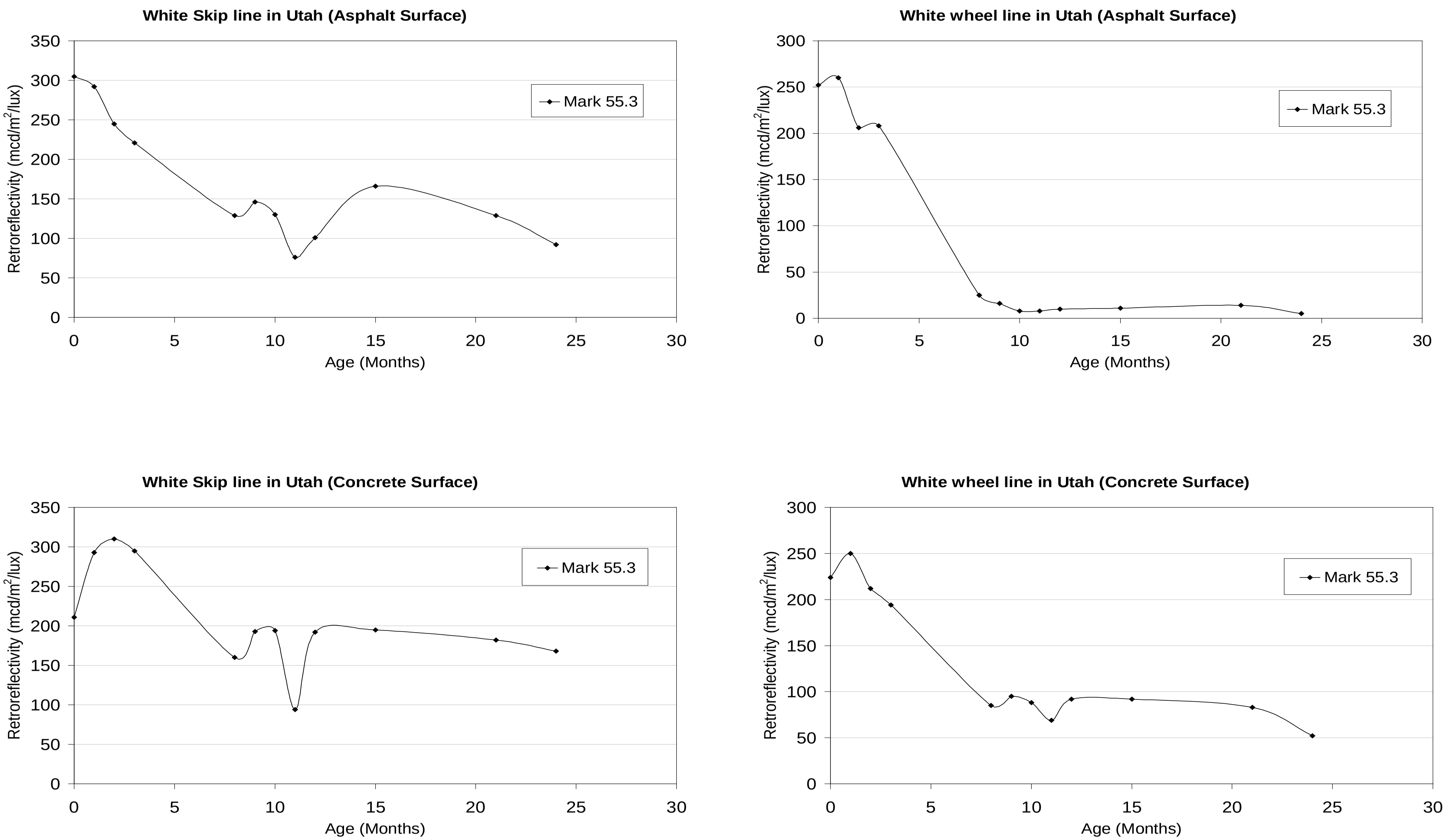


Figure 5.7- Retroreflectivity Comparison between Material Groups for White Color in Utah deck.

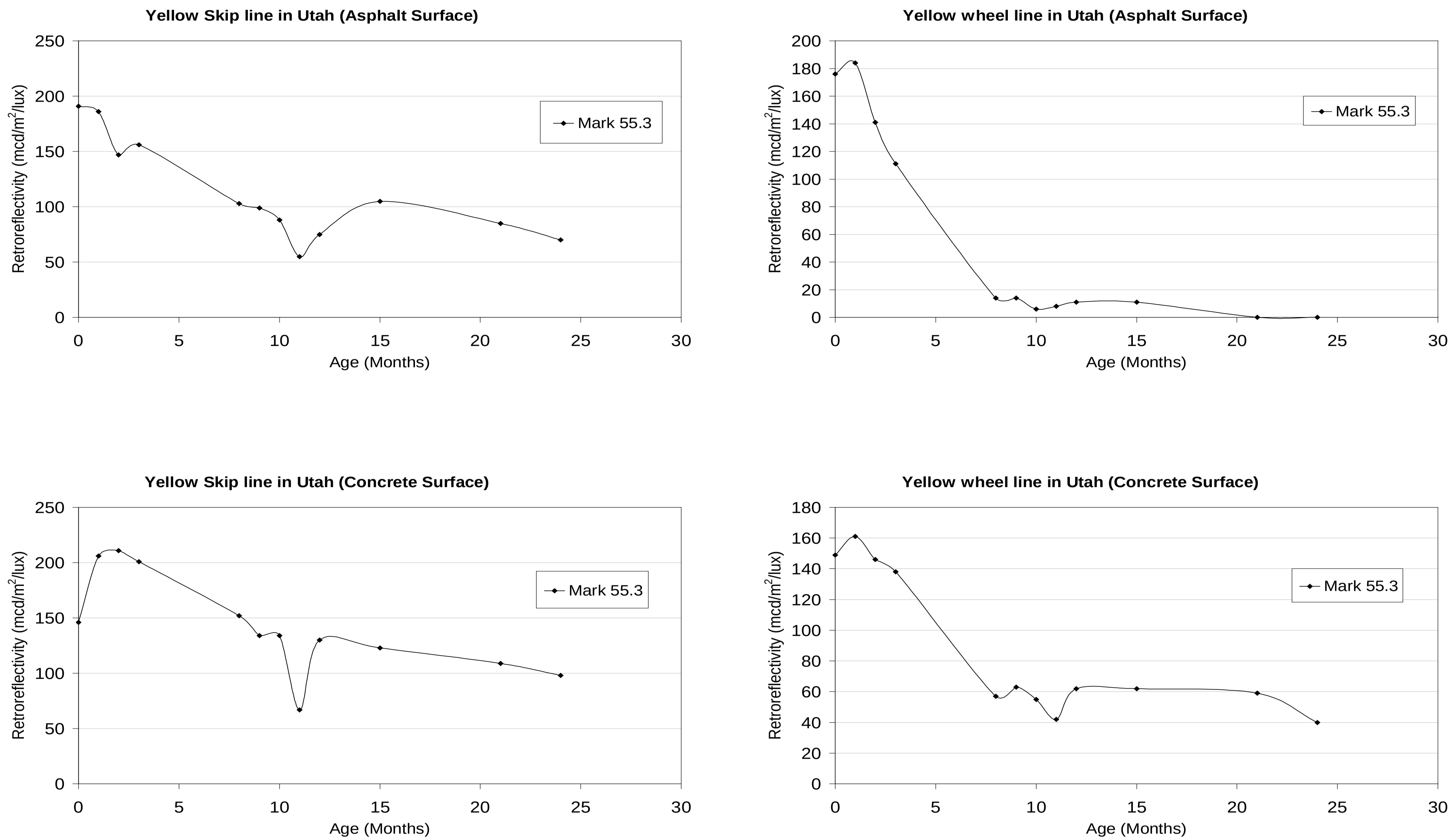


Figure 5.8- Retroreflectivity Comparison between Material Groups for Yellow Color in Utah deck.

CHAPTER VI

COMPARISON BETWEEN NTPEP TEST DECKS

6.1 Introduction

In the previous chapters, general observations were made pertaining to performance variations between white and yellow markings, skip and wheel locations, asphalt and concrete surfaces, and general trends in data from one year to another. In addition, a comparison between the retroreflectivity performance of individual material groups was discussed.

In this chapter, comparisons are made between the retroreflectivity performance on the four NTPEP test decks investigated in this research (Mississippi, Pennsylvania, Wisconsin, and Utah). Similar to the previous chapters, the comparison herein is based on retroreflectivity, durability, and color.

6.2 Retroreflectivity

A comparison between the retroreflectivity performances on the four test decks is presented in Figures (6.1) through (6.14). Figures (6.1) and (6.2) present the retroreflectivity performance of white and yellow HPS-4 modified urethane, respectively. Figures (6.3) and (6.4) present the retroreflectivity performance of white and yellow Tuffline alkyd thermoplastic, respectively. Figures (6.5) and (6.6) present the retroreflectivity performance of white and yellow MARK-55.3 epoxy, respectively.

Figures (6.7) and (6.8) present the retroreflectivity performance of white and yellow HPS-5 polyurea, respectively. Figures (6.9) and (6.10) present the retroreflectivity performance of white and yellow 3M 380 durable tape, respectively. Figures (6.11) and (6.12) present the retroreflectivity performance of white and yellow Premark Plus preformed thermoplastic, respectively. Figures (6.13) and (6.14) present the retroreflectivity performance of white and yellow Dura-Stripe methyl methacrylate, respectively. Each figure consists of four subfigures for retroreflectivity in skip and wheel locations, and on asphalt and concrete surfaces.

By reviewing the data presented in these figures, the following observations can be made:

- Not all materials were evaluated on all NTPEP test decks. HPS-4 modified urethane was evaluated on three test decks (MS, PA, and WI); Tuffline alkyd thermoplastic was evaluated on two test decks (MS and PA); Mark 55.3 epoxy was evaluated on two test decks (PA and UT); HPS-5 polyurea was evaluated on three test decks (MS, PA, and WI); 3M 380 durable tape was evaluated on three test decks (MS, PA, and WI); Premark plus preformed thermoplastic was evaluated on three test decks for white (MS, PA, and WI) and two test decks for yellow (MS and PA); and Dura-Stripe methyl methacrylate was evaluated on two test decks (MS and PA).
- In general, the variability in pavement marking retroreflectivity was lower for wheel than for skip line. In other words, comparable retroreflectivity results among the test decks were obtained for the wheel location in comparison with the skip location for each individual material.

- In general, white markings had higher retroreflectivity than their yellow counterparts. Similar deterioration trends, however, were noticed for white and yellow markings of the same material. The deterioration trends, however, were different from one material to another.
- Minor differences are noticed for the performance of the pavement markings on asphalt and concrete surfaces. These differences were less evident in wheel retroreflectivity than skip retroreflectivity.
- For HPS-4 modified urethane, comparable retroreflectivity performance was obtained on all three test decks (MS, PA and WI) for wheel retroreflectivity. Skip retroreflectivity, on the other hand, varied from one test deck to another.
- The retroreflectivity performance of Tuffline alkyd thermoplastic was slightly better on PA test deck than on MS test deck.
- The retroreflectivity performance of Mark 55.3 epoxy was much better on PA test deck than on UT test deck.
- For HPS-5 polyurea, comparable retroreflectivity performance was obtained on all three test decks (MS, PA and WI) for wheel retroreflectivity. Skip retroreflectivity, on the other hand, varied from one test deck to another.
- For 3M 380 durable tape, the retroreflectivity performance was slightly better on the MS and WI test decks.
- The retroreflectivity performance of Premark Plus preformed thermoplastic was better on PA test deck than on MS test deck. WI test deck had even higher retroreflectivity values for white color.

