This research evaluated longitudinal pavement marking performance and developed useful degradation models for paint pavement markings which can help transportation agencies meet the pending FHWA minimum retroreflectivity requirements. The impacts of several important factors (such as directionality, pavement type and roughness) on marking retroreflectivity were evaluated. With a large dataset in hand, we determined whether these factors had significant impacts on marking retroreflectivity. Paint pavement marking centerline retroreflectivity values measured in the direction of paint striping were found to be significantly higher than the values measured in the opposite direction. The mean values of the retroreflectivity measurements collected on the plant mixed pavements were found to be significantly larger than the values collected on the bituminous surface treatment (BST) pavements. Image processing techniques were used to analyze paint pavement marking surface glass bead density. Bead density values were found to have a positive correlation with marking retroreflectivity measurements. Higher glass bead density led to higher marking retroreflectivity. The research also compared existing marking retroreflectivity degradation models. A linear mixed effects model (LMEM) was selected as most appropriate for the paint marking retroreflectivity data. LMEMs were established for paint pavement markings based on the data collected in NC. The research outcomes can help transportation agencies have a better understanding of paint pavement marking performance, which can lead to cost savings by maximizing the marking service lifecycles.
Performance Analysis and Strategic Management of Longitudinal Pavement Markings

by
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DEDICATION

This work is dedicated to my beloved wife Feng Qiu and my parents. Their support and understanding during my Ph.D. studies were crucial in my successful completion of this research.
Guanghua Zhang grew up in Jiangsu province in China. He received his Bachelor of Science and Master of Science degrees from Southeast University in August 2002 and May 2005, respectively. Both degrees were in transportation engineering. After he received his master degree, he came to the US to pursue a Ph.D. degree in transportation engineering in August 2005. He studied at Mississippi State University from August, 2005 to July, 2007, where he worked on a pavement marking performance evaluation project under the National Transportation Products Evaluation Program. He transferred to North Carolina State University in August, 2007. He finished a successful pavement marking performance analysis research project for the NCDOT under the direction of Dr. Joseph Hummer and Dr. William Rasdor. After graduation, he will continue to work in a transportation related area.
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1.0 INTRODUCTION

Traffic markings and markers, like traffic signs, are considered to be traffic control devices having the function of controlling traffic and encouraging safe and efficient vehicle operation according to the American Association of State Highway and Transportation Officials (AASHTO). For highways and streets three general types of markings are in use: pavement markings, object markers, and delineators [AASHTO 2004]. Pavement markings include centerline stripes, lane lines, and edge lines. These may be supplemented by other pavement markings such as approaches to obstructions, stop and crosswalk lines, and various word and symbol markings [AASHTO 2004]. The Manual on Uniform Traffic Control Devices (MUTCD) for Streets and Highways specifies that pavement markings are commonly placed using paint and thermoplastic materials although other suitable marking materials can also be used [FHWAa 2003].

The first-time installation and later restriping of pavement markings impose a high cost on transportation agencies. Pavement markings generally have a shorter service life than the pavement on which the markings are applied. Markings need to be restriped when their retroreflectivity values fall below a minimum level or when a portion of the markings are worn away by the traffic. The US nationwide annual pavement marking expenditure was approximately $2 billion in 2007 [Carlson et. al. 2009]. In North Carolina, pavement markings cost approximately $14.5 million a year in contractor-performed work alone which represents two percent of the $700 million North Carolina Department of Transportation (NCDOT) highway maintenance budget [Craig et. al. 2007]. Understanding pavement marking performances is important to maximizing the material’s service lifecycle which can eventually reduce the costs of markings.

At the present time, no national standard specifies the minimum retroreflectivity levels below which the markings should be replaced. However, a Congressional mandate, section 406 of the 1993 Department of Transportation and Related Agencies Appropriations Act, directed
the Secretary of Transportation to revise the MUTCD to include a standard for minimum levels of retroreflectivity that must be maintained for traffic signs and pavement markings [Vereen et. al. 2004]. The minimum retroreflectivity levels and maintenance methods for traffic signs were published in revision 2 of the 2003 version of the MUTCD. The final rule has been effective since January, 2008 [FHWA 2007, FHWA 2008]. The Federal Highway Administration (FHWA) is working with other research agencies to establish a similar minimum retroreflectivity standard for pavement markings.

The American Society for Testing and Materials (ASTM) Specification E 1710-05 provides a method of measuring pavement marking retroreflectivity using a handheld retroreflectometer that can be placed on the roadway markings. The ASTM specification requires that the measurement geometry of the instrument is based on a 30-meter viewing distance, an eye height of 1.2 meters and a headlight mounting height of 0.65 meters [ASTM 2005]. ASTM E 1710-05 specifies the marking retroreflectivity measurement method but does not provide a protocol to meet the minimum levels.

1.1 Research Objectives

The minimum retroreflectivity requirement for pavement markings is expected to be included in the MUTCD soon. When the minimum standard is published, it will be a mandate for highway agencies to meet the minimum requirements established by the FHWA.

The major objective of this research was to fill gaps in the current knowledge base on pavement marking performance. A better understanding of pavement marking material performance will help transportation agencies maximize the material’s lifecycle and avoid replacing markings which still have sufficient retroreflectivity, will help transportation agencies meet the pending FHWA minimum requirements, and will help reduce the potential of lawsuits once the FHWA regulations are in place.
This research focuses on three major problems related to pavement marking maintenance. First, the impacts of several important factors (such as directionality and pavement roughness) on marking retroreflectivity are unclear. With a large dataset collected in this study, we can determine if these factors have significant impacts on marking retroreflectivity. Second, we provide insights into the reasons why pavement markings lose retroreflectivity over time by determining the impact of bead density on paint marking retroreflectivity. Third, we compare existing degradation modeling techniques and establish useful retroreflectivity degradation models for paint pavement markings.

To meet the research objective, a set of research tasks is listed below:
1) Collect pavement marking retroreflectivity data on a selected set of roads,
2) Analyze the impact of directionality on paint pavement marking retroreflectivity,
3) Study the impact of pavement roughness on paint pavement marking retroreflectivity,
4) Study the impact of bead density on paint pavement marking retroreflectivity, and
5) Develop degradation models for paint pavement markings.

Those tasks have been successfully completed. The results of tasks 2-5 are reported in chapters 3-6, respectively.

1.2 Research Scope

The focus of this research is mainly on paint longitudinal pavement markings. The majority of marking materials in use are thermoplastics and paints. They are estimated to make up 89% of all marking materials in the US according to a survey by Migletz and Graham [2002]. In North Carolina, the NCDOT primarily uses four types of materials which are paint, thermoplastics, epoxy, and polyurea. More than 80% of total marking mileage uses paint pavement markings [NCDOT 2008]. Thermoplastic markings are mostly used on multiple-lane highways. Epoxy and polyurea are mainly applied on concrete pavement surfaces in the mountain region of the state. A previous study focused on thermoplastic marking performance in NC [Sitzabee 2008]. This research focused on paint pavement markings.
Two main sources of retroreflectivity data have been pursued in this research. The first source of data was from the NCDOT Work Zone Traffic Control Unit (WZTCU). The NCDOT has been collecting pavement marking retroreflectivity data via mobile device (Laserlux) by a contractor, Precision Scan LLC. Nearly 30,000 lane miles of marking data were collected though NC from May 2001 to July 2007. The collected data were mostly on thermoplastic markings. The paint markings were contractor-applied and the sample size of paint markings was small in the NCDOT database. The second source of retroreflectivity data was collected of paint markings by the NCSU research team. The research team collected paint data on secondary roads in NC because they comprise the majority of roadways. The paint data were collected by a handheld measuring instrument (LTL 2000). The data were collected in central region of NC. The results of the research could differ by regions.

The extent of the data collection activity of this research is large compared to similar research reported in the literature. The relatively large datasets enable us to evaluate the impacts of several factors on pavement marking retroreflectivity and to create credible retroreflectivity degradation models.

Though the NCDOT follows a typical pavement marking management procedure, readers should note that the direct results of this research (such as the retroreflectivity degradation models) may not be directly applicable to other geographic regions in the US and other countries. The readers in other geographic regions could use the methodologies and procedures presented here, but they need to use their own data and draw their own conclusions based on the data collected in their regions. This research concentrated on paint marking material. The methodologies are also applicable to other types of marking materials (e.g. epoxy and polyurea).
1.3 Outcomes and Benefits

The results of this research were that the impact of directionality on paint pavement marking retroreflectivity was significant. In addition, we showed that pavement type had a significant impact on paint marking retroreflectivity. We also demonstrated that bead density was an important factor that determines paint pavement marking retroreflectivity. Another important outcome of this research was a useful retroreflectivity degradation model for paint pavement markings.

The research outcomes can help the NCDOT have a better understanding of paint pavement marking performance, which can lead to cost savings by optimizing the marking service lifecycle. The NCDOT can better allocate its limited equipment and personnel resources by using performance-based pavement marking management. The results of this research can also help NCDOT and other transportation agencies to meet future FHWA minimum retroreflectivity standards and reduce their liabilities. To meet the standards and reduce liabilities agencies will need to have valid procedures and systems, which this research can help provide.

This research will also be beneficial to future researchers. The retroreflectivity datasets can be used by others. The modeling method and procedure can be used to create models for other types of marking material or for markings in other geographic regions.
2.0 RESEARCH BACKGROUND

This chapter provides background information relevant to the pavement marking research. We first review pavement marking application policies in the US. Then, we address pavement marking materials and glass bead types. Pavement marking performance evaluation and FHWA proposed minimum retroreflectivity requirement are also discussed in this chapter.

2.1 Pavement Marking Application Policies

The Manual on Uniform Traffic Control Devices for Streets and Highways (MUTCD) is the most important document guiding pavement marking use in United States. It specifies where centerline, lane line, and edge line markings are to be provided based on the type of roadway, the width of the road, and the annual average daily traffic (AADT) on the road [FHWAa 2003]. It also provides guidelines for pavement marking application in special road areas such as intersections, interchanges, and crosswalks. Transportation engineers should refer to the MUTCD regarding pavement marking application criteria, methods, and policies.

The MUTCD specifies that pavement markings are commonly placed using paint and thermoplastic materials although other suitable marking materials can also be used. There are 27 sections in the MUTCD explaining different pavement marking application scenarios and 4 sections specifying raised reflective pavement markers. General specifications require that pavement marking colors should be yellow, white, blue, or black. White longitudinal markings delineate the separation of traffic flows in the same directions; yellow markings delineate the separation of traffic in opposite directions. The normal longitudinal pavement marking line is 4 or 6 inches wide. The broken lines or skip lines should consist of 10 feet line segments and 30-foot gaps or they may consist of other dimensions in a similar ratio. The dotted lines for line extension may consist of 2 feet line segments and 2 to 6-foot gaps [FHWAa 2003].
The MUTCD requires that markings which must be visible at night shall be retroreflective unless ambient illumination assures that the markings are adequately visible, and all markings on interstate highways shall be retroreflective [FHWAa 2003]. However, no minimum retroreflectivity requirement for pavement markings is specified in the 2003 version of the MUTCD. The FHWA is working with other research agencies to establish the minimum retroreflectivity standard for pavement markings. The minimum retroreflectivity requirement for pavement marking is expected to be included in a future version of the MUTCD.

Detailed delineation practices including pavement markings are discussed in the *Roadway Delineation Practice Handbook* [Migletz et. al. 1994]. In addition, the Transportation Research Board published a synthesis in 2006 which identified typical placement of pavement markings in United States [Friedman 2006].

*The Standard Specifications for Construction of Roads and Bridges on Federal Highway Projects (FP-03)* defines 11 types of permanent pavement markings (designated as Type A to Type K) and their respective specifications. For example, Type B designates waterborne traffic paint with type I glass beads and Type C represents waterborne traffic paint with type III glass beads. Pavement marking construction requirements are specified in section 634 of FP-03. Six types of pavement marking materials – including conventional paint, waterborne paint, epoxy, polyester, thermoplastic, and preformed plastic – and five types of glass beads are specified in this standard. Material requirements such as waterborne paint composition, viscosity, drying time, and color are specified in section 718 of FP-03 [FHWAAb 2003].