- The retroreflectivity performance of Dura-Stripe methyl methacrylate was better on PA test deck than on MS test deck.
- Based on the previous, the retroreflectivity performance on the PA test deck is slightly higher than the retroreflectivity performance on the MS test deck, especially along the skip line. This can be attributed to variations in traffic among these two locations; the average daily traffic (ADT) on the PA test deck is about 10,000 vehicles per day for both asphalt and concrete sites, while the ADT on the MS test deck is 20,000 vehicles per day for the concrete site and 15,000 vehicles per day for the asphalt site.
- Slightly higher retroreflectivity values were also noticed for some materials on the WI test deck, which has an ADT in the range between 5,200 and 5,800 vehicles per day.

6.3 Durability

By reviewing the data presented in Tables (4.9) through (4.15), the following observations can be made:

- For HPS-4 modified urethane, HPS-5 polyurea, 3M 380 durable tape, comparable durability performances were obtained on two test decks (MS and PA).
- The durability performances of Tuffline alkyd thermoplastic, Premark Plus preformed thermoplastic and Dura-Stripe methyl methacrylate were slightly better on MS test deck than on PA test deck.
- For Mark 55.3 epoxy, PA had better performance than UT on asphalt surface, but UT had better performance than PA on concrete surface.

- Although some material groups have slightly performance variance in different test decks, but in general, most material groups performances are comparable between test decks.

6.4 Color

By reviewing the data presented in Figures (4.1) through (4.18), the following observations can be made:

- In general, the color readings are comparable between test decks for all seven test material groups.

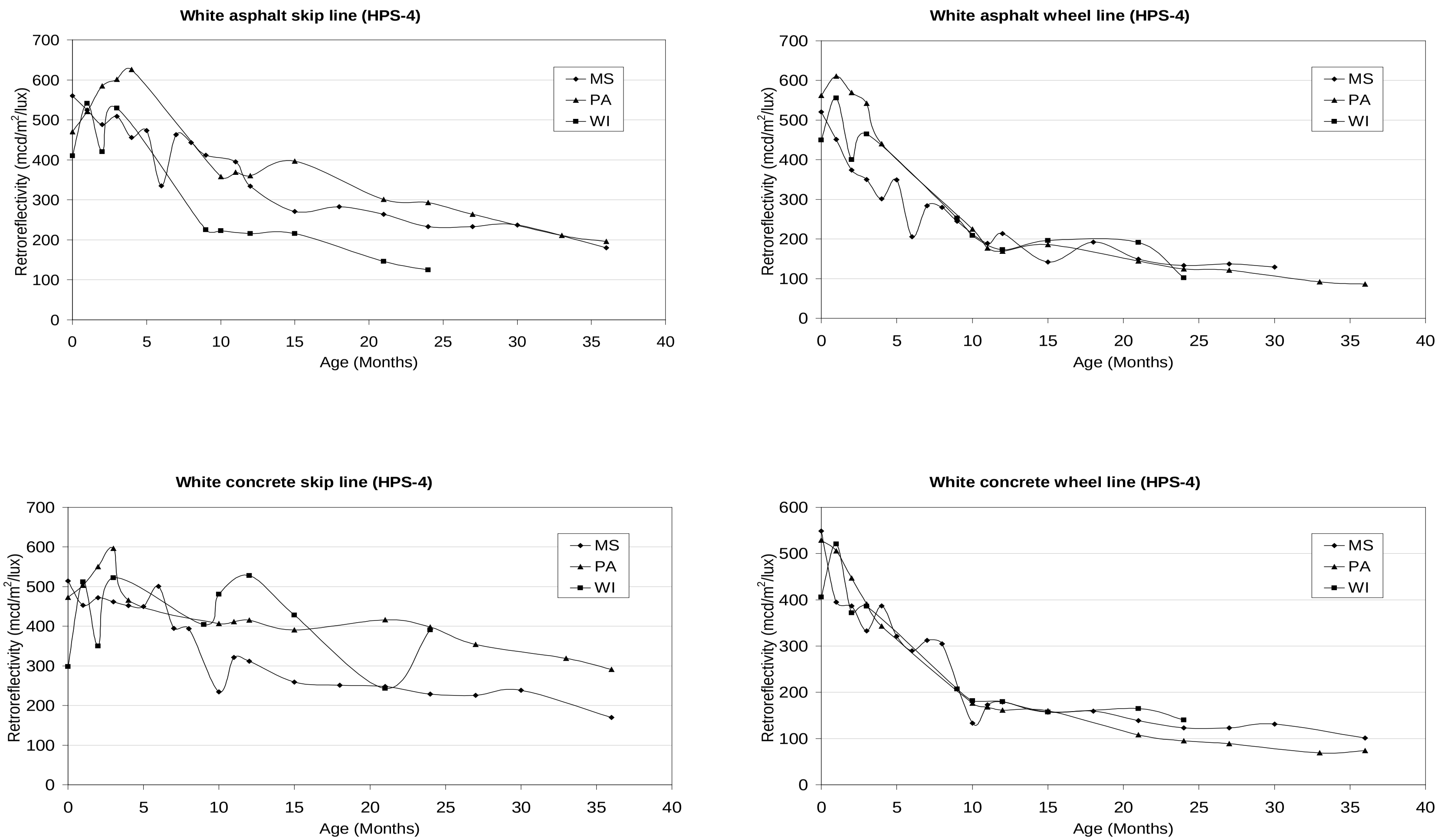


Figure 6.1- Retroreflectivity Comparison between NTPEP Test Decks for White Color HPS-4(Modified Urethane).

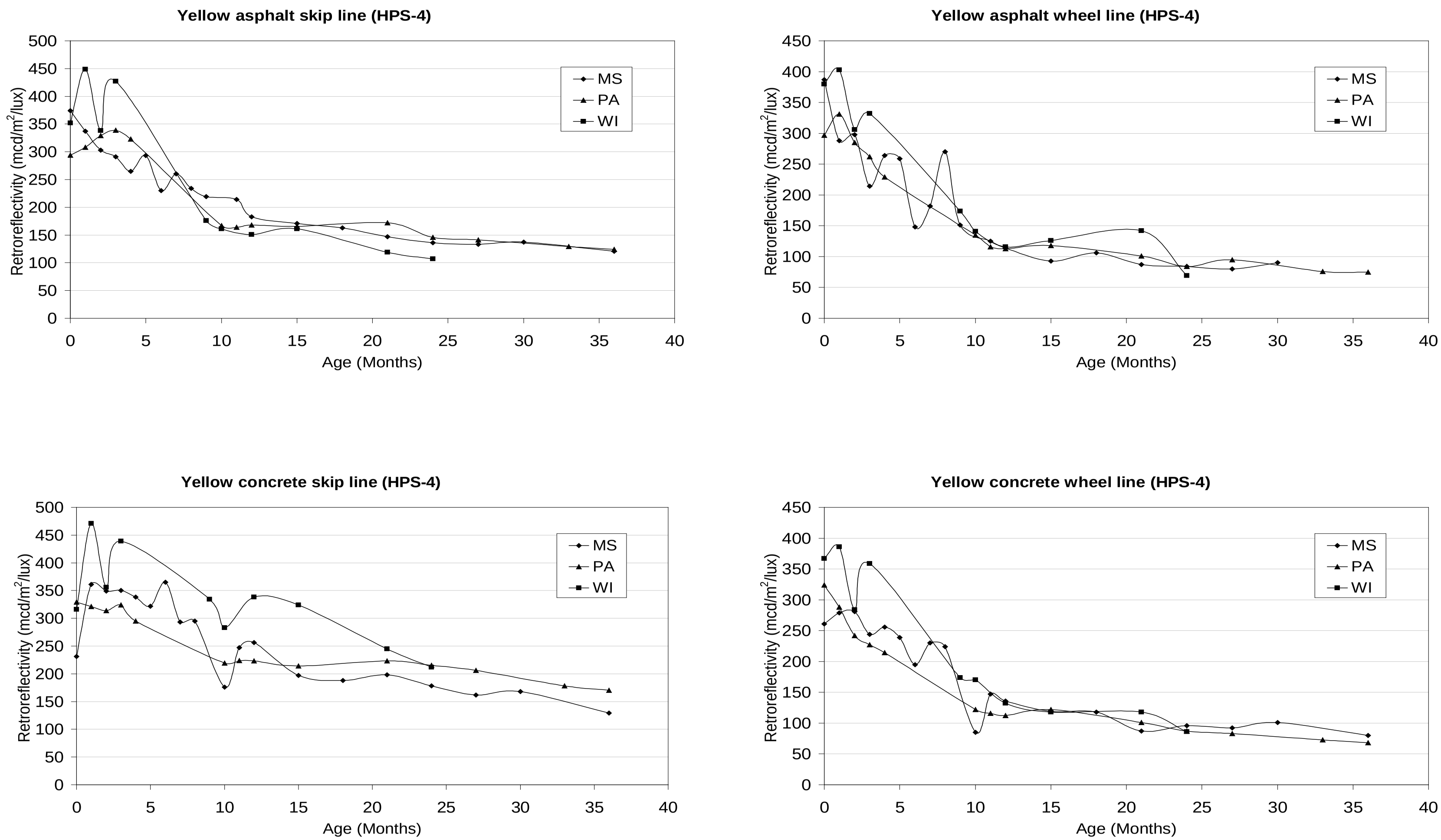


Figure 6.2- Retroreflectivity Comparison between NTPEP Test Decks for Yellow Color HPS-4(Modified Urethane).

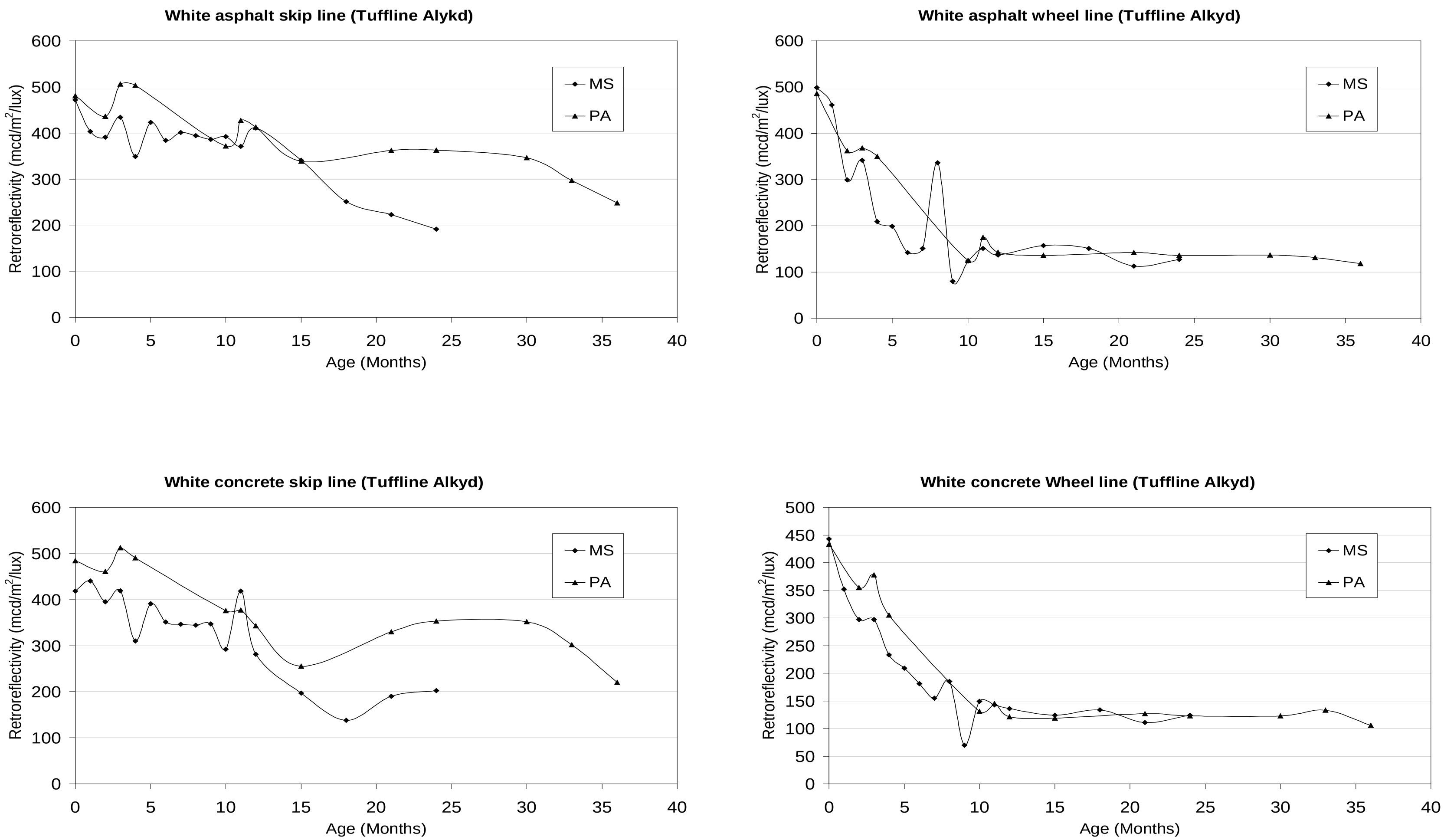


Figure 6.3- Retroreflectivity Comparison between NTPEP Test Decks for White color Tuffline Alkyd.

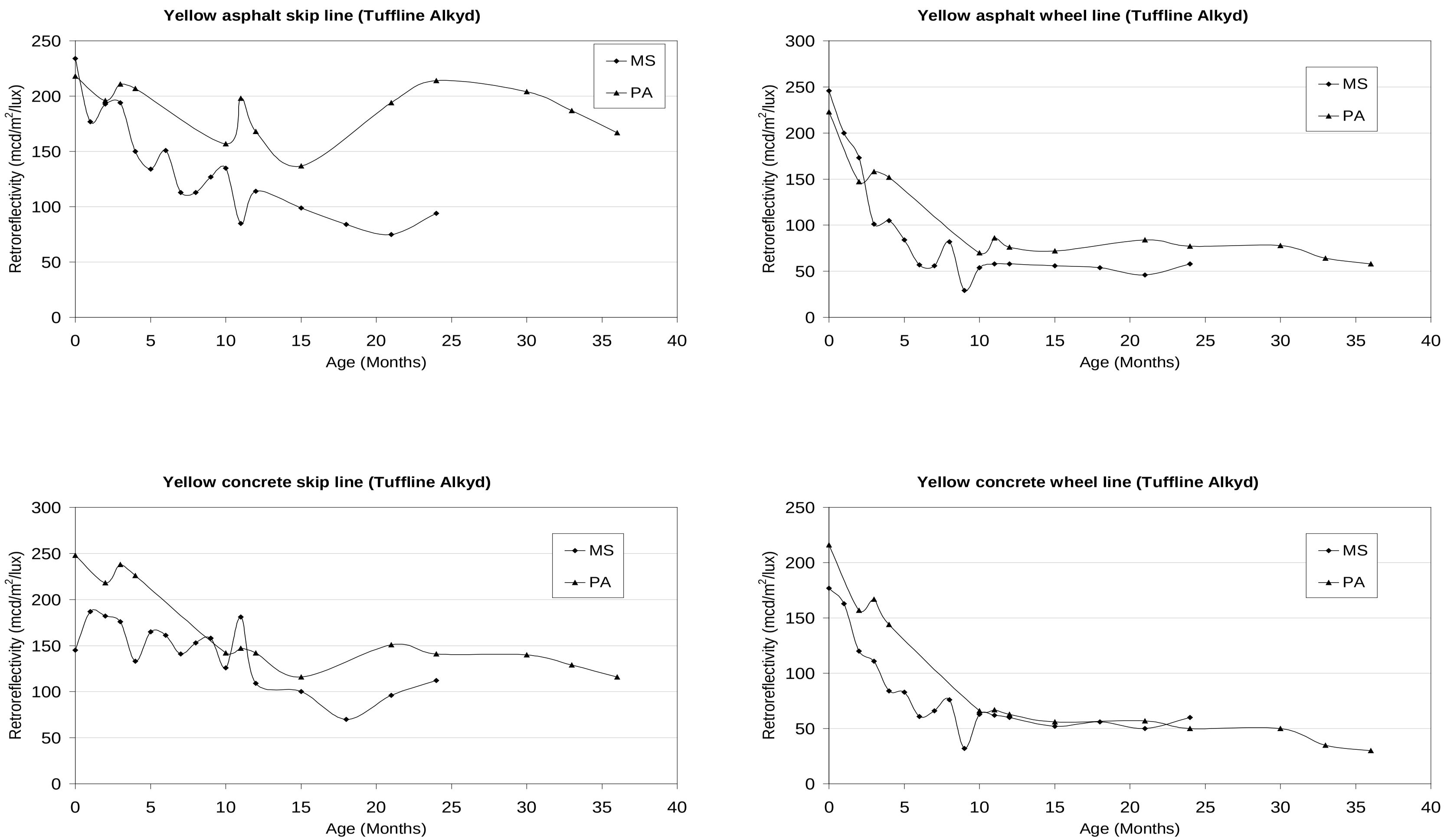


Figure 6.4- Retroreflectivity Comparison between NTPEP Test Decks for Yellow color Tuffline Alkyd.

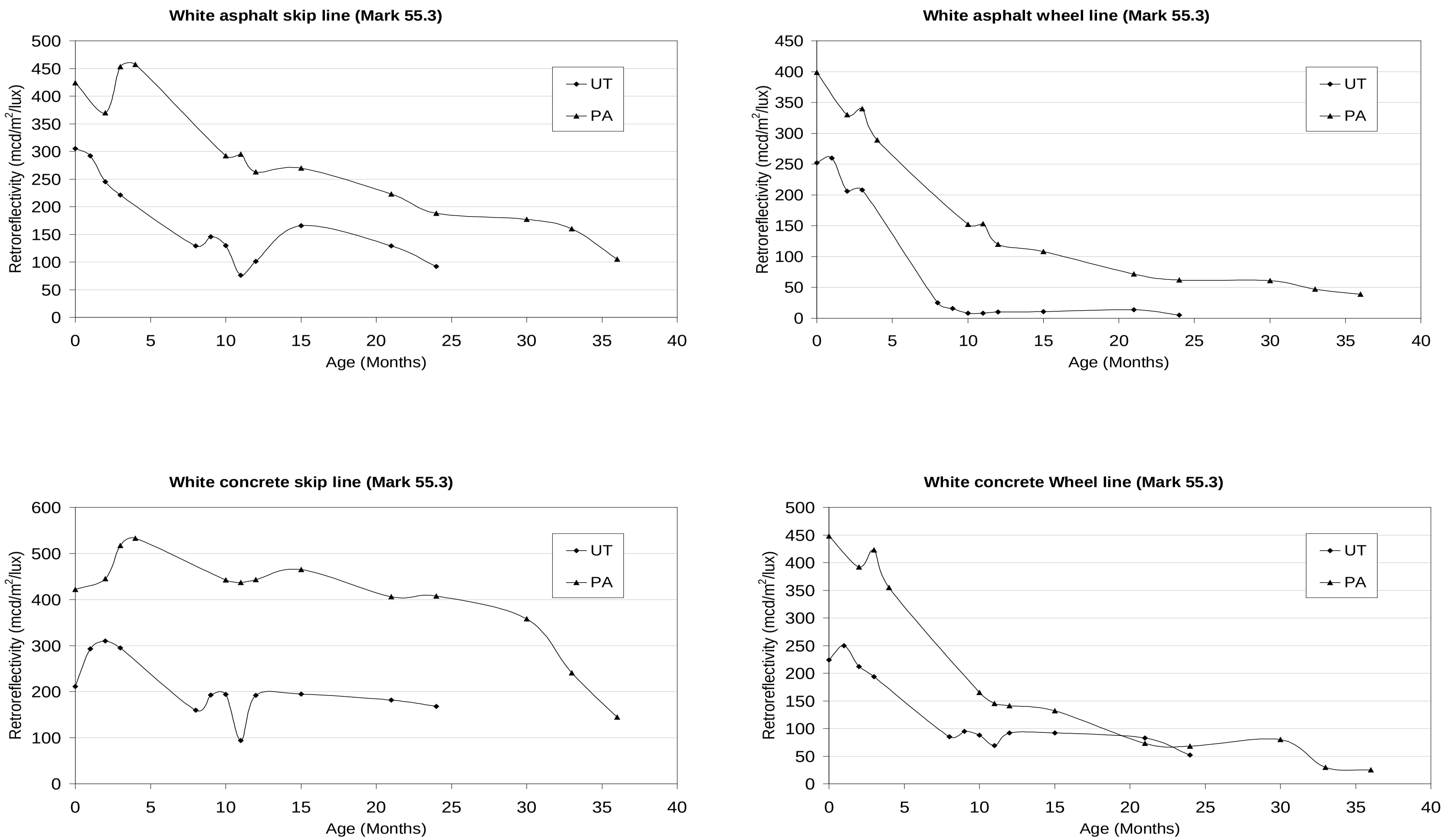


Figure 6.5- Retroreflectivity Comparison between NTPEP Test Decks for White Color MARK 55.3.