The Federal specification (FP-03) defines the basic pavement marking requirements. States may have higher requirements and more detailed regulations beyond the Federal required levels. For example, FP-03 requires that the minimum thermoplastic thickness is 90 mils (1mil = 1/1000 inch) for center and lane lines and 60 mils for edge lines. However, the Texas Department of Transportation (TxDOT) requires 90 mils minimum thickness for all
thermoplastics lines [TxDOT 2004]. The North Carolina Department of Transportation (NCDOT) requires a 120 mils minimum thickness for thermoplastic center and lane lines and 90 mils for edge lines [NCDOT 2006]. Both states have higher minimum thickness requirements than the Federal standard.

2.2 Pavement Marking Materials

As noted above six types of pavement marking materials are specified in FP-03. The first five types of materials - conventional paint, waterborne paint, epoxy, polyester, and thermoplastic - are the most commonly used pavement marking materials in the US and Canada (Migletz and Graham 2002). Altogether, sixteen types of pavement marking materials were being used by different state and transportation agencies according to the Migletz and Graham survey. Waterborne paints and thermoplastics are the most commonly used pavement marking types and they make up 59.9% and 22.7% of the total pavement marking mileages in the US, respectively [Migletz and Graham 2002].

2.2.1 Paint

Paint is the oldest and most widely used pavement marking material. Paint is mainly composed of finely ground pigments that are mixed into a resin or binder system. Various ingredients and additives are incorporated for certain desired properties. A liquid (water or solvent) is added to the mixture to produce a material that is pliable by application equipment [VDOT 2008]. Paint can be classified into two broad categories, solvent borne and water based paint. Solvent borne paint is also known as conventional paint.

An NCHRP project reported that paint is associated with high volatile organic compound (VOC) contents [Andrady 1997]. VOC is defined as any organic compound that participates in atmospheric photochemical reactions which have a negative impact on the environment. Two-part pavement marking systems such as epoxy may also have small amounts of volatiles in their composition. Thermoplastic and tape are unlikely to have any volatile components
associated with them [Andrady 1997]. The average VOC content values of solvent-borne and water-based paints are shown in Table 2.1.

The U. S. Environmental Protection Agency (EPA) published a standard with the initial goal of reducing VOC from architectural coatings [USEPA 1998]. The standard has been in effect since September 11, 1998. It specifies that traffic marking coatings are subject to a 150 g/l VOC content limit. Traffic marking coatings refer to the pavement markings formulated and recommended for striping streets, highways, or other traffic surfaces.

EPA added a separate category for zone marking coatings and established the VOC content limit at 450 g/l for this category. This level allows the use of solvent borne paints to mark surfaces such as parking lots, driveways, sidewalks, and airport runways. However, the new category applies only to zone marking coatings sold in containers of 5 gallons or less. Paint pavement marking materials are generally sold in 30-gallon containers. The size restriction limits the use of solvent borne paints. Table 2.2 shows the EPA VOC content limits for pavement markings [USEPA 1998].

Table 2.1. Average VOC Content Level of Paints [Andrady 1997]

<table>
<thead>
<tr>
<th>Category</th>
<th>VOC Content (g/l)</th>
<th>VOC Content (lbs/gal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solvent Borne Paints</td>
<td>383</td>
<td>3.2</td>
</tr>
<tr>
<td>Water Based Paints</td>
<td>84</td>
<td>0.7</td>
</tr>
</tbody>
</table>

Table 2.2. EPA VOC Content Limits for Pavement Markings [USEPA 1998]

<table>
<thead>
<tr>
<th>Category</th>
<th>VOC Content Limit (g/l)</th>
<th>VOC Content Limit (lbs/gal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traffic Marking</td>
<td>150</td>
<td>1.25</td>
</tr>
<tr>
<td>Zone Marking</td>
<td>450</td>
<td>3.75</td>
</tr>
</tbody>
</table>

The EPA does not completely prohibit the use of solvent borne paint materials with high VOC contents, but their uses are limited to zone markings and are subject to a container size restriction. Most transportation agencies in United States have eliminated the use of solvent
born paints and replaced them with water based paints. Water based paint is now the most commonly used pavement marking material.

Paint markings are typically 15 to 25 mils thick when applied. Paint drying time depends on the thickness and the formulation. As a rule of thumb, a paint truck speed of 10-12 mph should result in a paint thickness of 15-18 wet mils without beads. Paint materials often have a lower initial retroreflectivity values and degrade at a faster rate than other pavement marking materials. They are usually classified as non-durable marking materials [TxDOT 2004]. Paint markings can last 3 months to 2 years or more depending on the traffic volume, snowplow frequency, application quality, and other factors. A research study conducted by North Carolina State University from 1989 to 1994 concluded that proper installation of paints could significantly extend their service life. If the paints were installed with careful equipment setup and calibration, the service life may be as long as 4 years [ITRE 1995].

Paint pavement markings can be installed either using premixed paint or plain paint. Premixed traffic paint has glass beads mixed into the paint during the manufacturing process which, when combined with drop-on glass beads during application, ensures that the pavement marking is retroreflective over the entire service life of the markings. This is compared to plain traffic paint which has no glass beads mixed in during manufacturing, but has all drop-on glass beads applied to provide a comparable amount of glass beads in the finished product. Premixed traffic paint was once quite common in use but due to equipment problems, crew downtime, special handing requirements, crew complaints, etc., most state highway departments have switched to plain traffic paints with all drop-on glass beads [ITRE 1995]. Currently NCDOT requires that glass beads be dropped (using a suitable pressurized means) into the wet paint as the paint is applied to roads [NCDOT 2006].

2.2.2 Thermoplastic

Thermoplastic has been used as a pavement marking material in the United States since the late 1950s. The mixture of plasticizer and resins that serve to hold all of the other ingredients
Together exists as a solid at air temperature, and becomes liquid when heated. Thermoplastic materials are classified into two basic categories based on the type of binder: hydrocarbon and alkyd. Hydrocarbon thermoplastic is made from petroleum-derived resins, while alkyd thermoplastic is made from wood-derived resins [TxDOT 2004].

Thermoplastic materials have several advantages compared with other types of pavement marking materials. They have high initial retroreflectivity and a long service life. The materials are ready for immediate use and there is no need to close traffic for a cure period after application. Thermoplastics can be directly applied on top of older thermoplastics which can save the cost of removing old pavement markings [Bahar et. al. 2006]. Typical thermoplastic marking thickness is 90 to 120 mils. Thermoplastic pavement markings have been known to last from 5-8 years depending on traffic volumes and other factors.

Thermoplastic materials perform well on asphalt surfaces because of the good bonding between the thermoplastic and asphalt. However, they appear to perform inconsistently on concrete surfaces because the bonding with concrete surfaces is achieved solely by mechanical bonding. Some applications of thermoplastic material perform very well on concrete, while others perform poorly [Gates et. al. 2003]. The research by Gates et al. provides guidelines for using thermoplastics on concrete surfaces. Currently very few states recommend using thermoplastics on concrete surfaces [Gates et. al. 2003]. For the NCDOT thermoplastic markings are used primarily on asphalt surfaces, and there are limited applications on concrete surfaces in North Carolina [McDiarmid 2007].

Thermoplastic materials can be preformed by the manufacturers into their final shapes and thicknesses. The material includes a top layer of glass beads. These are known as heat-in-place thermoplastic or preformed thermoplastic materials. They are durable pavement markings generally used for stop bars, symbols, and characters. Those materials do not have any pre-applied adhesive; the bonding to the pavement is achieved by placing the material in the desired location and heating it with a torch [TxDOT 2006].
2.2.3 **Epoxy**

Epoxy pavement marking material has two components. The first component of the epoxy typically contains resin, pigment, extenders, and fillers. The second component acts as a catalyst to accelerate setting time. Epoxy is recognized as a durable material on both asphalt and concrete surfaces. Epoxy is most often used on concrete surfaces. A survey in 2002 showed that state agencies use more epoxy than any other pavement marking material on concrete surfaces with high volume traffic. Epoxy markings are normally applied 15-25 mils thick and can last 3-5 years. On low to medium traffic volume roads, epoxy has been known to provide service lives more than 5 years [Gates et al. 2003].

Epoxy materials are generally less sensitive to application factors than thermoplastic materials. They can be applied at surface temperatures as low as 35°F. However, surface preparation is an important factor in the use of epoxy; the surface must be clean to achieve good bond. Application of a primer material is not necessary on roadway surfaces [Gates et al. 2003]. However, several problems are associated with epoxy pavement marking materials in the past. Many epoxy materials have been known to fade over time due to color instability resulting from ultraviolet lighting. They also need a longer time to dry than other materials, with some formulations taking over 40 minutes to dry. Epoxy materials cannot be placed over markings made from other materials, which limits their use as a re-stripe material [TxDOT 2006].

2.2.4 **Polyurea**

Polyurea is relatively a new type of pavement marking material. Like epoxy, it is a two-component, 100 percent solid thermosetting material. Polyurea maintains good color stability when exposed to ultraviolet light and has a short drying time of 2 minutes or less [TxDOT 2006]. Polyurea is mainly used on concrete surfaces as epoxy. NCDOT changed its policy in 2005 to use polyurea on concrete surfaces instead of epoxy [McDiarmid 2007].
2.2.5 Preformed Plastics

Preformed plastics (refer to as cold applied plastics, or as preformed tapes) are usually used on concrete surfaces. Preformed tapes can be classified into permanent and temporary categories depending on their expected service life and chemical materials. Permanent tapes have a significantly higher initial cost than other materials and have longer lifecycle. If they are applied properly, they can provide 4 to 8 years of service life. Temporary tapes are usually used in short term work zone applications and can be easily removed from road surfaces.

2.2.6 Polyester

Polyester is a two component system consisting of a pigment material and a peroxide catalyst. The catalyst is methyl ethyl ketone (MEK) or benzoyl peroxide. The polyester resin system will not cure properly if an inappropriate quantity of catalyst is added [VDOT 2008]. The disadvantage of the material is that the catalyst is flammable and requires careful handing as a hazardous material and requires operators with commercial driver’s licenses. It is also difficult to determine if the materials have been mixed properly. Only 5 of 37 surveyed states were reported to have experience with polyester as a pavement marking material in Migletz’s survey [Migletz and Graham 2002].

2.3 Glass Beads

Pavement marking retroreflectivity is achieved through the use of glass beads partially embedded in the surface of marking binder material. Using glass beads to achieve nighttime retroreflectivity is now a world-wide accepted practice. Pavement markings without glass beads may not be visible at night. In Figure 2.1, the headlight will be reflected in all directions when illuminated on markings without beads, and only a small amount of light will be reflected back to the driver. In contrast, a much greater quantity of light will reflect back into the driver if the marking is applied with glass beads embedded in the surface.
Figure 2.1. Pavement Markings Without and With Glass Beads [VDOT 2008]

Figure 2.2 shows how the glass beads reflect back the headlight by examining the path of light as it enters a single bead in the paint. There are actually millions of beads in each mile of beaded pavement markings. The amount of retroreflected light depends on the characteristic of the glass beads known as the refractive index. The refractive index is determined by the chemical and physical makeup of the glass material [VDOT 2008]. The higher a refractive index the more lights is reflected back to the driver. Glass beads provide their best retroreflection when about 40% of each bead is exposed above the marking and 60% is embedded in the marking. The bead shown in Figure 2.2 approximates this ideal embedment depth.

Five types of glass beads are defined in FP-03. The classification of pavement marking glass beads is based on their gradation. The first two types of glass beads are defined in an AASHTO standard and their gradations are shown in Table 2.3 [AASHTO 2007]. The reader should recall that a smaller sieve represent a larger bead. Type I is referred to as the standard glass bead, while type II is known as a uniform gradation glass bead. Type IM is called a modified gradation glass bead. Types III to Type V glass beads are defined in the FP-03. They are known as large glass beads and their gradations are shown in Table 2.4. FP-03 requires that all types of glass beads have a refractive index of 1.50-1.55. Bead coatings are available for assisting applicators in achieving proper bead embedment depth [TxDOT 2006].

The NCDOT requires that all drop-on glass beads used on epoxy, thermoplastic, paint, and heated-in-place thermoplastic meet a different standard which is shown in Table 2.5.
[NCDOT 2006]. All glass beads premixed in markings must meet AASHTO M-247 Type I in NC.