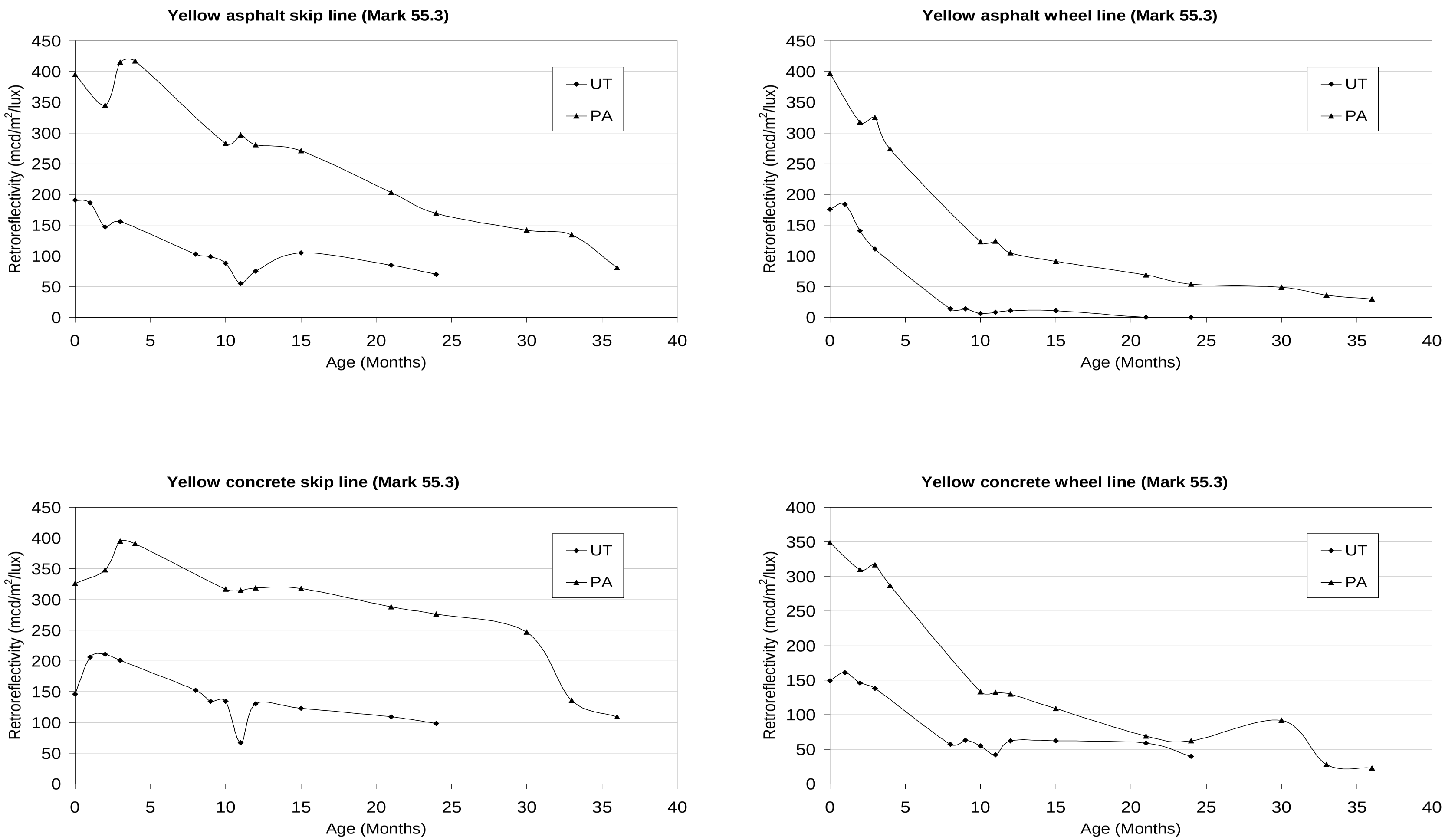


Figure 6.6- Retroreflectivity Comparison between NTPEP Test Decks for Yellow MARK 55.3.

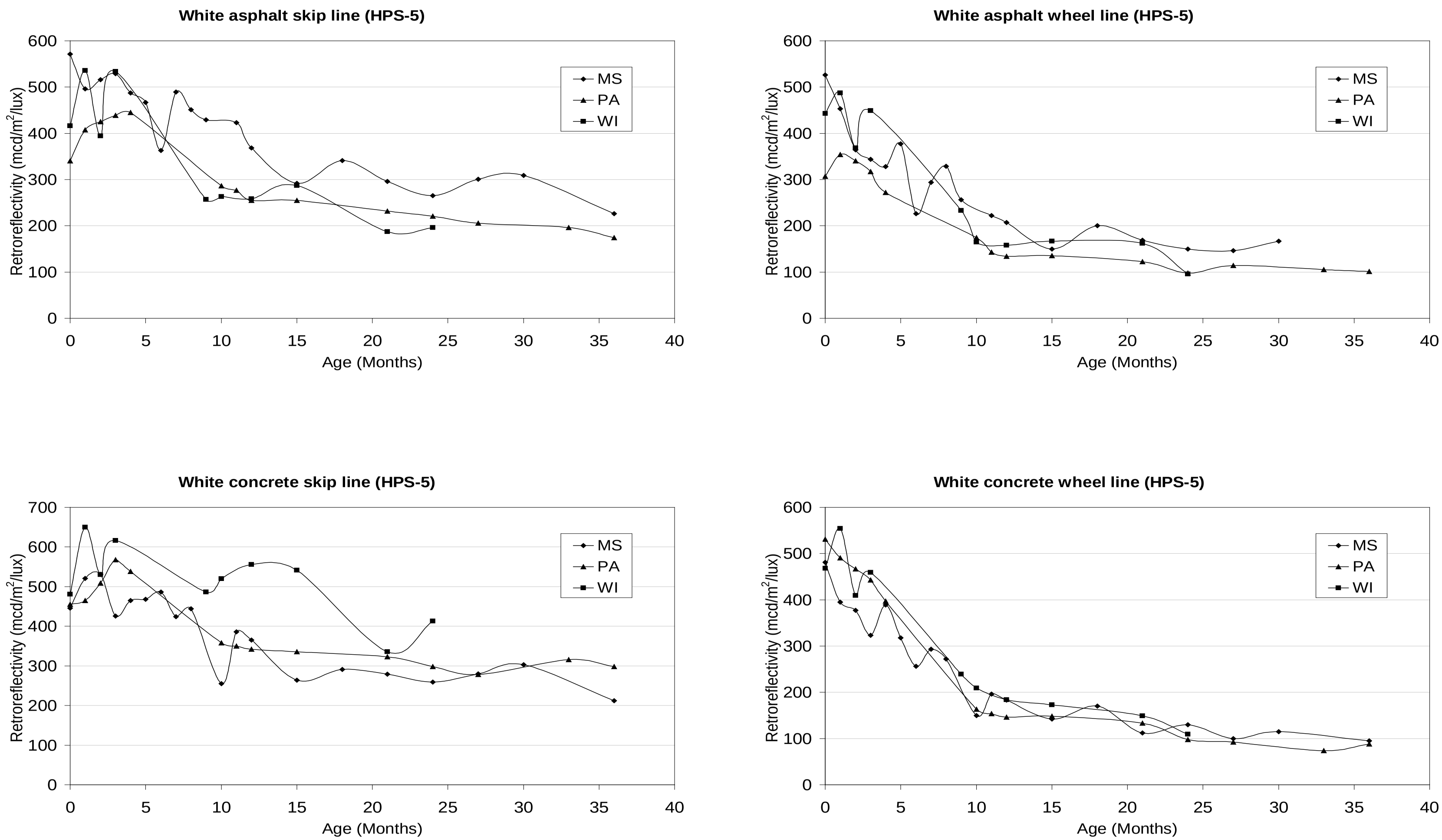


Figure 6.7- Retroreflectivity Comparison between NTPEP Test Decks for White Color HPS-5(Polyurea).

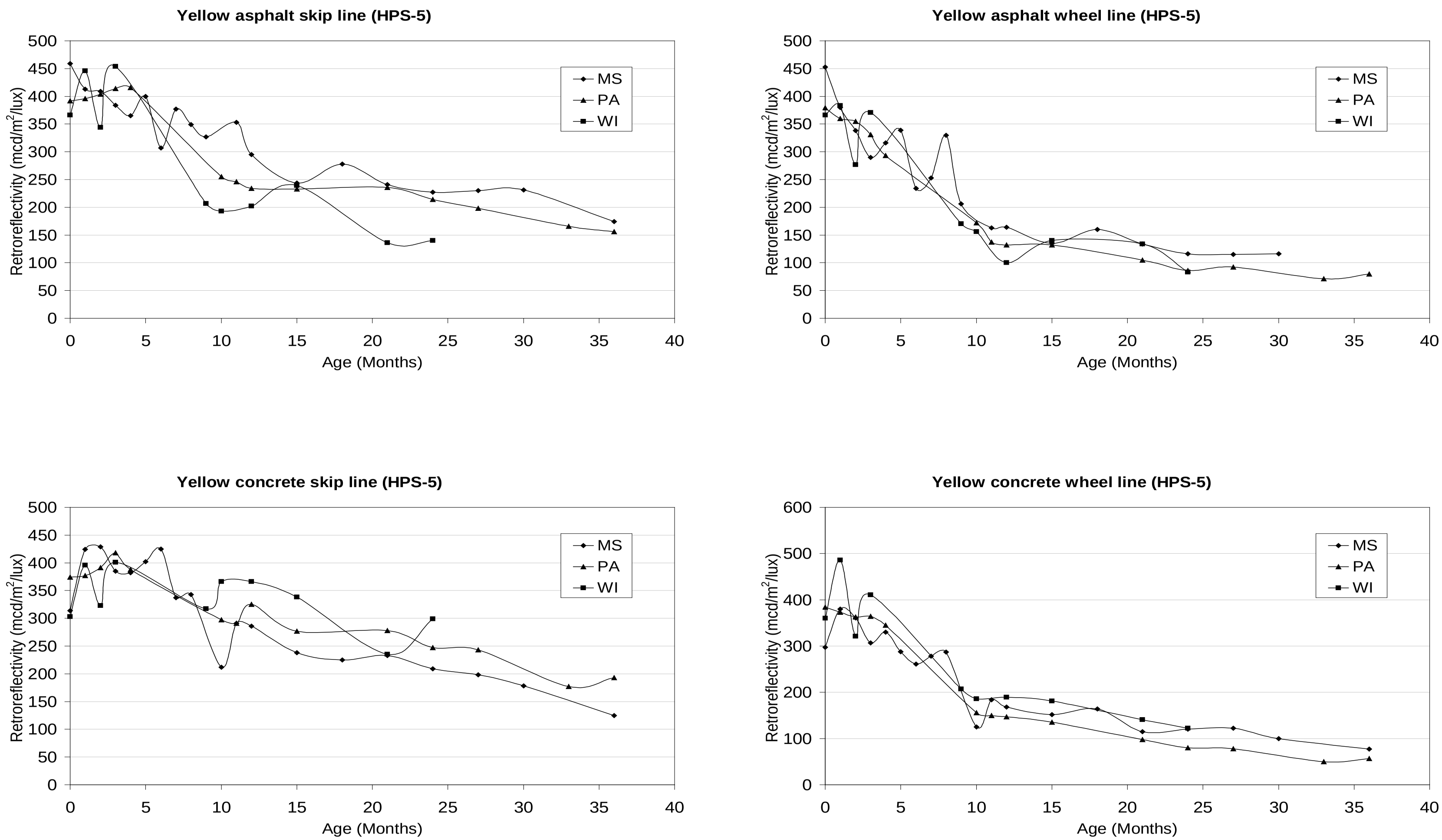


Figure 6.8- Retroreflectivity Comparison between NTPEP Test Decks for Yellow Color HPS-5(Polyurea).

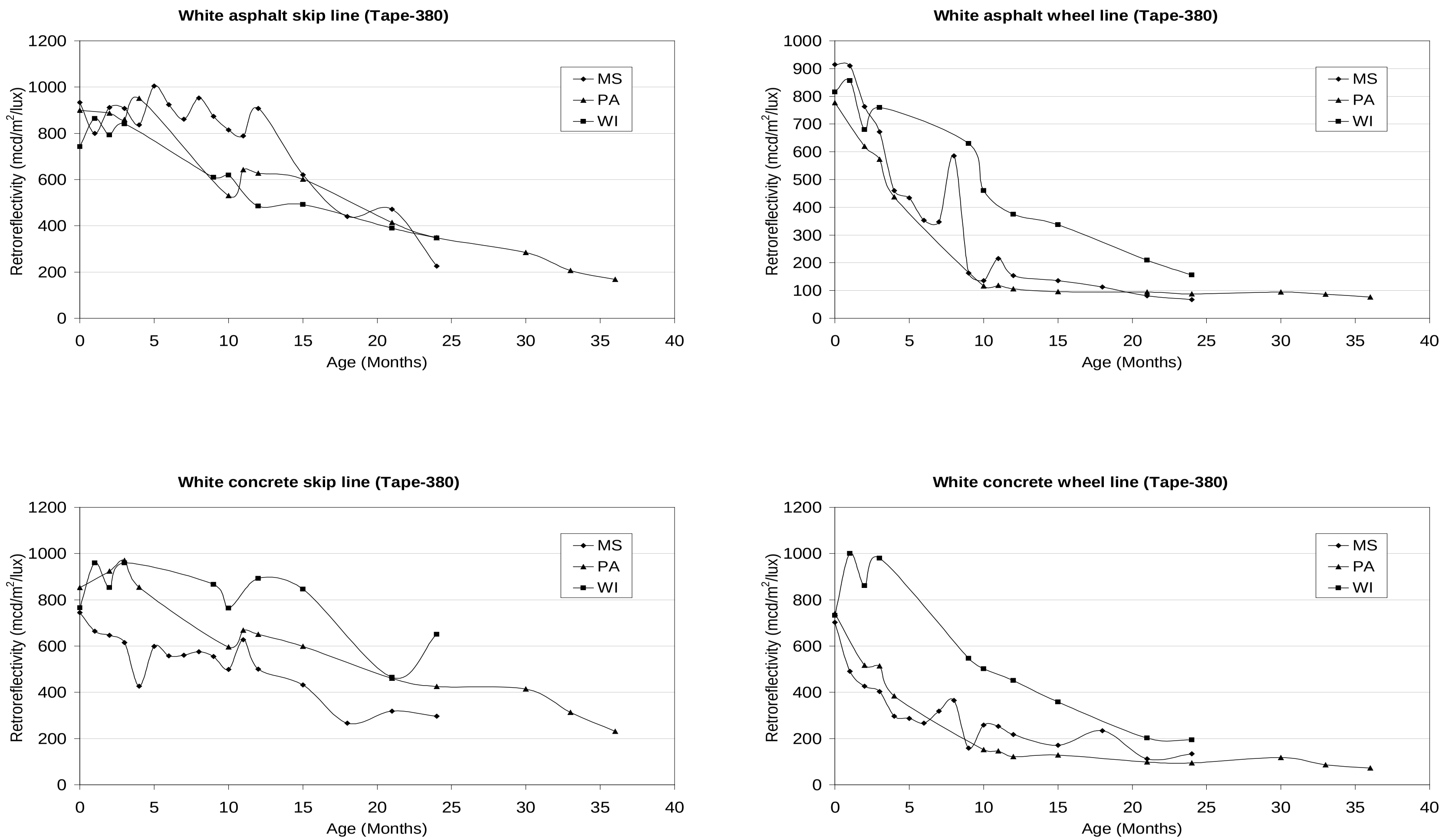


Figure 6.9- Retroreflectivity Comparison between NTPEP Test Decks for White Color Durable Tape 3M 380.

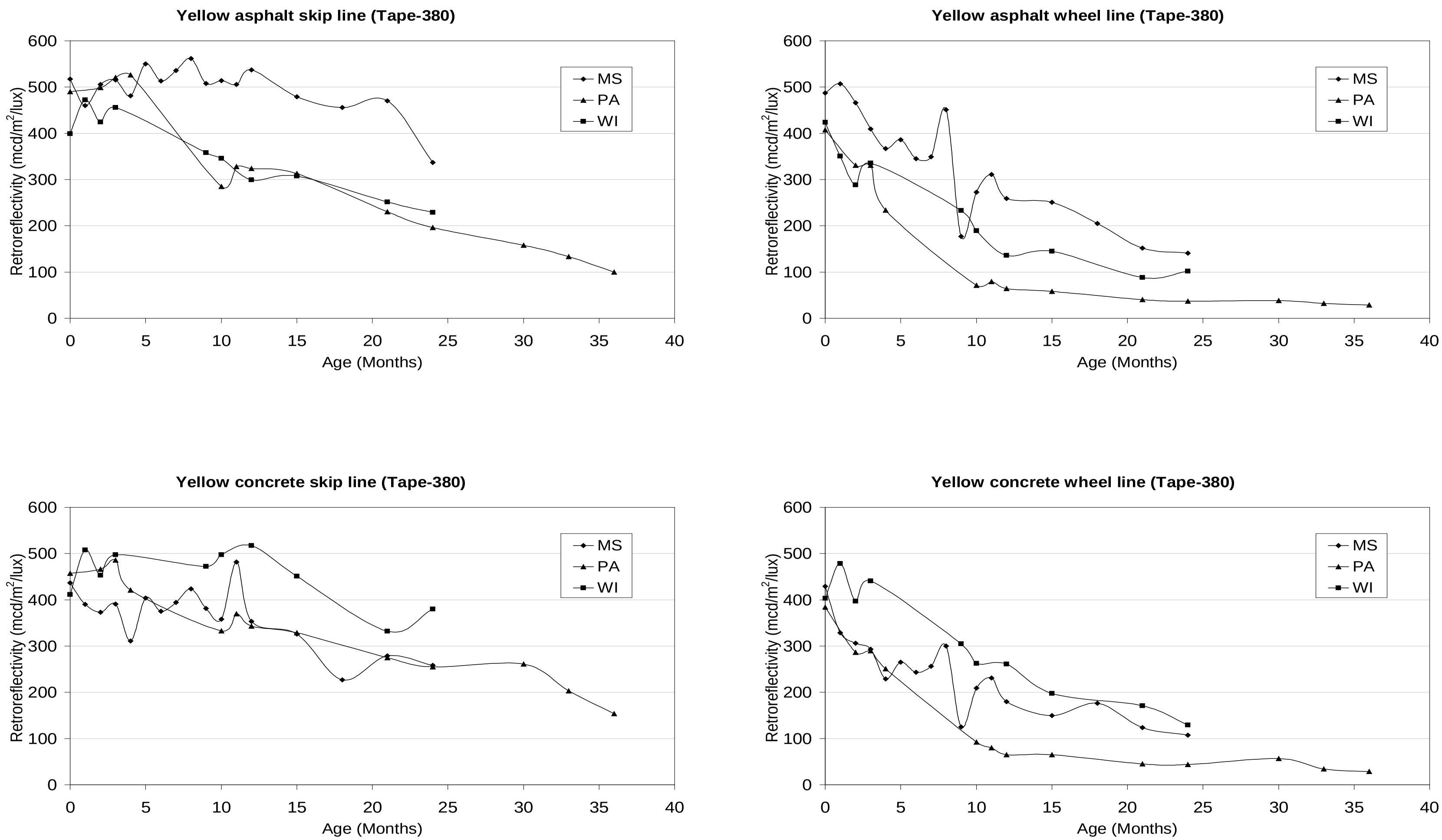


Figure 6.10- Retroreflectivity Comparison between NTPEP Test Decks for Yellow Color Durable Tape 3M 380.

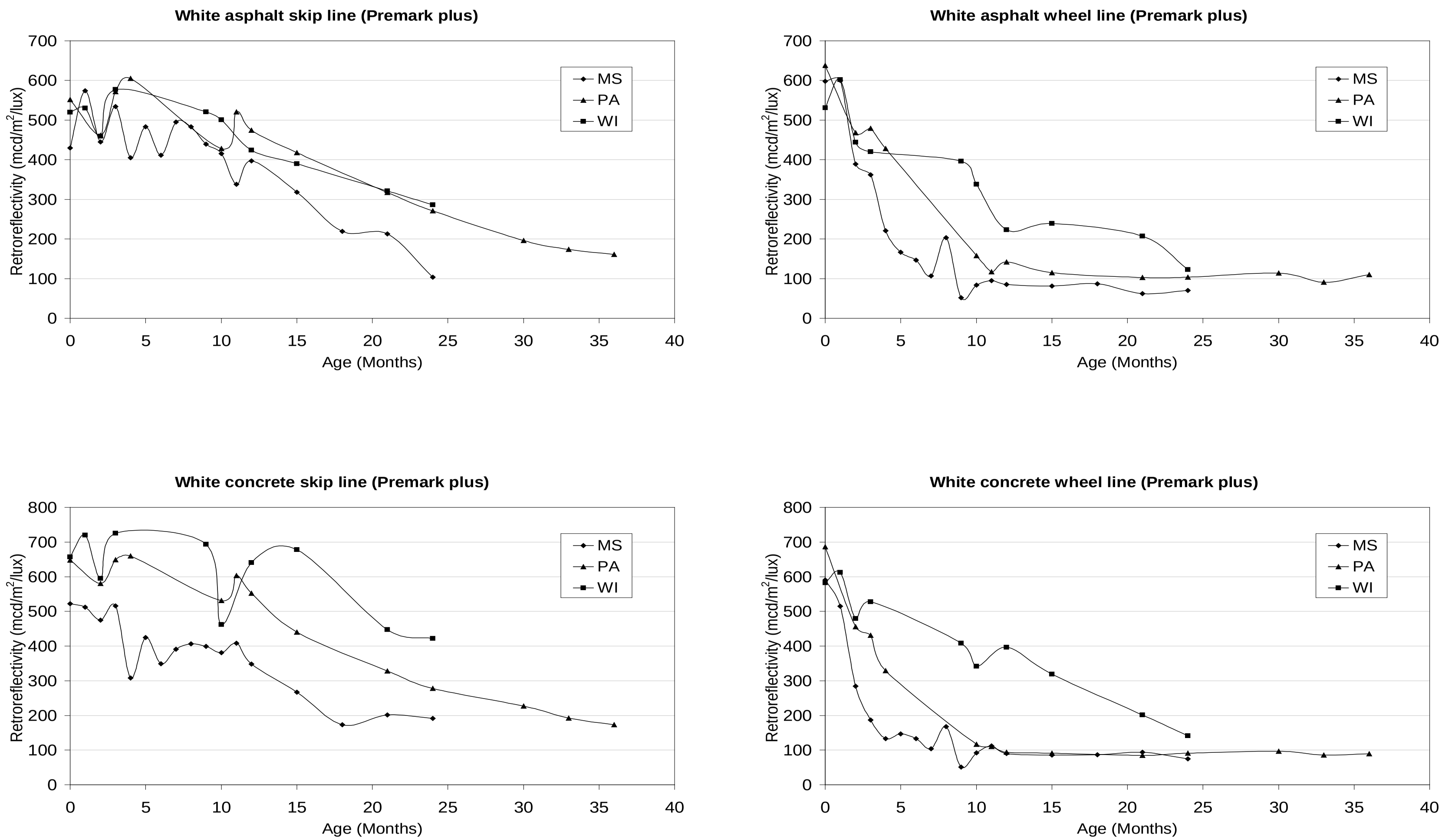


Figure 6.11- Retroreflectivity Comparison between NTPEP Test Decks for White Color Premark Plus.