Figure 2.2. Pavement Marking Retroreflectivity Using Glass Beads

Table 2.3. Gradations of Type I and Type II Glass Beads [AASHTO 2007]

<table>
<thead>
<tr>
<th>Sieve Size</th>
<th>Mass Percent Passing</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Type I</td>
</tr>
<tr>
<td>No. 16</td>
<td>100</td>
</tr>
<tr>
<td>No. 20</td>
<td>95-100</td>
</tr>
<tr>
<td>No. 30</td>
<td>75-95</td>
</tr>
<tr>
<td>No. 40</td>
<td>-</td>
</tr>
<tr>
<td>No. 50</td>
<td>15-35</td>
</tr>
<tr>
<td>No. 80</td>
<td>-</td>
</tr>
<tr>
<td>No. 100</td>
<td>0-5</td>
</tr>
</tbody>
</table>
Table 2.4. Gradations of Type III, IV, V Glass Beads [FHWAb 2003]

<table>
<thead>
<tr>
<th>Sieve Size</th>
<th>Mass Percent Passing</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Type III</td>
</tr>
<tr>
<td>No. 8</td>
<td>-</td>
</tr>
<tr>
<td>No. 10</td>
<td>-</td>
</tr>
<tr>
<td>No. 12</td>
<td>100</td>
</tr>
<tr>
<td>No. 14</td>
<td>95-100</td>
</tr>
<tr>
<td>No. 16</td>
<td>80-95</td>
</tr>
<tr>
<td>No. 18</td>
<td>10-40</td>
</tr>
<tr>
<td>No. 20</td>
<td>0-5</td>
</tr>
<tr>
<td>No. 25</td>
<td>0-2</td>
</tr>
</tbody>
</table>

Table 2.5. NCDOT Drop-On Glass Bead Requirement [NCDOT 2006]

<table>
<thead>
<tr>
<th>Sieve Size</th>
<th>Mass Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Minimum</td>
</tr>
<tr>
<td>Passing No. 20</td>
<td>100</td>
</tr>
<tr>
<td>Retained on No. 30</td>
<td>5</td>
</tr>
<tr>
<td>Retained on No. 50</td>
<td>40</td>
</tr>
<tr>
<td>Retained on No. 80</td>
<td>15</td>
</tr>
<tr>
<td>Passing No. 80</td>
<td>0</td>
</tr>
<tr>
<td>Retained on No. 200</td>
<td>0</td>
</tr>
</tbody>
</table>

2.4 Pavement Marking Performance Evaluation

Pavement marking performance can be evaluated by drying time, appearance, durability, color, and retroreflectivity under both dry and wet road conditions. However, retroreflectivity and durability are the most commonly used variables to evaluate longitudinal pavement marking performance. Retroreflectivity describes nighttime visibility of markings. Durability is related to day time visibility of markings. These two variables describe two of the most important marking properties.

Wearing between tires and markings causes the loss of pavement marking material. Durability is a performance measure which represents the percentage of material remaining on the pavement when examined by evaluators. Thus, a durability value is obtained through
a subjective rating, which is defined in the ASTM D 713 specification [ASTM 2004]. This study will focus on the retroreflectivity performance measurements because they are measured by retroreflectometers and their values are more objective than the durability ratings.

Pavement marking retroreflectivity is used to describe the amount of light returned back to a driver from the vehicle’s headlight as it is reflected back from the markings. The reflected light provides the driver with information about the road and enables a safer drive at night. Thus, retroreflectivity value is relevant to roadway safety. Retroreflectivity is represented by coefficient of retroreflected luminance, $R_L$, and is expressed in units of candelas per square meter per lux (cd/m$^2$/lx). The unit commonly used for pavement markings is millicandelas per square meter per lux (mcd/m$^2$/lx) because of the low values [ASTM 2001].

The measurement geometry of a handheld retroreflectivity measuring instrument (retroreflectometer) is based on a viewing distance of 30 meters, headlight at the height of 0.65 meter over the pavement marking, and the driver’s eye at a height of 1.2 meters above the pavement [ASTM 2005]. The entrance angle is fixed at 88.76° and the observation angle is 1.05°. Figure 2.2 showed the retroreflectivity measurement geometry. The ASTM standard requires that a retroreflectometer uses a 30-meter viewing distance. Historically, 15-meter viewing distance instruments were developed and may still be used by some transportation agencies. The instrument used to collect the retroreflectivity data should be considered before using data made available by others.

Retroreflectometers can be divided into two categories, handheld and mobile instruments. A handheld retroreflectometer is a portable instrument that can be operated by a technician, testing spots on the pavement marking one at a time. Figure 2.3 shows a handheld retroreflectometer, the LTL 2000. A mobile retroreflectometer is mounted on a vehicle and can measure pavement marking retroreflectivity continuously at normal driving speed. The American Society for Testing Materials (ASTM) has published a series of specifications for
using handheld retroreflectometers, while specifications for mobile instruments are still under development.

Several models of 30-meter handheld and mobile retroreflectometers are used by different transportation agencies. Correlations studies have been conducted in the past to explore if retroreflectivity values measured from different models of retroreflectometers are compatible with each other.

A South Carolina study compared field data collected under various conditions and via several retroreflectometers from different vendors. The study found good correlation between handheld units MX-30 and LTL 2000. The correlation between handheld units LTL 2000 and MP-30 devices was also good. The correlation between the mobile device Laserlux and handheld unit LTL 2000 was not as good as the fit between handheld instruments, but the readings of a Laserlux and an LTL 2000 generally fell within the same ranges [Sarasua et. al. 2003].

Figure 2.3. A Handheld Retroreflectometer LTL 2000 (Photo by G. Zhang)
2.5 FHWA Proposed Minimum Retroreflectivity Requirement

The FHWA is responsible for developing a standard for pavement marking retroreflectivity. The FHWA has developed several candidate minimum levels for pavement markings in the past [Sitzabee, 2008], but none of those have been approved and included in the MUTCD. The FHWA has been cautious about publishing the minimum requirement for pavement markings. Transportation agencies may have to change their pavement marking policies to meet the FHWA requirement. There is also a concern that pavement marking budgets will increase significantly because of the requirement to meet the minimum levels [Migletz and Graham 2002].

A recent FHWA publication proposed a new recommendation for minimum level of pavement marking retroreflectivity based on the results of a Target Visibility Predictor (TARVIP) model [FHWA 2007]. The recommended values are shown in Table 2.6. The values in the table apply to both yellow and white pavement markings and are measured under dry conditions. The proposed standard considers three major variables. First, the standard separates the roads into two categories: with and without retroflected raised pavement markers (RRPMs). Figure 2.4 shows a picture of an RRPM. Second, the without RRPM category is divided into three options based on the speed of the road. Third, the roadway marking configuration is divided into roadways with center lines only and fully marked roadways.

### Table 2.6. Recommend Minimum $R_l$ Values from TARVIP Model [FHWA 2007]

<table>
<thead>
<tr>
<th>Roadway Marking Configuration</th>
<th>Without RRPMs</th>
<th>With RRPMs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>≤50 mi/h</td>
<td>50-65 mi/h</td>
</tr>
<tr>
<td>Fully marked roadways (with center line, lane lines, and/or edgeline, as needed)</td>
<td>40</td>
<td>60</td>
</tr>
<tr>
<td>Roadways with center lines only</td>
<td>90</td>
<td>250</td>
</tr>
</tbody>
</table>

Note: Applied to both yellow and white pavement markings. Retroreflectivity values are in mcd/m²/lux and measured with 30-m geometry.
The FHWA held two workshops in the summer of 2007 discussing the proposed rulemaking on pavement marking retroreflectivity. The recommendations from the two workshops were summarized in a FHWA technical report [Falk and Carlson, 2008]. Both workshops proposed MUTCD language regarding pavement marking retroreflectivity. During the first workshop, the recommended minimum $R_L$ values were same as the FHWA supported research results shown in Table 2.6. The second workshop suggested three options for minimum $R_L$ values. Table 2.7 shows the first option in which marking color becomes a decisive factor. On the roads with RRPMs, this option suggested that no minimum levels were required. The second option is shown in Table 2.8. The minimum $R_L$ values in Table 2.7 are same as the ones presented in Table 2.6. However, marking color replaced roadway marking configuration in becoming a decisive variable. Table 2.9 shows the third option in which roads are divided into two types: roads with RRPMs, lighting, or delineation and other roads. The minimum values are application to both yellow and white pavement markings in this option.

Currently, none of the proposed minimum retroreflectivity requirements for pavement markings has been approved. The FHWA is still working with other research institutes on
this issue. The minimum retroreflectivity levels for pavement markings are expected to be included in a future edition of the MUTCD.

Table 2.7. Recommend Minimum \( R_L \) Levels (Option 1) [Falk and Carlson, 2008]

<table>
<thead>
<tr>
<th>Color</th>
<th>Without RRPMs</th>
<th>With RRPMs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>50 mph or less</td>
<td>( \geq 55 ) mph</td>
</tr>
<tr>
<td>White</td>
<td>80</td>
<td>100</td>
</tr>
<tr>
<td>Yellow</td>
<td>65</td>
<td>80</td>
</tr>
</tbody>
</table>

Note: Retroreflectivity values are in mcd/m\(^2\)/lux and measured with 30-m geometry. X in the table represents that “No minimums are required”.

Table 2.8. Recommend Minimum \( R_L \) Levels (Option 2) [Falk and Carlson, 2008]

<table>
<thead>
<tr>
<th>Color</th>
<th>Without RRPMs</th>
<th>With RRPMs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \leq 50 ) mi/h</td>
<td>50-65 mi/h</td>
</tr>
<tr>
<td>White</td>
<td>40</td>
<td>60</td>
</tr>
<tr>
<td>Yellow</td>
<td>90</td>
<td>250</td>
</tr>
</tbody>
</table>

Note: Retroreflectivity values are in mcd/m\(^2\)/lux and measured with 30-m geometry.

Table 2.9. Recommend Minimum \( R_L \) Levels (Option 3) [Falk and Carlson, 2008]

<table>
<thead>
<tr>
<th>Other Roads</th>
<th>Without RRPMs</th>
<th>With RRPMs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Less than 50 mph</td>
<td>50 mph or more</td>
<td>All Roads with RRPMs, lighting, or delineation</td>
</tr>
<tr>
<td>100</td>
<td>150</td>
<td>50</td>
</tr>
</tbody>
</table>

Note: Applied to both yellow and white pavement markings. Retroreflectivity values are in mcd/m\(^2\)/lux and measured with 30-m geometry.
3.0 THE IMPACT OF DIRECTIONALITY ON PAINT PAVEMENT MARKING RETROREFLECTIVITY

Water-based paint is currently the most commonly used pavement marking material. Paint is used on almost 60% of the total pavement marking mileages [Migletz and Graham 2002]. In North Carolina, water-based paint markings are reported to make up more than 80% of the total marking mileages [NCDOT 2008]. As a result, the primary focus of this study is on paint pavement markings. Normally, paint markings are applied on secondary routes where traffic volumes are relative low [NCDOT 2008]. This is because paint materials often have lower initial retroreflectivity values and degrade at a faster rate than other pavement marking materials. They are usually classified as non-durable marking materials [TxDOT 2004].

A congressional mandate, section 406 of the 1993 Department of Transportation and Related Agencies Appropriations Act, directed the Secretary of Transportation to revise the MUTCD to include a standard for minimum levels of retroreflectivity that must be maintained for traffic signs and pavement markings [Vereen et. al. 2004]. The minimum retroreflectivity levels and maintenance methods for traffic signs were published in revision 2 of the 2003 version of the MUTCD. The final rule has been effective since January, 2008 [FHWAa 2008]. The Federal Highway Administration (FHWA) is working with other research agencies to establish a similar minimum retroreflectivity standard for pavement markings. The minimum retroreflectivity requirement for pavement markings is expected to be included in a future version of the MUTCD.

Concern about meeting future MUTCD minimum retroreflectivity levels led the North Carolina Department of Transportation (NCDOT) to initiate a research project to evaluate pavement marking material performances and service lives. The retroreflectivity directionality study reported herein is part of the overall research effort to evaluate paint marking performance on roads with low traffic volumes. While collecting field data on paint markings, the research team found that painted centerline pavement markings have significant directionality, which means the retroreflectivity values measured in one traffic
direction are significantly different from the values measured in the opposite direction on the same segment of roadway. Since this finding could affect how public agencies respond to the new standards and how they maintain their markings, public works managers need to be aware of this phenomenon and its implications.

Sparrow pointed out that the new and recent legislation in the areas of transportation and environment has highlighted the need to incorporate a variety of previously extraneous factors into infrastructure decision marking [Sparrow 2001]. Paint marking directionality is one of those factors which public works managers normally do not attend to. However, when the FHWA publishes a minimum retroreflectivity requirement, it must be met.

Public works managers are also well aware of the need to achieve increasing infrastructure performance and productivity [Price 2002]. Performance standards for infrastructure systems describe the qualities needed by the owner, users, and other stakeholders [Switzer and McNeil, 2004]. This chapter provides some useful insight into this subject.

3.1 Research Objective

Paint retroreflectivity directionality is important because drivers experience different centerline levels of retroreflectivity in each travel direction. It is possible that the paint pavement marking retroreflectivity in one direction meets the minimum requirement while in the other direction it does not. The objective of this study was to investigate the retroreflectivity directionality property of paint pavement markings to find the relationship between the retroreflectivity values and the paint installation direction, to quantify these differences, and to determine whether retroreflectivity directionality could have an impact on paint markings meeting the pending FHWA minimum retroreflectivity levels.

3.2 Research Scope

The scope of this study is on the retroreflectivity directionality of paint pavement markings on two-lane highway centerlines. The data collection efforts were made on two-lane
highways because two-lane highways comprise the majority of the highway system and traffic control for data collection (for safety) was much easier on two-lane highways than on other types of highways. In North Carolina, 74,015 of the total 79,042 roadway miles (93.6%) are two-lane highways [NCDOT 2007]. Since most two-lane highways were marked with paint pavement markings, NCDOT estimated that more than 80% of its total marking mileages were paint [NCDOT 2008]. This study does not address multi-lane roads or divided highways.

The centerline pavement markings were measured in both directions of traffic flow. The retroreflectivity values in each direction were averaged separately for each stripe. The centerline pavement markings did not provide the same retroreflectivity levels for each travel direction. Instead the average of all readings for each of the two directions (for each stripe) differs significantly.

The retroreflectivity values of edge pavement marking lines were measured in one direction because they are always painted in the direction of travel. Thus, driver always see the same retroreflectivity no matter which edge line is being considered.

Other types of marking materials with glass beads dropped on during installation (such as thermoplastics and epoxy) are known to have the same retroreflectivity directionality property as paint, but they were not investigated in this study due to the time and budget constraints of the project.

3.3 Background

Numerous papers and reports relevant to pavement marking research have been published in recent years. The congressional mandate to include the minimum levels of retroreflectivity in the MUTCD has given rise to a number of recent research efforts related to pavement markings. Various sources of information relevant to pavement marking studies were
obtained and reviewed. A summary of the findings of these studies and sources is presented in the following paragraphs.

3.3.1 Paint Marking Material

Paint is the oldest and most widely used pavement marking material. Paint is mainly composed of finely ground pigments that are mixed into a resin or binder system. Various ingredients and additives are incorporated to obtain certain desired properties. A liquid (water or solvent) is added to the mixture to produce a material that is pliable by application equipment [VDOT 2008]. Paint can be classified into two broad categories, solvent-borne and water-based. Solvent-borne paint is also known as conventional paint. Both categories will be discussed below.

One NCHRP project reported that paint is associated with high Volatile Organic Compound (VOC) content [Andrady 1997]. A VOC is defined as any organic compound that participates in atmospheric photochemical reactions which have a negative impact on some aspect of the environment. The average VOC content of solvent-borne and water-based paints are 383 g/l and 84 g/l respectively [Andrady 1997]. The U. S. Environmental Protection Agency (EPA) published its initial standard with the goal of reducing VOCs in architectural coatings [USEPA 1998]. The standard also addressed paint pavement markings and specified that all types of pavement markings (including paints) are subject to a 150 g/l VOC content limit. The EPA did not completely prohibit the use of solvent-borne paint materials with high VOC content, but their uses are limited and are subject to container size restrictions. Most transportation agencies in United States have eliminated their use and replaced solvent-borne paint with water-based paint because of the VOC content limit requirement. Water-based paint is currently the most commonly used pavement marking material.

Paint markings are typically 15 to 25 mils (1 mil = 0.001 inch) in thickness when applied. Paint drying time depends on the thickness and the formulation. As a rule of thumb, a paint
truck speed of 10-12 mph will result in a paint thickness of 15-18 wet mils without beads. Paint markings can last 3 months to 4 years depending on the geographic region, traffic volume, snowplow frequency, application quality, and other factors that influence both performance and durability. Paint markings last longer in the southern states where snowplowing does not impact marking performance. In northern states, paint markings deteriorate significantly faster over the winter due to the severe weather conditions and snowplow activity. Some northern states report that they restripe paint markings more than once a year [Hawkins et. al. 2006a].

Traffic paint can be installed either using premixed paint or plain paint. Premixed traffic paint has glass beads mixed into the paint during the manufacturing process. Plain traffic paint, on the other hand, has no glass beads mixed in during manufacturing. Both premixed paint and plain paint have glass beads dropped on during application to provide immediate surface retroreflectivity in the finished product. Premixed traffic paint was once quite commonly used but due to equipment problems, crew downtime, special handing requirements, crew complaints, etc., most state highway departments have switched to plain traffic paints with drop-on glass beads [ITRE 1995]. For example, the NCDOT requires that glass beads be dropped (using a suitable pressurized means) into the wet paint as the paint is applied to roads [NCDOT 2006].

3.3.2 Pavement Marking Retroreflectivity

Pavement marking retroreflectivity is a term used to describe the amount of light returned back to a driver from a vehicle’s headlight as it is reflected back from the markings. The reflected light provides the driver with information about the road (e.g. its center or its edge) and enables a safer drive at night. Thus, retroreflectivity is highly relevant to roadway safety. Retroreflectivity is represented by a measure referred to as the coefficient of retroreflected luminance \( R_L \), and is expressed in units of candelas per square meter per lux \( \text{cd/m}^2/\text{lux} \). The unit commonly used for pavement markings is millicandelas per square meter per lux \( \text{mcd/m}^2/\text{lux} \) because of the low values [ASTM 2001].
Pavement marking retroreflectivity is achieved through the use of glass beads embedded partially in the surface of the marking binder material (e.g. paint). Using glass beads to achieve nighttime marking retroreflectivity has a long history and is now an accepted practice worldwide. Pavement markings without glass beads are nowhere near as visible at night. During daytime hours, a non-beaded pavement marking will display richer and more uniform color [VDOT 2008]. Still, a much greater quantity of light will be reflected back at night if the marking is applied with glass beads embedded in its surface. Figure 2.2 shows how glass beads reflect back light from a headlight. There are actually thousands of beads in each segment of beaded pavement marking.

The glass bead refractive index, their embedment, and their density all have impacts on the retroreflectivity values of the pavement marking as a whole. The amount of retroreflected light depends on these parameters and on the type of the glass beads. The refractive index is determined by the chemical and physical makeup of the glass material [VDOT 2008]. AASHTO standard M247-07 requires glass beads to have a refractive index of 1.50-1.55 [AASHTO 2007]. Glass beads are recognized to provide their best retroreflection when about 40% of each bead is exposed above the marking and 60% is embedded in the marking. The Standard Specifications for Construction of Roads and Bridges on Federal Highway Projects (FP-03) specifies the glass bead application rate to be 6 lb/gal or 12 lb/gal for waterborne paint depending on the type of glass bead used [FHWAb 2003]. This application rate generally provides a density that results in an optimal number of beads to always be exposed at this 40/60 rate.

3.3.3 Paint Application

In this section we described the typical paint application practices in use by the NCDOT. Readers should note that while these are relatively standard practices, other transportation agencies may have minor differences in painting operation details. The NCDOT is divided into 14 divisions. Each division typically has one paint truck (one division has two). Figure
3.1 shows one of those paint trucks. Each paint truck requires 4-5 crew members to operate. The paint truck can hold 210 gallons of paint materials in each of two tanks. One tank contains white paint and the other contains yellow paint.

Paint materials supplied by a manufacturer are usually made available in 30-gallon cans so a paint truck can hold 14 cans of paint in both tanks. Normally 210 gallons of yellow paint is enough for one day to apply but about 400 gallons of white paint are needed. Thus several extra cans of white paint are carried to the field in another truck and at some point during the day need to be added to the white tank. It should be noted that the same paint (supplied by N. C. Department of Correction) is used in all the divisions throughout the state. Thus, there should generally be excellent uniformity in paint materials used statewide by NCDOT personnel.

![Figure 3.1. NCDOT Paint Truck](image)

On two-lane highways, the centerlines are striped in one of the three patterns. Figure 3.2 illustrates the three patterns – two solid lines, one solid line and one skip line, or one skip line only. The striping work on a two-lane road consists of two runs of a paint truck. One
run paints the yellow center lines and one white edge line, which is illustrated by direction 3 in Figure 3.2 (a). The other run paints the other white edge line, which is shown as direction 4 in Figure 3.2 (a). The key question is whether the paint striping direction is related to the retroreflectivity directionality. In other words, if the paint striping direction is same as that shown in Figure 3.2 (a), we want to know if the retroreflectivity values measured in directions 5 and 7 are higher than, the same as, or lower than in directions 6 and 8.

3.3.4 Driver Line of Sight

Figure 3.3 shows the vehicle travel, paint application and driver line of sight directions. Figure 3.3 (a) illustrates the driver line of sight in one direction and Figure 3.3 (b) illustrates the other direction. In Figure 3.3 (a), the driver line of sight direction 9 is same as the paint striping direction 3. In Figure 3.3 (b), the driver line of sight direction 10 is opposite to the centerline paint striping direction 3. If the $R_L$ values measured in the directions 9 and 10 are different for the centerlines, the drivers in the directions 1 and 2 would perceive different levels of retroreflectivity for the same centerline.

![Diagram of Vehicle Travel, Paint Application, and $R_L$ Measurement Directions](image)

**Figure 3.2. Vehicle Travel, Paint Application, and $R_L$ Measurement Directions**
3.3.5 \( R_L \) Measurement Directions

\( R_L \) values are measured in two directions for each centerline on two-lane roads. Figures 3.4 (a) and (b) show the \( R_L \) measurement directions for one centerline. Figure 3.4 (c) and (d) show the measurement directions for the other centerline. The measurement directions in Figure 3.4 (a), (b), (c), (d) correspond to the direction 5, 6, 7, 8 in Figure 3.2 (a).

3.3.6 Retroreflectivity Directionality Explanation

The hypothesis that explains the directionality phenomenon is that glass beads have a horizontal velocity when sprayed from a pressurized dispenser, which causes more paint resin to cover one side of their surface than the other side. Figures 3.5 (a) and (b) illustrate an idealized paint application in which the glass beads are sprayed (or dropped) vertically into the paint resin. Alternatively, Figures 3.5 (c) and (d) show a more realistic painting scenario in which the glass beads have a horizontal speed when they are sprayed from a moving truck traveling at a speed of 10-12 mph. More headlight will enter and be retroreflected back from these glass beads in one direction than the other as is illustrated in

Figure 3.3. Vehicle Travel, Paint Application, and Driver Line of Sight Directions
Figure 3.5 (d). Thus, the retroreflectivity values measured in the paint truck striping direction are higher than the other direction.

3.3.7 Data Collection Instrument

Two types of retroreflectometers can be used to measure pavement marking retroreflectivity values: a handheld unit (or portable unit) and a vehicle-mounted mobile unit. Handheld and mobile collection instruments each have advantages and disadvantages. Handheld units have a lower initial cost, but require a large crew (for safety reasons) to collect a small number of samples. Mobile devices are significantly more expensive initially, but provide a safer collection method and can collect continuous data throughout the highway system at highway speeds.

ASTM has published a series of standards related to retroreflectivity measurement. The measurement geometry of the handheld instrument is based on a viewing distance of 30 meters with a headlight at the height of 0.65 meter over the pavement marking and the driver’s eye at a height of 1.2 meters above the pavement [ASTM 2005]. The entrance angle of the light into the glass beads is fixed at 88.76° and the observation angle is 1.05°. Figure 2.1 illustrates this retroreflectivity measurement geometry. The ASTM specification requires that a retroreflectometer uses a 30-meter viewing distance. Historically, 15-meter viewing distance instruments were developed and may still be used by some transportation agencies. Thus, when using retroreflectivity data made available by others, we must determine whether the instrument used to collect the data conforms to the ASTM specification.
Figure 3.4. Retroreflectivity Measurement Directions*

* The retroreflectometer directions in Figure 3.4 (a), (b), (c), (d) correspond to directions 5, 6, 7, 8 in Figure 3.2 (a).
A mobile retroreflectometer is capable of measuring pavement marking retroreflectivity while driving at highway speeds. Currently there are no specifications on using a mobile retroreflectometer to measure marking retroreflectivity values. A South Carolina study compared field data collected under various conditions and via several types of retroreflectometers. The study found good correlation between handheld units but the linear fit between a mobile Laserlux device and a handheld unit (LTL 2000) was not found to be as good as the fit between handheld to handheld instruments. Still, the readings made by the Laserlux and LTL 2000 generally fell within the same ranges [Sarasua et. al. 2003].