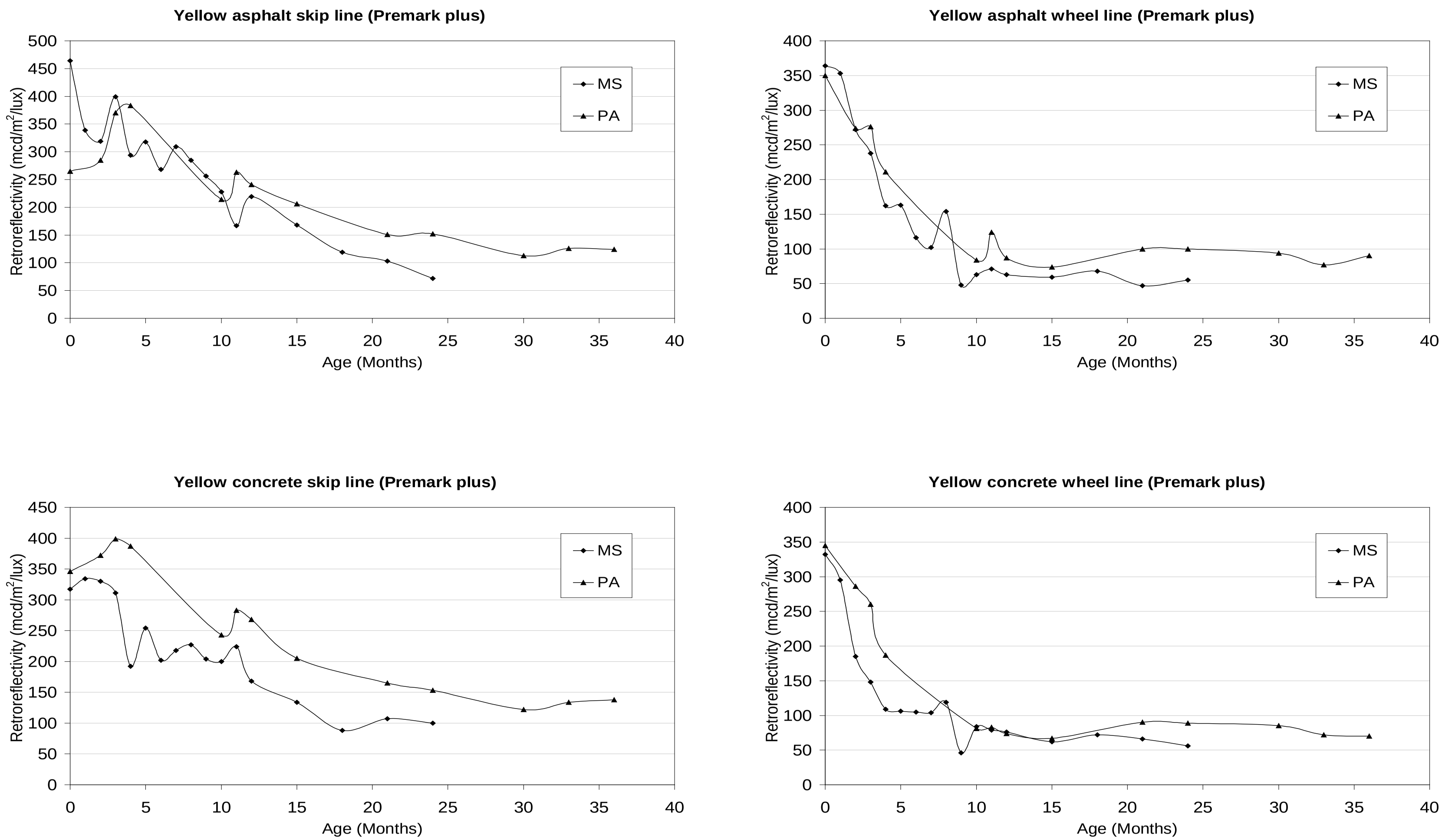


Figure 6.12- Retroreflectivity Comparison between NTPEP Test Decks for Yellow Color Premark Plus.

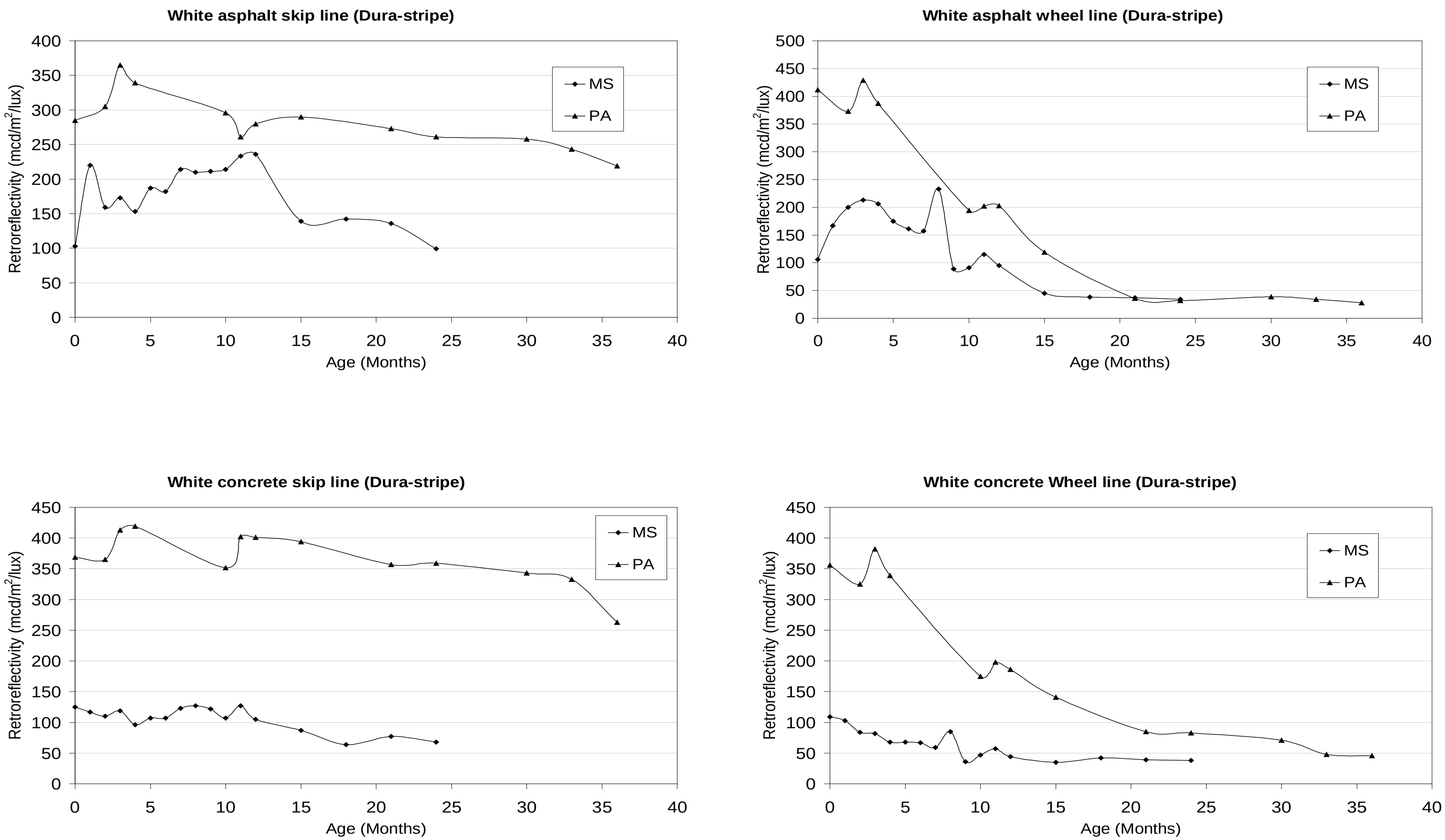


Figure 6.13- Retroreflectivity Comparison between NTPEP Test Decks for White color Dura-Stripe.

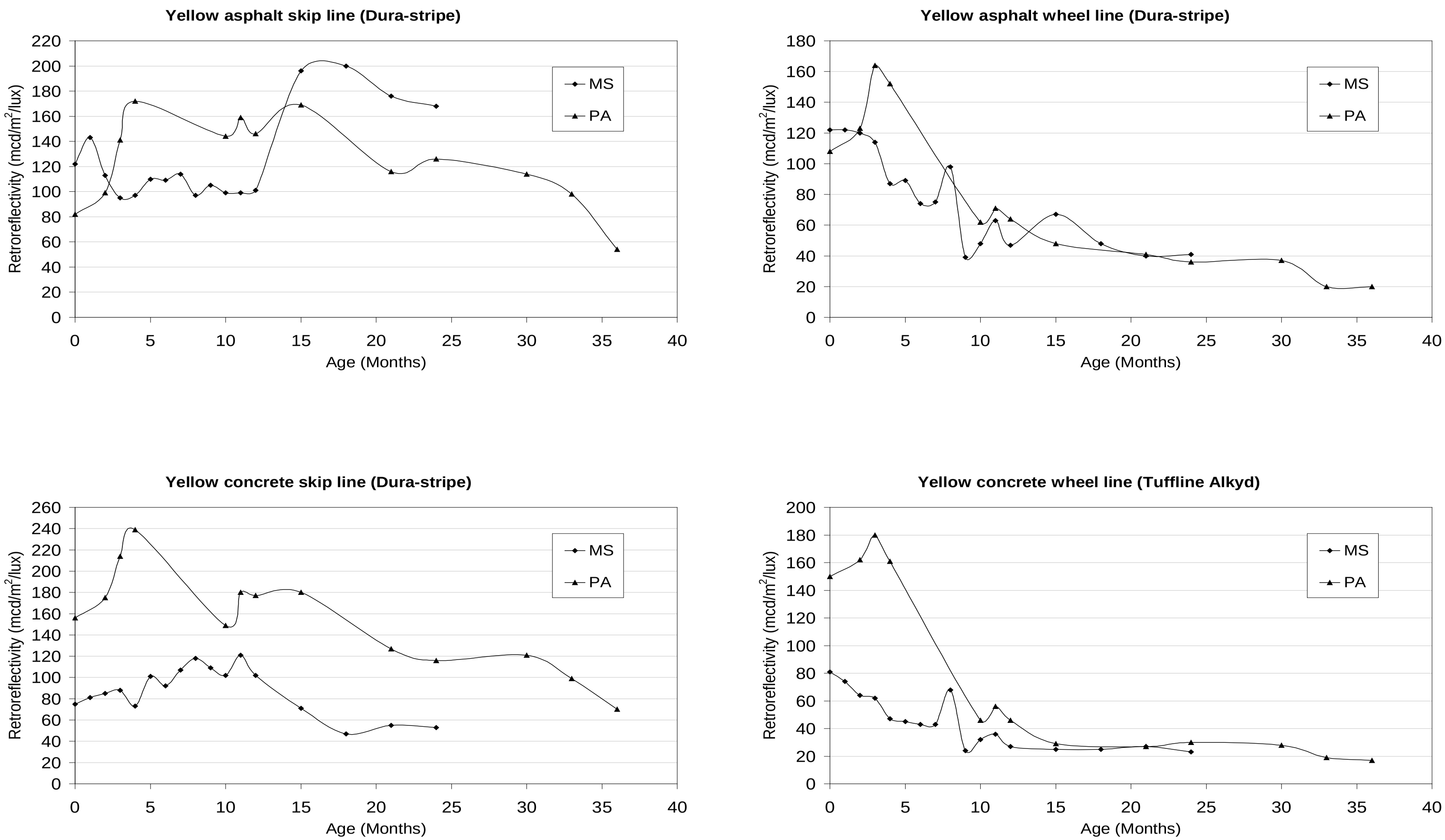


Figure 6.14- Retroreflectivity Comparison between NTPEP Test Decks for Yellow Color Dura-Stripe.

CHAPTER VII

PREDICTION OF PAVEMENT MARKING SERVICE LIFE

7.1 Introduction

In the previous chapters, the performance of evaluated materials was compared to milestone criteria between material groups and different NTPEP test decks. These comparisons were based on actual field observations and ratings during the periodic NTPEP evaluations.

In this chapter, several mathematical models were used to predict the future retroreflectivity performance of material groups in different test decks by fitting these models to actual field retroreflectivity data. These models were then used to predict the service life of the pavement markings. Pavement marking service life defined as the time required for its retroreflectivity to drop below a preselected threshold value. In this study, a retroreflectivity value of 150 mcd/m^2/lux was used for white markings and a retroreflectivity value of 100 mcd/m^2/lux was used for yellow markings.

7.2 Retroreflectivity models

Four mathematical models were used to define the deterioration trend of pavement markings. These models include the linear model, the exponential model, the power model and the natural logarithm model. The mathematical expressions for these four models are presented in Table (7.1) using both x-y and Retroreflectivity, R_L, Versus

Age forms. Retroreflectivity, R_L , was represented in these models using mcd/m^2/lux and Age was represented by days.

Table 7.1- 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	$y = a + b.\ln(x)$	$R_L = a + b.\ln(Age)$

A Matlab code was developed to handle the large amount of data involved in the analysis. The developed code employed the Ordinary Least Square (OLS) method in obtaining the regression model parameters. In brief, this method is based on minimizing the sum of the squared difference between the data points and the model predictions in obtaining the model parameters.

7.3 Aptness of the Retroreflectivity Models

The aptness of the resulting retroreflectivity models was determined using various statistical methods, including the coefficient of determination, r^2, and several diagnostic plots such as the measured and predicted retroreflectivity versus age and predicted versus measured retroreflectivity. Due to the large mount of data generated using the Matlab and Excel, only results for white HPS-4 skip line on asphalt surface in Mississippi, will be presented in the figure (7.1) to demonstrate the concepts.

7.4 Pavement Marking Service Life

Table (7.2) present example predicted service life for HPS-4 Modified Urethane, as shown in the table, 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. Therefore, only results for the linear and the exponential models are presented in this section.

Table (7.3) 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. 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 based on the service life predictions presented in Table (7.3):

- 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 estimated service life of wheel line is usually below or little higher than two years for all test materials on different NTPEP test decks.

- Comparing with the wheel line, the skip line usually had higher predicted service life of two to six years, which is consistent with the performance evaluation results in previous chapters.
- 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 most test marking materials on the wheel lines 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 Dura-stripe Methyl Methacrylate on concrete skip lines of Pennsylvania deck. 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 Yellow HPS-5 Polyurea on concrete skips lines of Wisconsin Deck. The retroreflectivity of this material first decreased then increased 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.

- As for the service life prediction of pavement markings on asphalt and concrete surfaces, comparable predictions were obtained on these surfaces for most cases.

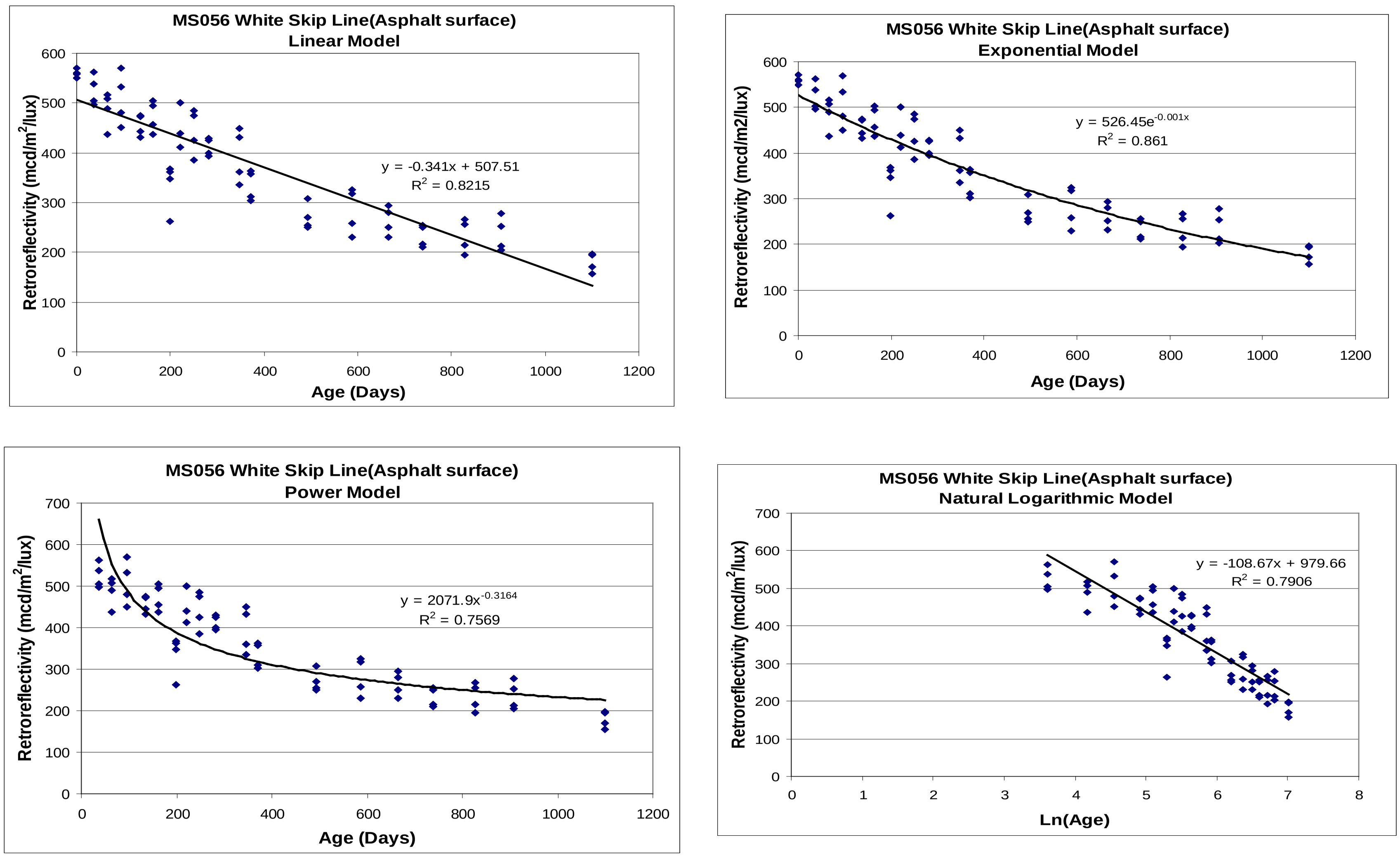


Figure 7.1- Diagnostic plots of white HPS-4 skip line on asphalt surface in Mississippi.

Table 7.2- predicted service life for HPS-4 Modified Urethane.

Products	Type	Models	Test Decks	White Color				Yellow Color			
				Asphalt Surface		Concrete Surface		Asphalt Surface		Concrete Surface	
				Skip	Wheel	Skip	Wheel	Skip	Wheel	Skip	Wheel
HPS-4	Modified Urethane	Exponential Model	Mississippi 2004	3.38	1.83	3.23	1.78	3.03	1.71	3.83	2.01
			Pennsylvania 2005	3.78	1.82	**7.13**	1.46	3.16	1.93	5.3	1.82
			Wisconsin 2004	1.62	1.55	**10.67**	1.58	1.86	1.6	4.83	1.68
		Linear Model	Mississippi 2004	2.87	1.82	2.79	1.88	2.64	1.75	3.12	2.05
			Pennsylvania 2005	3.15	2	5.09	1.79	2.8	2.03	4.14	1.96
			Wisconsin 2004	1.59	1.57	**8.49**	1.54	1.69	1.57	3.45	1.6
		Power Model	Mississippi 2004	**11**	1.95	**9.32**	1.6	**6.89**	1.71	**13.96**	2.05
			Pennsylvania 2005	**18.62**	1.47	**1135**	0.95	**6.74**	1.63	**113.44**	1.45
			Wisconsin 2004	1.91	1.7	**39266**	1.64	2.58	1.8	**176.21**	2.07
		Natural Logarithmic Model	Mississippi 2004	5.68	1.84	5.27	1.74	4.16	1.76	**6.12**	2.05
			Pennsylvania 2005	**7.55**	1.69	**75.66**	1.33	4.26	1.72	**23.69**	1.62
			Wisconsin 2004	1.67	1.61	**2436.61**	1.47	1.87	1.62	**19.77**	1.74