3.3.8 Data Collection Method

ASTM Specification E 1710-05 specifies a method of measuring pavement marking retroreflectivity using a handheld retroreflectometer that can be placed on the road marking. The standard requires that readings shall be taken for each direction of traffic and averaged separately for each of the yellow centerlines. The standard also requires that the average of the readings shall be reported for each traffic direction for centerlines [ASTM 2005].
A critical shortcoming of the ASTM E 1710-05 standard is that it does not specify the sampling method to be employed when using a handheld unit to measure retroreflectivity values. Instead, the number of readings to be taken at each test location and the spacing between test locations shall be specified by the user. The ASTM E 1710 recommends readers to use the sampling method in the ASTM Specification D 6359 [ASTM 2005]. However, the ASTM D 6359-99 specification was withdrawn in December 2006 because the sampling methods were not being used [ASTM 2008]. Thus, there is no current specified standard sampling method when using a handheld instrument to measure retroreflectivity values. An Iowa study reported that they collect samples once every 5 miles, unless conditions change. Each sample consists of an average of 5 readings over a minimum segment length of 160 feet [Hawkins et. al. 2006a].

3.4 Methodology

The methodology of this study was to collect field retroreflectivity values using a handheld retroreflectometer and compare the retroreflectivity values of each traffic direction for two-lane road centerlines. First, we collected data at test locations on 40 roads. The markings on those 40 roads were installed at different times ranging from about 1 to 23 months after marking installation. The paint striping direction on those roads were not observed. The results of the first study strongly pointed to directionality as a factor affecting retroreflectivity. Then, a controlled study was initiated to determine to what extend the paint striping direction influences the retroreflectivity. We observed paint striping operations in field and measured the centerline $R_L$ values in each direction. The two studies were described in the following sections.

3.4.1 Unknown Striping Direction Study

The research team used a handheld LTL 2000 retroreflectometer for data collection. The LTL 2000 retroreflectometer uses 30-meter geometry, which is the geometry required by ASTM Specification E 1710-05. The standard operating procedure in the instrument manual was strictly followed during field data collection. Field calibration of the LTL 2000 on each
site was conducted before measurements were taken. A Global Position System (GPS) device was used to record the coordinates of starting and ending points on each test location and the field team used a digital camera to photograph the measured markings.

The paint data were collected on the secondary roads in four divisions in NC. Those roads have low traffic volumes, with annual average daily traffic (AADT) on most roads at less than 4000 vehicles per day. All measured roads were two-lane highways with asphalt pavement surfaces. Included in the study were 40 roads which were painted in 2006 and 2007. Paint installation data were provided by the NCDOT before the field data collection effort was undertaken. The installation data that was given to us included the road name, length, paint installation date, starting point, ending point, and other related information. The roads were measured twice by the research team. These measurements were taken in November, 2007 and May, 2008. Each round of data collection took about two weeks.

The purpose of the data collection activity was to evaluate paint marking performances. The research team selected a test location of the road to be measured. Test locations were not selected where there were sharp horizontal or vertical curves, but were otherwise randomly chosen. Test locations were about 200 feet long. Twenty measurements, approximately evenly distributed along the 200 feet segment, were taken for each pavement marking line. It is necessary to average numerous instrument readings in each direction on each line to account for variability in retroreflectivity along a line. The centerlines were measured in each direction of traffic. The average of the 20 readings was reported separately for each traffic direction for centerlines. It is this average that we present in our tables (3.1-3.4) of results.
Table 3.1. Centerline $R_s$ Readings for 35-73 Day Old Paint Markings
(Paint Striping Direction Unknown)

<table>
<thead>
<tr>
<th>Days Since Installation</th>
<th>First Yellow Center Line</th>
<th></th>
<th>Second Yellow Center Line</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Measurement Direction</td>
<td>Difference</td>
<td>Measurement Direction</td>
<td>Difference</td>
</tr>
<tr>
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</tr>
<tr>
<td></td>
<td>160</td>
<td>103</td>
<td>57</td>
<td>166</td>
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<tr>
<td>51</td>
<td>208</td>
<td>190</td>
<td>18</td>
<td>140</td>
</tr>
<tr>
<td>52</td>
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<tr>
<td>52</td>
<td>174</td>
<td>160</td>
<td>14</td>
<td>199</td>
</tr>
<tr>
<td>58</td>
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<td>212</td>
<td>-7</td>
<td>212</td>
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<td>70</td>
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</tr>
<tr>
<td>Average</td>
<td>170</td>
<td>146</td>
<td>25</td>
<td>170</td>
</tr>
</tbody>
</table>

* Measurement directions are illustrated in Figure 3.2 (a).
Table 3.2. Centerline $R_L$ Readings for 190-273 Day Old Paint Markings
(Paint Striping Direction Unknown)

<table>
<thead>
<tr>
<th>Days Since Installation</th>
<th>First Yellow Center Line</th>
<th>Second Yellow Center Line</th>
</tr>
</thead>
<tbody>
<tr>
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<td>Measurement Direction</td>
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</tr>
<tr>
<td></td>
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<td>128</td>
</tr>
<tr>
<td>204</td>
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<td>217</td>
<td>149</td>
<td>127</td>
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<tr>
<td>223</td>
<td>196</td>
<td>182</td>
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<td>138</td>
<td>127</td>
</tr>
<tr>
<td>Average</td>
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<td>108</td>
</tr>
</tbody>
</table>

* Measurement directions are illustrated in Figure 3.2 (a).
Table 3.3. Centerline R\textsubscript{L} Readings for 518-696 Day Old Paint Markings
(Paint Striping Direction Unknown)

<table>
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<tr>
<th>Days Since Installation</th>
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<th></th>
<th>Second Yellow Center Line</th>
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</thead>
<tbody>
<tr>
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<td>Measurement Direction</td>
<td>Difference</td>
<td></td>
</tr>
<tr>
<td></td>
<td>↑5*</td>
<td>↓6*</td>
<td></td>
<td>↑7*</td>
<td>↓8*</td>
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<td>59</td>
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</tr>
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<td>538</td>
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<td>34</td>
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<td>696</td>
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<td>99</td>
<td>27</td>
<td>112</td>
<td>97</td>
<td>15</td>
</tr>
<tr>
<td>Average</td>
<td>109</td>
<td>84</td>
<td>25</td>
<td>105</td>
<td>85</td>
<td>20</td>
</tr>
</tbody>
</table>

* Measurement directions are illustrated in Figure 3.2 (a).

Table 3.4. Centerline R\textsubscript{L} Readings for 14-22 Day Old Paint Markings
(Paint Striping Direction Known)

<table>
<thead>
<tr>
<th>Loc. **</th>
<th>Days Since Installation</th>
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<th></th>
<th></th>
<th>Second Yellow Center Line</th>
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</thead>
<tbody>
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<td>Difference</td>
<td></td>
<td>Measurement Direction</td>
<td>Difference</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>↑5*</td>
<td>↓6*</td>
<td></td>
<td>↑7*</td>
<td>↓8*</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>19</td>
<td>212</td>
<td>136</td>
<td>76</td>
<td>181</td>
<td>114</td>
<td>67</td>
</tr>
<tr>
<td>2</td>
<td>19</td>
<td>230</td>
<td>152</td>
<td>78</td>
<td>226</td>
<td>142</td>
<td>84</td>
</tr>
<tr>
<td>3</td>
<td>18</td>
<td>190</td>
<td>135</td>
<td>55</td>
<td>153</td>
<td>89</td>
<td>64</td>
</tr>
<tr>
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<td>232</td>
<td>156</td>
<td>76</td>
<td>214</td>
<td>119</td>
<td>95</td>
</tr>
<tr>
<td>5</td>
<td>22</td>
<td>192</td>
<td>126</td>
<td>66</td>
<td>134</td>
<td>82</td>
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<td>6</td>
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<td>215</td>
<td>144</td>
<td>71</td>
<td>190</td>
<td>116</td>
<td>74</td>
</tr>
</tbody>
</table>

* Measurement directions are illustrated in Figure 3.2 (a).
** Locations are shown in Figure 3.6.
3.4.2 Data Analysis

Tables 3.1-3.3 show the centerline data from the 40 roads that were measured but the paint striping direction was unknown. The direction numbers in Tables 3.1-3.3 correspond to Figure 3.2 (a). The ages of the markings are listed in the first column. The $R_L$ readings for each line in each direction are shown in columns 2, 3, 5, and 6. The differences between readings in each direction for each line are shown in columns 4 and 7. The data are sorted by the age of the markings.

In Tables 3.1-3.3, the $R_L$ values measured in one direction for both centerlines (directions 5 and 7, directions 6 and 8) are close to each other. The $R_L$ values measure in two directions for the same centerline (directions 5 and 6, directions 7 and 8) are different, which is the paint pavement marking retroreflectivity directionality property we investigate in this chapter. We used hypothesis tests to determine if the differences were statistically significant.

Paired t-tests were used to test if the retroreflectivity differences measured in two directions are statistically significant. The null hypothesis is that $H_0$: The $R_L$ mean values in two directional are equal. The alternative hypothesis is that $H_1$: the $R_L$ mean value measured in one direction is larger than the value measured in the other direction. We used a one-tailed hypothesis test for this specific problem.

3.4.3 Known Striping Direction Study

In addition to the unknown striping direction study, an additional field study was conducted to investigate the relationship between the paint striping direction and retroreflectivity. We worked directly with a NCDOT paint crew to identify the paint striping direction beforehand. First, the paint application and application direction were observed and recorded. Then, six routes were selected to measure retroreflectivity values just a few days after paint installation.
Figure 3.6 shows arterial roads (e.g. NC 905, US 701) and secondary roads (e.g. SR1147) in the field study area. Thinner lines represent the state routes. Darker lines indicate the observed and measured road segments. The arrows in Figure 3.6 show direction of striping. The arrows correspond to the paint striping direction 3 in Figures 3.2 and 3.3. The numbers correspond to the first column in Table 3.4. Table 3.4 shows the collected data for this known striping direction study. The ages of the markings, the $R_L$ measurements, and the differences between readings in each direction are shown in Table 3.4.

3.5 Results

We found that the centerline retroreflectivity values have obvious directionality, which means that the $R_L$ values measured in one traffic direction were higher than the values measured in the opposite direction. The difference could be as large as 66 mcd/m$^2$/lux. Tables 3.1-3.3 show the yellow centerline retroreflectivity data for the unknown paint striping direction study. The data were sorted by the age of the paint markings. The average directional differences are generally in the range of 20-30 mcd/m$^2$/lux for the paints that are 35 to 696 days old. This represents between 15 and 30% more retroreflectivity in the painted direction than in the reverse.

The mean values for each direction are 141 and 114 mcd/m$^2$/lux for the data collected in the four divisions. The t-test hypothesized mean difference is 0. The one tailed p-value is $6.09 \times 10^{-28}$. We specified the significance level $\alpha = 0.05$. We can reject the $H_0$ since the p-value is less than $\alpha$, which means that the $R_L$ mean value measured in one direction is larger than the other direction at a 0.05 significance level.

The retroreflectivity readings from the known striping direction study are shown in the Table 3.4. The average $R_L$ differences of the two yellow centerlines measured in two directions (directions 5 and 6, directions 7 and 8) are 71 and 74 mcd/m$^2$/lux. The retroreflectivity differences are larger in this known striping direction study than the first study. Here one direction is 50% higher than the other. One reason for this significant difference is that new
paint markings have higher directionality differences than the older markings. In this study the measurements were made within days of the paint application. This is a point at which markings generally exhibit their highest $R_L$ values.

Figure 3.6. Directionality Data Collection Map (Columbus County, NC)
The overall result of this study is that paint centerline retroreflectivity values measured in the direction of paint striping are significantly higher than the values measured in the opposite direction. If the paint is striped in the pattern as shown in Figure 3.2 (a), the $R_L$ values measured in the direction 5 and 7 will be significantly higher than the values measured in the direction 6 and 8. The differences are in the range of 20-30 mcd/m$^2$/lux for older paints. For newer paint markings, the differences can be as large as 95 mcd/m$^2$/lux based on our field data.