Unreasonable service life predictions are bolded

Table 7.3- Estimated Pavement Marking Service Life

Products	Type	Models	Test Decks	White Color(yrs)				Yellow Color(yrs)			
				Asphalt Surface		Concrete Surface		Asphalt Surface		Concrete Surface	
				Skip	Wheel	Skip	Wheel	Skip	Wheel	Skip	Wheel
Tuffline Alkyd	Thermoplastic	Exponential Model	Mississippi 2002	3.30	1.15	2.2	1.03	1.32	0.39	1.43	0.16
			Pennsylvania 2002	6.00	1.82	5.38	1.61	--[1]	1.09	2.78	0.73
		Linear Model	Mississippi 2002	2.84	1.23	2.01	1.13	1.37	0.66	1.62	0.36
			Pennsylvania 2002	4.63	1.94	4.2	1.81	--[1]	1.35	2.98	1.04
HPS-4	Modified Urethane	Exponential Model	Mississippi 2004	3.38	1.83	3.23	1.78	3.03	1.71	3.83	2.01
			Pennsylvania 2005	3.78	1.82	--[1]	1.46	3.16	1.93	5.3	1.82
			Wisconsin 2004	1.62	1.55	--[1]	1.58	1.86	1.6	4.83	1.68
		Linear Model	Mississippi 2004	2.87	1.82	2.79	1.88	2.64	1.75	3.12	2.05
			Pennsylvania 2005	3.15	2	5.09	1.79	2.8	2.03	4.14	1.96
			Wisconsin 2004	1.59	1.57	--[1]	1.54	1.69	1.57	3.45	1.6
HPS-5	Polyurea	Exponential Model	Mississippi 2004	4.47	2.08	4.21	1.67	4.99	2.3	3.9	2.35
			Pennsylvania 2005	3.36	1.51	5.74	1.56	4.07	2.03	5.5	1.75
			Wisconsin 2004	2.24	1.39	--[1]	1.5	2.37	1.68	--[1]	2.17
		Linear Model	Mississippi 2004	3.47	1.98	3.35	1.82	3.67	2.1	3.14	2.27
			Pennsylvania 2005	2.96	1.72	4.22	1.83	3.3	2.11	4.1	2.02
			Wisconsin 2004	1.97	1.46	4.8	1.51	1.97	1.61	--[1]	1.84
3M Series 380	Durable Tape	Exponential Model	Mississippi 2002	3.95	1.28	3.48	1.58	--[1]	2.68	5.99	--[1]
			Pennsylvania 2002	3.37	1.42	4.32	1.5	3.12	1.07	4.69	1.14
			Wisconsin 2004	3.77	2.15	--[1]	2.25	4.4	1.25	--[1]	2.47
		Linear Model	Mississippi 2002	3.09	1.36	2.61	1.51	--[1]	2.13	4.2	5.22
			Pennsylvania 2002	2.85	1.79	3.27	1.81	2.74	1.58	3.58	1.59
			Wisconsin 2004	2.65	1.89	5.14	1.9	3.07	1.65	7.93	2.05

[1] the regression models was not able to produce reasonable service life predictions.

[2] No available retroreflectivity data for yellow color Premark plus on Wisconsin Deck.

Table 7.3 (Continued) - Estimated Pavement Marking Service Life

Products	Type	Models	Test Decks	White Color(yrs)				Yellow Color(yrs)			
				Asphalt Surface		Concrete Surface		Asphalt Surface		Concrete Surface	
				Skip	Wheel	Skip	Wheel	Skip	Wheel	Skip	Wheel
Premark Plus	Preformed Thermoplastic	Exponential Model	Mississippi 2002	2.22	0.78	2.31	0.63	1.87	0.9	1.78	0.79
			Pennsylvania 2002	3.22	1.57	3.31	1.3	3.16	1.84	3.23	1.54
			Wisconsin 2004	4.29	1.92	6.00	2.17	---[2]	---[2]	---[2]	---[2]
		Linear Model	Mississippi 2002	2.09	1.03	2.05	0.91	1.76	1.09	1.68	0.97
			Pennsylvania 2002	2.92	1.84	2.93	1.69	2.82	1.96	2.8	1.79
			Wisconsin 2004	3.3	1.8	4.67	1.98	---[2]	---[2]	---[2]	---[2]
Dura-Stripe	Methyl Methacrylate	Exponential Model	Mississppi 2002	1.29	0.26	0	0	0.18	0	0.04	0
			Pennsylvania 2002	--[1]	1.04	--[1]	1.2	2.39	0.46	2.46	0.43
		Linear Model	Mississppi 2002	2.23	0.52	0	0	0.05	0.24	0.01	0
			Pennsylvania 2002	5.5	1.55	--[1]	1.58	2.9	0.62	2.62	0.76
Mark 55.3	Epoxy	Exponential Model	Utah 2001	0.86	0.03	1.86	0.4	0.92	0.17	1.66	0.39
			Pennsylvania 2002	2.52	1.03	4.53	1.12	2.85	1.36	2.58	1.36
		Linear Model	Utah 2001	1.01	0.33	1.78	0.57	1.04	0.34	1.63	0.57
			Pennsylvania 2002	2.48	1.41	4.09	1.55	2.77	1.74	3.68	1.79

[1] the regression models was not able to produce reasonable service life predictions.

[2] No available retroreflectivity data for yellow color Premark plus on Wisconsin Deck.

CHAPTER VIII

SUMMARY AND CONCLUSIONS

8.1 Project Summary

The performance of several pavement markings including thermoplastic (Tuffline Alkyd), performed thermoplastic (Premark Plus), epoxy (MARK - 55.3), polyurea (HPS-5), modified urethane (HPS-4), methyl methacrylate (Dura-Stripe), and high performance durable tape (Tape Series 380), were extracted and evaluated from four different test decks (Mississippi, Pennsylvania, Wisconsin and Utah) in NTPEP database.

The performance evaluation lasted from two to three years. The performance evaluation plan included measuring retroreflectivity using LTL 2000 or LTL-X handheld retroreflectometers or other acceptable devices and color using BYK Gardner Color-guide 45/0 spectrophotometer. Subjective durability ratings are made by a team of experienced evaluators, whereby durability is rated by visually assessing the percentage of material remaining on the surface on a scale of 0 to 10.

Retroreflectivity values were compared with milestone criteria for initial, 1-year and 2-year 3-yr (if available)performance. Color readings are checked with Ohio DOT specifications for white and yellow markings. At last, durability and performance comparison between different marking material groups are also presented.

Several mathematical models were built to predict the future retroreflectivity performance of material groups in different test decks by fitting to actual field retroreflectivity data. These models then are used to predict the service life of the pavement markings with the corresponding model parameters which is defined as the time required for retroreflectivity value to drop to a threshold value.

8.2 Conclusions

Base on the preformance evaluation results and the analysis findings, the following conclusions can be made:

- Retroreflectivity:
  - White markings have higher retroreflectivity than yellow markings. For most cases, yellow markings deteriorated at almost the same rate as white markings.
  - For the same pavement marking and on the same test deck, initial skip and wheel retroreflectivity was very close. The wheel deterioration rate, however, was higher than that of the skip since the former comes more frequently in contact with traffic.
  - In general, comparable initial retroreflectivity values were obtained for asphalt and concrete surfaces and there was no obvious difference in pavement marking performance on asphalt and concrete surfaces.
  - For most materials, the highest deterioration took place in the first year. Based on skip retroreflectivity, most materials did not reach the end of their service life and most materials reached the end of their service in less than 2 years for wheel retroreflectivity.

- A significant drop in retroreflectivity is noticed during the winter in Pennsylvania, Wisconsin, and Utah, especially the first winter, which is probably due to snow plowing. This is not the case in Mississippi where snow plowing is not used.
- Higher retroreflectivity values were obtained for 3M 380 durable tape than the rest of the materials especially during the first two years. After the first two years, however, the performance of 3M 380 was comparable to the rest of the materials.
- The lowest retroreflectivity performance was obtained for Dura Stripe methyl methacrylate and the performance of HPS-4 modified urethane, HPS-5 polyurea, and Premark Plus preformed thermoplastic is comparable.
- The performance of Tuffline Alkyd thermoplastic was slightly lower than HPS-4, HPS-5, and Premark Plus; and better than Dura Stripe.
- For HPS-4 modified urethane, comparable retroreflectivity performance was obtained on all three test decks (MS, PA and WI) for wheel retroreflectivity. Skip retroreflectivity, on the other hand, varied from one test deck to another.
- The retroreflectivity performance of Tuffline alkyd thermoplastic was slightly better on PA test deck than on MS test deck.
- The retroreflectivity performance of Mark 55.3 epoxy was much better on PA test deck than on UT test deck.
- For HPS-5 polyurea, comparable retroreflectivity performance was obtained on all three test decks (MS, PA and WI) for wheel retroreflectivity. Skip retroreflectivity, on the other hand, varied from one test deck to another.

  - For 3M 380 durable tape, the retroreflectivity performance was slightly better on the MS and WI test decks.
  - The retroreflectivity performance of Premark Plus preformed thermoplastic was better on PA test deck than on MS test deck. WI test deck had even higher retroreflectivity values for white color.
  - The retroreflectivity performance of Dura-Stripe methyl methacrylate was better on PA test deck than on MS test deck.
  - Based on the previous, the retroreflectivity performance on the PA test deck is slightly higher than the retroreflectivity performance on the MS test deck, especially along the skip line. This can be attributed to variations in traffic among these two locations; the average daily traffic (ADT) on the PA test deck is about 10,000 vehicles per day for both asphalt and concrete sites, while the ADT on the MS test deck is 20,000 vehicles per day for the concrete site and 15,000 vehicles per day for the asphalt site.
  - Slightly higher retroreflectivity values were also noticed for some materials on the WI test deck, which has an ADT in the range between 5,200 and 5,800 vehicles per day.
- Color:
  - White pavement markings continued to receive white color readings well within specifications. It is believed that either the current white color specifications are not strict enough or that existing color measuring devices are not sensitive enough to measure changes in white color.

- Even though white color readings were well within the white color specification box, it was noticed that initial white color readings were close to the center of the white color specification box and over time color readings moved towards the upper right side of the specification box.
- As for yellow markings, initial yellow color readings were close to the bottom left side of the yellow color specification box and over time color readings moved towards the lower left side of the specification box.
- As for the performance of pavement markings on asphalt and concrete surfaces, comparable color readings were obtained on these surfaces.
- In general, for all seven test material groups, white initial color readings were close to the center of the white color specification box and yellow initial color reading were close to the bottom left of the yellow color specification and with time going, white color reading move up towards the upper right side of the specification box and yellow move down towards the lower left side of the specification box.
- In general, the color readings are comparable between test decks for all seven test material groups

- Durability:
  - All materials investigated in this study are durable pavement markings. As such, the durability of most materials did not drop below a durability rating of five.
  - Lower durability ratings were obtained for wheel than skip and comparable durability performance was obtained on asphalt and concrete surfaces.

- The ranking of seven test material groups is: 3M 380 durable tape, followed by HPS-4 modified urethane, HPS-5 polyurea, and Premark Plus preformed thermoplastic; followed by Dura Stripe methyl methacrylate, Tuffline Alkyd thermoplastic; Mark 55.3 epoxy was the lowest.
- Although some material groups have slightly performance variance in different test decks, but in general, most material groups' performances are comparable between test decks

- Pavement Marking Service Life
  - Results for the linear and the exponential models are more reasonable than the power and the natural logarithmic models.
  - The estimated service life of wheel line is usually below or little higher than two years for all test materials on different NTPEP test decks and the skip line usually had higher predicted service life of two to six years.
  - 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. 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.
  - The retroreflectivity of some materials first decreased then increased 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.

- As for the service life prediction of pavement markings on asphalt and concrete surfaces, comparable color readings were obtained on these surfaces for most cases.

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