3.6 Conclusions

Tables 3.1-3.4 consistently affirm that retroreflectivity values on painted centerlines measured in the direction of the striping (painting) are significantly higher than the values measured in the opposite direction on two-lane highways. In reality we did not watch the painting process for the unknown striping direction study, but the research results are so strong that we actually can identify the striping direction from the analysis. For example, the $R_L$ values measured in the directions 5 and 7 in Figure 3.2 (a) are obviously higher than the values measured in directions 6 and 8, leading to the conclusion that the paint striping direction is same as direction 3. The results from the known striping direction study enabled us to draw this conclusion.

The research result implies that drivers perceive different levels of retroreflectivity, for the same pair of yellow centerlines, while driving in different directions on two-lane highways at night. In the paint striping direction, the retroreflectivity values are higher than the other direction. This research result is consistent with the measuring requirement in the ASTM E 1710-05 that the average readings shall be reported for each traffic direction for centerlines. The ASTM data collection procedures should be followed when collecting retroreflectivity data on two-lane highway centerlines with a handheld retroreflectometer. What this study demonstrates is how to interpret and use that data.
Paint pavement marking directionality also has a significant impact on determining whether or not a centerline meets the pending FHWA minimum retroreflectivity standard. On two-lane highways with two yellow centerlines, it is possible that one centerline meets the standard while the other does not. The lower average retroreflectivity value for a yellow centerline, measured in the opposite direction from the direction of paint striping (measurements 6 and measurement 8 in Figure 3.2 (a)), should be used to compare with the future FHWA minimum standard to determine whether or not the centerline meets the standard. Both lines are compared with the minimum. This is because drivers in that direction experience lower marking retroreflectivity at night, but they do see both lines. We should not use the average value of the two directions to compare with the minimum standard because no drivers observe the centerline with the average retroreflectivity from both directions simultaneously.

The readers should note that the proposed FHWA standard does not specify a measurement protocol for determining if a line meets the new standard. The proposed standard merely specifies a minimum retroreflectivity value. This chapter provides both measurement and analysis protocols to determine how to meet the standard. It provides an important addition to the standard in that it demonstrates the significant impacts of directionality on retroreflectivity and explains how to account for this in meeting the requirement.

Transportation officials and policy makers must be aware of the issues noted herein in order to effectively manage their pavement marking assets. It is important to measure and collect data according to ASTM standards. It is then essential to meet the minimum requirement established by FHWA. This study shows how to determine the correct values to compare to the minimum. It also firmly quantifies retroreflectivity differences as a function of both paint application direction and travel direction for two lane roads with painted pavement markings. It is highly recommended that a similar study be conducted for thermoplastics as well. This study addressed paints because they comprise the majority of markings on secondary roads.
One further question of interest, that could not be determined at the present time, is the persistence of the retroreflectivity difference over time. In the unknown striping direction study the range at which we collected data was generally between 1 and 23 months old. In the controlled study we collected data on essentially new markings. In a previous study we determined that paint markings should provide adequate performance for 2 years. Our future plans are to measure the controlled sites at a 2 year age. Doing so would bring closure to the work and would indicate what happens to retroreflectivity over the lifetime of a marking with respect to directionality.
4.0 THE IMPACT OF PAVEMENT TYPE AND ROUGHNESS ON PAINT MARKING RETROREFLECTIVITY

Prior research revealed that many factors might have impacts on pavement marking retroreflectivity values and degradation rates. Those factors include but are not limited to:

- Age of markings, type of pavement marking materials, and marking color;
- Glass bead type, glass bead density, and quality control during marking installation;
- Annual average daily traffic (AADT), type of traffic, heavy vehicle percentages, and road speed limit;
- Pavement type, pavement surface roughness, and roadway geometry; and,
- Weather/climate, snowplowing, salt and sand use, and studded tires.

Several research projects have been conducted to evaluate the impacts of these factors on pavement marking retroreflectivity values and establish degradation models. We review a few of those studies in this section.

Pavement marking age has long been recognized as one of the most important factors affecting pavement marking retroreflectivity degradation. The marking retroreflectivity values decrease over time. If the marking installation and measurement dates are known, the marking ages are easy to calculate. Most previous studies agreed on using marking age as an independent variable in degradation models. What they disagreed on was the form of marking age variable. Some studies assumed that retroreflectivity had a linear relationship with marking age [Lee et. al 1999, Sitzabee et. al. 2009]. Other studies proposed to use exponential transform [Perrin et. al 1998] or logarithmic transform [Andrady 1997] of marking age as an independent variable.

Pavement marking material type and color were normally identified as categorical variables in degradation models. Waterborne paints and thermoplastics were the most commonly used pavement marking types and they make up 59.9% and 22.7% of the total pavement marking mileages in the US [Migletz and Graham 2002]. Other types of pavement marking materials
such as epoxy, polyurea, preformed plastics, and polyester were also widely used. The lifecycles and degradation rates of different marking materials varied in a wide range (13). Previous research has shown that white and yellow markings had different levels of retroreflectivity. White markings generally had higher retroreflectivity readings than yellow markings assuming the same materials were applied [Craig et. al. 2007].

Traffic volume (or AADT) was believed by many traffic engineers to have an impact on the marking retroreflectivity values. A recent study included traffic volume as an independent variable in a multiple linear regression model [Sitzabee et. al. 2009a]. Abboud and Bowman [Abboud and Bowman 2002] proposed a logarithmic model which multiplied the AADT and time and used the result as a variable - vehicle exposure. Vehicle exposure was the estimated total number of vehicles that had passed through the road in each lane since the installation of the new pavement markings. However, the values of traffic volume as a variable were constantly changing and accurate traffic counting data overtime were normally unavailable for most of the roads.

A recent study found that bead density had a correlation with paint marking retroreflectivity readings [Zhang et. al. 2009]. Bead density was defined as the surface percentage of glass beads partially exposed above the paint marking material. Higher bead density led to higher paint marking retroreflectivity readings.

The study presented in this chapter investigated the impact of two new factors, pavement type and roughness, on paint marking retroreflectivity. Paint marking performance was evaluated on two types of asphalt pavements, plant mixed and bituminous surface treatment (BST) pavements. The paint marking performance on these two types of pavements was analyzed separately. The impact of pavement roughness on paint marking retroreflectivity was also investigated in the study.
4.1 Research Objective

The study reported herein was part of an overall research effort to evaluate paint marking performance in NC. While collecting field marking retroreflectivity data on paint markings, the research team observed that pavement markings applied on smooth pavement surfaces generally have higher retroreflectivity readings than on rough surfaces. The observation led to the collection of pavement roughness data and a systematic investigation of its effects on the paint markings retroreflectivity.

The pavement type and roughness impacts on paint marking retroreflectivity are important because the same paint markings may have different levels of retroreflectivity readings when they are applied to the pavements with different roughness characteristics. The objectives of the study were to collect pavement marking retroreflectivity data and roughness data, analyze the pavement roughness and marking retroreflectivity readings based on the pavement type, and determine the impact of pavement type and roughness on pavement marking retroreflectivity.

4.2 Research Scope

The scope of this research is focused on the waterborne paint pavement markings applied on two-lane highways with flexible pavements. Water-based paint is currently the most commonly used pavement marking material. Paint is used on almost 60% of the total pavement marking mileages in the US [Migletz and Graham 2002]. In North Carolina, water-based paint markings are reported to make up more than 80% of the total marking mileage [NCDOT 2008]. Normally, paint markings are applied on secondary routes where traffic volumes are relatively low [NCDOT 2008]. This is because paint materials, though they often have lower initial retroreflectivity values and degrade at a faster rate, are less expensive than other marking materials.

Pavement roughness and marking retroreflectivity data were collected on two-lane highways with asphalt pavement and low traffic volumes. The measured roads were paved with
asphalt pavements. The data collection efforts were made on two-lane highways because two-lane highways comprise the majority of the highway system. Data collection was also much easier and safer on two-lane highways than on other types. In North Carolina, 74,015 of the total 79,042 roadway miles (93.6%, maintained by the NCDOT) are two-lane highways [NCDOT 2007].

4.3 Methodology

Field marking retroreflectivity values were collected using a handheld retroreflectometer. Pavement roughness data were collected using a high speed inertial road profiler. The collected information was analyzed to determine the impact of pavement type and roughness on marking retroreflectivity.

4.3.1 Data Collection

The pavement marking retroreflectivity data were collected by the NC State research team and the pavement roughness data were collected by the NCDOT Pavement Management Unit. The data collection procedures are described in the following sections.

4.3.1.1 Pavement Marking Retroreflectivity Data Collection

The research team used a handheld LTL 2000 retroreflectometer for data collection. The LTL 2000 retroreflectometer uses 30-meter geometry, which is the geometry required by ASTM Specification E 1710-05 [ASTM 2005]. The standard operating procedure in the instrument manual was strictly followed during field data collection. Field calibration of the LTL 2000 on each site was conducted before measurements were taken. A global positioning system (GPS) device was used to record the coordinates of starting and ending points on each test location.

The paint data were collected on secondary roads in four of the highway divisions in NC. Those roads have low traffic volumes, with annual average daily traffic (AADT) on most roads of less than 4000 vehicles per day. All measured roads were two-lane highways with
asphalt pavement surfaces. The research team selected a test location on the road to be measured. Test locations were not selected on sections with sharp horizontal or vertical curves, but were otherwise randomly chosen. Test locations were about 200 feet long.

Twenty measurements, approximately evenly distributed along the 200 foot segment, were taken for each white edge pavement marking line. It is necessary to average numerous instrument readings in each direction on each line to account for variability in retroreflectivity along a line. A previous study found that that paint centerline retroreflectivity values measured in the direction of paint striping are significantly higher than values measured in the opposite direction [Rasdorf et. al. 2009] so the centerlines were measured in each direction. The centerlines on two lane highways could be either solid or skip lines. A total of 20 measurements for solid lines and 10 measurements for skip lines were taken in each direction of each the yellow centerline.

Figure 4.1 shows a typical data collection site layout. Pavement marking retroreflectivity data on one white edge line and two yellow center lines were used in this study. The right wheel track and left wheel track lines illustrate the location where the pavement profile data were collected.

4.3.1.2 Pavement Roughness Data Collection

The international roughness index (IRI) is developed by the World Bank in the 1980s and is widely used in the US for measuring road roughness. FHWA requires state highway agencies to submit roughness measurements in the form of IRI for the Highway Performance Monitoring System (HPMS). IRI defines the characteristic of the longitudinal profile of a traveled wheel track and constitutes a standardized roughness measurement [Sayers et. al. 1986]. The IRI values of roadway pavement are generally in the range of 50-700 inches/mile. Lower values represent smoother pavement surfaces [Sayers et. al. 1986].
Road profile measurements were collected using a high speed inertial road profiler capable of collecting pavement profile data at highway speeds. Figure 4.2 shows the photo of a road profiler. The data from the road profiler were provided by NCDOT in an ERD file format. The data collection road name, start point road name, vehicle travel direction, and end point road name were all recorded during the data collection. The data were collected in one traveling direction along the road and the profiles of both wheel tracks were recorded.

Figure 4.1. Field Data Collection Site Layout

Figure 4.2. NCDOT Road Profiler [NCDOT 2009]
The road profile data were collected in two rounds. The first round of data was collected on January 5, 2009, which included profile readings on 8 roads. The retroreflectivity readings were collected 35-38 days before the profile data collection. The second round of data was collected on May 14, 2009, which included profile readings on 9 more roads. The retroreflectivity readings were collected 6-10 days later.

The ProVAL software was used to computer IRI values from the road profile ERD files. ProVAL software was developed by the FHWA and the Transtec Group [The Transtec Group 2009]. It allows users to view and analyze pavement profiles in different ways. The IRI values were computed for each fixed interval of 200 feet. The 200-foot IRI computing interval was selected to match the approximate length of the retroreflectivity samples. The variations of the IRI values along the road were found to be large. Figure 4.3 shows the IRI readings along a typical road 6500 feet long. The lowest IRI value was 105 inches/mile and highest value was 271 inches/mile in this case. The large IRI variations required a careful selection of the IRI reading of the road section on which retroreflectivity values were measured for accurate analysis.

![Figure 4.3. IRI Readings along a Typical Road](image)
4.3.2 Pavement Type

The NCDOT pavement management system lists three types of asphalt pavements, plant mixed, bituminous surface treatment (BST), and slurry. The pavement roughness and marking retroreflectivity data were collected on the first two types of pavements. For plant mixed pavements, pavement materials are mixed in a central plant. It offers advantages such as more careful proportioning of the ingredients, more uniform mixtures, and less dependence on favorable weather conditions [Wright and Paquette 1987]. BST, also referred to as chip seal pavement, generally consists of aggregate spread over an asphalt emulsion layer. Plant mixed pavements generally have higher uniformity than BST pavements of the same age and the roughness readings (IRI) on plant mixed pavements are generally lower than BST pavements of the same age.

Figure 4.4 shows typical images of the pavement markings applied on BST and plant mixed pavements. The image on the left shows a BST pavement. The road surface texture appears rough. The image on the right is of a plant mixed pavement and the surface texture is smoother than the BST pavement. The pavement type directly impacts the pavement roughness and, as the image shows, likely affects marking retroreflectivity as well.

Readers should be aware that it is straightforward for an engineer to distinguish a BST and a plant mixed pavement either through a field inspection or examining an image of the pavement surface. We examined the pavement surface images and classified the pavements into BST and plant mixed types for the 17 roads where the roughness readings were measured. The results were exactly same as the pavement types reported in the 2008 NCDOT pavement condition survey.
4.3.3 Data Matchup

To make valid comparison, the pavement IRI readings need to match up with the marking retroreflectivity readings. A geographic information system (GIS) map was used to determine the distance from the profile measurement start point to the retroreflectivity measurement start point.

Figure 4.4 shows an example of matching up the computed IRI intervals with a retroreflectivity measurement interval. The pavement roughness data and marking retroreflectivity data were collected on the state route SR 1947. The pavement profile measurement start point is at SR 1945 and the end point is at NC 96. GPS coordinates were used to locate the retroreflectivity measurement start point and end point on the GIS map. We measured the distance from the profile measurement start point to the retroreflectivity measurement start point. The distance was 2515 feet. The distance between the retroreflectivity measurement start point to the end point was measured to be 245 feet, which was slightly longer than the planned measurement length of 200 feet. In this case, the
The retroreflectivity measurement location did not exactly match the IRI fixed intervals. We chose to analyze the mean IRI value of two involved intervals as the IRI value for the retroreflectivity measurement section. The two profile intervals completely overlapped the retroreflectivity measurement interval. In Figure 4.5, the computed IRI values for the right wheel track at the intervals 2400-2600 feet and 2600-2800 feet were 97.10 and 80.45 inches per mile, respectively. The mean IRI value of the two intervals was 88.78 inches per mile which was used as the right wheel track IRI value for the retroreflectivity measurement section.

4.3.4 Data Characteristics

Tables 4.1 and 4.2 list the marking retroreflectivity readings and pavement IRI readings from the 17 sample road sections. Table 4.1 includes 9 measured road sections on plant mixed pavements and Table 4.2 includes 8 sections on BST pavements. The marking ages are calculated from marking installation date to the RL measurement date. The RL measurement date was in the range of 6-38 days from the roughness measurement date.

Figure 4.5. Retroreflectivity Measurement Location in a GIS map
The $R_L$ readings on two yellow centerlines were measured in both directions of traffic flow. The values listed in the “Yellow Center $R_L$” column are the mean values of the retroreflectivity readings measured in both directions on the two yellow centerlines. The values in the “White Edge $R_L$” column are the mean values of the 20 measurements on the white edge marking. The IRI values are the mean values of two fixed intervals as described above.

The retroreflectivity readings on yellow centerlines are lower than white edge lines, which is consistent with other research findings [Craig et. al. 2007]. On plant mixed pavements, the average $R_L$ reading on yellow center markings is 137 mcd/m$^2$/lux, which is significantly lower than the average $R_L$ reading of 238 mcd/m$^2$/lux on white edge markings. On BST pavements, the average $R_L$ reading on yellow markings is 89 mcd/m$^2$/lux, which is also much lower than the 180 mcd/m$^2$/lux for white markings.

Table 4.1. Marking $R_L$ and Pavement Roughness Reading on Plant Mixed Pavements

<table>
<thead>
<tr>
<th>No.</th>
<th>Road No.</th>
<th>Marking Age in Days</th>
<th>$R_L$ Measurement Date</th>
<th>Roughness Measurement Date</th>
<th>Yellow Center $R_L$</th>
<th>White Edge $R_L$</th>
<th>Left Wheel IRI</th>
<th>Right Wheel IRI</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>SR 1623</td>
<td>448</td>
<td>12/1/2008</td>
<td>1/5/2009</td>
<td>128</td>
<td>243</td>
<td>97.67</td>
<td>84.01</td>
</tr>
<tr>
<td>2</td>
<td>SR 1613</td>
<td>440</td>
<td>12/1/2008</td>
<td>1/5/2009</td>
<td>119</td>
<td>310</td>
<td>66.22</td>
<td>86.63</td>
</tr>
<tr>
<td>3</td>
<td>SR 1736</td>
<td>1004</td>
<td>11/29/2008</td>
<td>1/5/2009</td>
<td>69</td>
<td>193</td>
<td>105.64</td>
<td>114.97</td>
</tr>
<tr>
<td>4</td>
<td>SR 1737</td>
<td>1004</td>
<td>11/29/2008</td>
<td>1/5/2009</td>
<td>136</td>
<td>219</td>
<td>57.79</td>
<td>67.64</td>
</tr>
<tr>
<td>5</td>
<td>SR 1947</td>
<td>575</td>
<td>5/20/2009</td>
<td>5/14/2009</td>
<td>169</td>
<td>179</td>
<td>55.81</td>
<td>88.78</td>
</tr>
<tr>
<td>6</td>
<td>SR 1382</td>
<td>585</td>
<td>5/24/2009</td>
<td>5/14/2009</td>
<td>156</td>
<td>177</td>
<td>68.37</td>
<td>85.51</td>
</tr>
<tr>
<td>7</td>
<td>SR 1008</td>
<td>1038</td>
<td>5/20/2009</td>
<td>5/14/2009</td>
<td>215</td>
<td>322</td>
<td>105.25</td>
<td>145.08</td>
</tr>
<tr>
<td>8</td>
<td>SR 1937</td>
<td>1042</td>
<td>5/20/2009</td>
<td>5/14/2009</td>
<td>192</td>
<td>336</td>
<td>87.59</td>
<td>100.07</td>
</tr>
<tr>
<td>9</td>
<td>SR 1537</td>
<td>1048</td>
<td>5/20/2009</td>
<td>5/14/2009</td>
<td>49</td>
<td>167</td>
<td>80.03</td>
<td>76.79</td>
</tr>
<tr>
<td>Avg</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>137</td>
<td>238</td>
<td>80.48</td>
<td>94.38</td>
</tr>
</tbody>
</table>

Note: The $R_L$ values are in the unit of mcd/m$^2$/lux
The IRI values are in the unit of inches/mile
Table 4.2. Marking $R_L$ and Pavement Roughness Reading on BST Pavement

<table>
<thead>
<tr>
<th>No.</th>
<th>Road No.</th>
<th>Marking Age in Days</th>
<th>$R_L$ Measurement Date</th>
<th>Roughness Measurement Date</th>
<th>Yellow Center $R_L$</th>
<th>White Edge $R_L$</th>
<th>Left Wheel IRI</th>
<th>Right Wheel IRI</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>SR 1713</td>
<td>442</td>
<td>11/28/2008</td>
<td>1/5/2009</td>
<td>92</td>
<td>243</td>
<td>91.81</td>
<td>156.86</td>
</tr>
<tr>
<td>12</td>
<td>SR 1715</td>
<td>438</td>
<td>11/28/2008</td>
<td>1/5/2009</td>
<td>90</td>
<td>218</td>
<td>93.79</td>
<td>156.07</td>
</tr>
<tr>
<td>14</td>
<td>SR 1101</td>
<td>591</td>
<td>5/24/2009</td>
<td>5/14/2009</td>
<td>80</td>
<td>186</td>
<td>114.62</td>
<td>134.45</td>
</tr>
<tr>
<td>Avg</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>89</td>
<td>180</td>
<td>139.13</td>
<td>163.41</td>
</tr>
</tbody>
</table>

Note: The $R_L$ values are in the unit of mcd/m$^2$/lux
The IRI values are in the unit of inches/mile

The retroreflectivity readings on plant mixed pavements were higher than the readings on BST pavements. The result is as expected because the plant mixed pavements generally have smoother pavement surfaces than BST pavements. The average $R_L$ measurements of yellow center marking and white edge markings on plant mixed pavements are 48 mcd/m$^2$/lux and 58 mcd/m$^2$/lux higher than on BST pavements, respectively.

The IRI readings show the same pattern as the retroreflectivity readings. Note that a higher IRI value represents a rougher road surface. The average left wheel IRI reading is slightly smaller than right wheel reading, which indicates that the left wheel road surface is smoother than right wheel. The IRI readings on BST pavements are much higher than the readings on plant mixed pavements. The roughness readings are consistent with the observation that BST pavements are generally rougher than plant mixed pavements.
4.3.5 **Data Analysis**

A statistical test, t-test assuming unequal variances for two groups, was used to determine if the retroreflectivity readings (or roughness readings) measured on plant mixed pavements and BST pavements are statistically significant. The null hypothesis (H0) was that: The mean retroreflectivity readings (or roughness readings) on two types of pavements were equal. The alternative hypothesis (H1) was that: the mean retroreflectivity reading (or roughness readings) on plant mixed pavements were larger (smaller) than the values measured on BST pavements. We used a one-tailed hypothesis test for this specific scenario.

A multiple linear regression model was used to fit the retroreflectivity data and the IRI roughness data. The linear regression model can be expressed as:

\[ Y = \alpha + \beta_1X_1 + \cdots + \beta_nX_n + e \]

Where:
- \( Y \) = Response variable, \( R_L \) values in mcd/m\(^2\)/lux
- \( X_1, \ldots, X_n \) = Independent variables
- \( \alpha, \beta_1, \ldots, \beta_n \) = Regression coefficients, estimated from the data
- \( e \) = Random error with mean zero

The coefficient of determination, \( R^2 \), is the proportion of the variability in the response explained by the regression model, which was used to determine how well the regression line approximates the real data. The overall range of the \( R^2 \) value is from 0 to 1.0. A 1.0 \( R^2 \) value indicates that the regression line fits the data perfectly.

4.4 **Results**

The t-test was used to test if the yellow centerline retroreflectivity values, the white edge retroreflectivity values, the left wheel IRI values, and the right wheel IRI values measured on plant mixed pavements are statistically significantly different from the values measured on BST pavements. The t-test hypothesized that the mean differences were zero. The one tailed
p-values were 0.0157, 0.0288, 0.0132, and 0.0001, respectively for each of the four tests. The p-values were all less than the specified significant level 0.05.

The mean values of the yellow centerline retroreflectivity measurements and the white edge retroreflectivity measurements collected on the plant mixed pavements (137 and 238 mcd/m\(^2\)/lux, respectively) were larger than the values collected on the BST pavements (89 and 180 mcd/m\(^2\)/lux). The mean values of left wheel IRI values and right wheel IRI values measured on plant mixed pavements (80.48 and 94.38 inches/mi) were also smaller than the values measured on the BST pavement (139.13 and 163.41 inches/mi).

We used a multiple linear regression model to fit the data. Two variables, marking age and roughness reading, were considered as independent variables in the model. However, the coefficient of the marking age variable was found to be positive (0.020 and 0.043 for white and yellow markings, respectively). This is unexpected; literature shows that the coefficient should be negative, that is, markings generally lose retroreflectivity as they age. The reason might be that we observed large retroreflectivity values on roads 7 and 8 where markings were almost 3 years old. Furthermore, the marking age variable was not found to be significant at a 95% level. Thus, we did not include the marking age variable in the regression model. The linear regression model only included one independent variable - IRI reading.
Figure 4.6 shows the white edge retroreflectivity values plotting against right wheel track IRI values and the yellow centerline retroreflectivity values plotting against left wheel track IRI values. The solid line is the linear regression line for the white edge markings and the skip line is for the yellow markings. The equations of the two lines are:

\[ R_L = 237 - 0.212 \text{IRI} \quad (R^2 = 0.021, \text{White edge line}) \]

\[ R_L = 130 - 0.147 \text{IRI} \quad (R^2 = 0.025, \text{Yellow centerline}) \]

The regression slopes are negative (-0.212 and -0.147) which indicates that RL values decrease when the IRI values increase. When the IRI values increase 100 inches/mile, the RL values decrease 21.2 and 14.7 mcd/m²/lux for white edge markings and yellow center markings, respectively. It means that the RL values are higher on the smoother roads (IRI
values are lower) and are lower on rougher roads (IRI values are higher). The result is same as expected.

The R2 values of the two regression lines are very low (0.021 and 0.025), which means a large portion of the variability in the data is not explained by the regression models. The data in Figure 4.6 also show the variability in the data is large. For example, when the IRI values are around 100 inches/mile, the retroreflectivity readings of white edge markings vary in the range 160-340 mcd/m²/lux. The large variability in the data indicates that pavement roughness (IRI value) is not the major impact factor that determines the paint pavement marking retroreflectivity values. Other factors (such as bead density) may have more impacts on the retroreflectivity values than pavement roughness.

4.5 Conclusions

The paint markings on plant mixed pavements have higher retroreflectivity values than markings on BST pavements. The pavement roughness readings on plant mixed pavements are lower than that on BST pavements. The research result implies that markings on BST pavements have shorter life cycles than markings on plant mixed. It indicates markings on BST pavements need to be restriped in a shorter time period than markings on plant mixed pavements to maintain the same marking quality.

A common practice of many transportation agencies is to restripe paint pavement markings in a fixed time period such as two years (some states have shorter restriping periods). The research results suggest that paint markings on BST pavements generally have lower retroreflectivity readings than the markings on plant mixed pavements all else being equal. The retroreflectivity values on BST pavements are more likely to fall below a minimum level than on plant mixed pavements. Thus, marking crews should consider applying higher quality paint markings on BST pavements to achieve the same service life as the markings on plant mixed pavement.
As a rule of thumb, a paint truck speed of 10-12 mph will result in a paint thickness of 15-18 wet mils without beads if the paint gun pressure is properly set. Paint markings are typically 15 mils (1 mil = 0.001 inch) in thickness when applied. A slower paint truck speed will lead to thicker paint markings and denser glass beads. The results suggest that on BST pavement roads, the paint truck crew should consider travelling slower than on plant mixed pavement to counter the naturally lower retroreflectivity values. The authors want to point out that many field paint truck crews already know this fact and apply paint markings in this way based on their experience. This study provides field data supporting the practice.

The study also found that pavement roughness has an impact on the pavement marking retroreflectivity readings. Pavement markings on smoother pavements (lower IRI readings) generally have higher retroreflectivity readings than markings rougher pavements (higher IRI readings). However, the pavement roughness is not a dominant factor that determines marking retroreflectivity. The marking retroreflectivity readings vary in a wide range on pavements with similar roughness readings.
5.0 THE IMPACT OF BEAD DENSITY ON PAINT PAVEMENT MARKING RETROREFLECTIVITY

Pavement markings are considered to be traffic control devices having the function of controlling traffic and encouraging safe and efficient vehicle operation [AASHTO 2004]. The Manual on Uniform Traffic Devices for Streets and Highways (MUTCD) is the most important document guiding pavement marking use in the United States. It specifies where centerline, lane line, and edge line markings are to be provided based on the type of roadway, the width of the road, and the annual average daily traffic (AADT) [FHWAa 2003].

Water-based paint is currently the most commonly used pavement marking material. Paint is used on almost 60% of the total pavement marking mileages according to a survey conducted in 2000 [Migletz and Graham 2002]. However, in NC at the present time, water-based paint markings are reported to make up more than 80% of the total marking mileages [NCDOT 2008]. Other types of pavement marking material such as thermoplastics, epoxy, polyurea, and preformed plastics are also used. The primary focus of this paper is on paint pavement markings though the research method presented herein can also be applied to other types of marking materials.

During daytime, drivers discern pavement markings mainly by the color contrast between the marking and the pavement surface. Nighttime visibility, however, is a function of the luminous contrast between the pavement markings and the road surface, which is generally determined by the pavement marking retroreflectivity. Retroreflectivity is a term used to describe the amount of light returned back to a source, such as the amount of light from a vehicle’s headlight that is reflected back towards the driver. The reflected light provides the driver with roadway information and enables a safer drive at night. Retroreflectivity is represented by a measure referred to as the coefficient of retroreflected luminance ($R_l$), which is expressed in units of millicandels per square meter per lux (mcd/m²/lux) [ASTM, 2001]. The current ASTM standard requires that retroreflectometers use a 30-meter
geometry [ASTM 2005]. This article discusses retroreflectivity of pavement markings and its relationship to the beads embedded in the markings.

Pavement marking retroreflectivity is achieved through the use of glass beads on the surface of, and partially embedded in, the paint. Auto headlights are reflected in all directions when illuminated on markings without beads, and only a small amount of light is reflected back to the driver. In contrast, a much greater quantity of light is reflected back to the driver if the marking contains glass beads. Using glass beads in a reflective binder, such as paint, to achieve nighttime retroreflectivity is now a world-wide accepted practice.

Pavement marking retroreflectivity values are intuitively thought to depend on the quantities and qualities of the glass beads in the markings. However, if a glass bead is fully embedded in the marking binding material, it will not reflect headlight back to the driver. Retroreflectivity is primarily achieved by the portion of the beads exposed above the paint. Traffic engineers generally believe that an optimum occurs when 40% of each bead is exposed above the marking and 60% is embedded in the marking. In this paper, we define the bead density as the surface percentage of glass beads that are exposed above the marking binding material.

This paper reports on the use of image processing techniques to measure the bead density of paint pavement markings. Additionally we are reporting on a correlation study between painted pavement marking bead density and retroreflectivity.

5.1 Literature Review

Much pavement marking research to this point has focused on modeling of marking retroreflectivity and on the performance and the safety effects of pavement markings. Few articles examine why and how retroreflectivity values degrade over time. This paper examines one degradation factor – bead density.
We reviewed several studies that provide insight into degradation models to predict long
term pavement marking performance. An early study by Dale reported that pavement
marking service life was a function of the type of pavement, the volume of traffic, and the
average snowfall per year if the materials were applied to a properly prepared surface using
the recommended application procedure [Dale 1988]. Several types of degradation models
such as logarithmic [Andrady 1997, Abboud and Bowman 2002], exponential [Perrin et. al.
1998], and linear regression models [Lee et. al. 1999, Sarasua et. al. 2003, Sitzabee 2008]
were established based on the data collected in each of these studies.

The above mentioned studies have established that longitudinal pavement markings can
reach the end of their service lives because of bead loss (resulting in poor retroreflectivity),
loss of the marking material because of chipping and abrasion, color change of the marking,
or loss of contrast between the base material of the marking and the pavement. Daytime and
nighttime visibility are closely related because as a marking is chipped or abraded by traffic
there typically is not only loss of marking material over time (which decreases the daytime
visibility of the markings) but there is also a loss of beads (which results in a reduction in the
nighttime retroreflectivity of the marking) [Migletz and Graham 2002].

Rich et. al. conducted a pioneering study of the impact of bead density on marking
retroreflectivity [Rich et. al. 2002]. The study used a specialized digital camera (Spot RT) to
collect high resolution glass bead images. The digital images were then converted into
binary images. The binary images were analyzed to extract bead density values.

The Rich study found that the surface percentage of glass beads (bead density), glass weight
percentage, and paint marking retroreflectivity variables were well correlated to each other
[Rich et. al. 2002]. However, the work was preliminary and had three major shortcomings.
First, the glass bead images used in that study were collected on roads with newly applied
paint. The glass beads and the paint were in an initial perfect condition. There were no glass
beads losses due to traffic wear, weather, or age. The elements on the images included both
the glass beads and the background markings. However, pavement markings which have been worn by traffic normally show different patterns than newly applied smooth paint. In such markings there are numerous holes left in the paint as the glass beads are knocked out by wear and these were not accounted for in the Rich study. Also, the images used in the Rich study were taken from aluminum plates that were painted in the field and returned to the laboratory for evaluation [Rich et. al. 2002]. The images were not taken on real world pavement markings applied to asphalt. Finally, the details of the image processing procedure were not revealed in the available literature.

In another study conducted in Iowa, Mizera et. al. manually counted the number of glass beads in a 1 inch by 1 inch sample. Four samples were counted and an average value from four samples was calculated as the number of glass bead for the pavement marking line [Mizera et. al. 2009]. The objective of the Mizera study was to compare how many beads two bead guns dispense when operating at the same speed.

The goal of our study was to determine bead density, which was different from Mizera study. In a similar manual counting effort we found that the method cannot produce an accurate bead density value as we defined above. We describe the details of the manual count method in the Methodology Section of this paper and compare our results to Rich and Mizera studies.

5.2 Research Objectives

The first objective of this study was to find a way to measure the bead density of pavement markings in the field. The measurement method has two requirements. First, the method should be able to produce an accurate bead density. Second, the method should be easy to perform. It should also not involve many specialized tools so that other researchers or engineers can replicate the method. Thus, we explored a number of digital image processing techniques to see if we could determine glass bead density accurately and rapidly and which method met our two requirements.
The second research objective was to investigate the impact of bead density on paint pavement marking retroreflectivity. To do so we collected retroreflectivity data and glass bead images in the field. To achieve both research objectives we processed the digital images and performed a correlation analysis between the bead density and the marking retroreflectivity.

5.3 PAINTING MATERIALS AND PROCESS

This section introduces the reader to various aspects of glass beads and paint marking materials. We also briefly discuss the paint marking application process.

5.3.1 Glass Beads

The glass bead refractive index, diameter, roundness, their embedment depth, and their density in the paint all have impacts on the retroreflectivity values of the pavement marking as a whole. The amount of retroreflected light depends on these parameters and on the type of the glass beads. This paper focuses on depth and density.

A bead refractive index is dictated by the chemical and physical makeup of the glass material [VDOT 2008]. AASHTO standard M247-07 requires glass beads to have a refractive index of 1.50-1.55 [AASHTO 2007]. Glass beads are recognized to provide their best retroreflection when about 40% of each bead is exposed above the marking and 60% is embedded in the marking. The Standard Specifications for Construction of Roads and Bridges on Federal Highway Projects (FP-03) specifies a glass bead application rate of 6 lb/gal or 12 lb/gal for waterborne paint depending on the type of glass bead used [FHWA 2003].

Five types of glass beads are defined in the FP-03. The classification of pavement marking glass beads into types is based on their gradation (size). The first two types of glass beads (I and II) are defined by an AASHTO standard and their gradations are shown in Table 5.1 [AASHTO 2007] as an example. The reader should recall that a smaller sieve size represents
a larger hole and thus, a larger bead. Type I is referred to as a standard glass bead and type II is known as a uniform gradation glass bead [AASHTO 2007]. Types III, IV, and V glass beads are known as large glass beads. These are not shown here as they pass through a large group of sieve sizes (8-25). Readers should note from Table 5.1 that each type classification of bead is comprised of beads of various sizes as specified in the table at the percentage levels shown. The fact that a bead type does not contain same size beads has a profound impact on bead density.

<table>
<thead>
<tr>
<th>Sieve Size</th>
<th>Sieve Size in μm</th>
<th>Sieve Size in Inches</th>
<th>Mass Percent Passing</th>
<th>Type I</th>
<th>Type II</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. 16</td>
<td>1180</td>
<td>0.0469</td>
<td>100</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>No. 20</td>
<td>850</td>
<td>0.0331</td>
<td>95-100</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>No. 30</td>
<td>600</td>
<td>0.0234</td>
<td>75-95</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>No. 40</td>
<td>425</td>
<td>0.0165</td>
<td>-</td>
<td>90-100</td>
<td></td>
</tr>
<tr>
<td>No. 50</td>
<td>300</td>
<td>0.0117</td>
<td>15-35</td>
<td>50-75</td>
<td></td>
</tr>
<tr>
<td>No. 80</td>
<td>180</td>
<td>0.0070</td>
<td>-</td>
<td>0-5</td>
<td>-</td>
</tr>
<tr>
<td>No. 100</td>
<td>150</td>
<td>0.0059</td>
<td>0-5</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Note: a 1000 μm = 1 mm

The NCDOT uses a slightly different bead specification (used in paints) which is similar to AASHTO type I beads. The graduation is reported in Table 2.5.

5.3.2 Paint Marking Material

Paint is mainly composed of finely ground pigments that are mixed into a resin or binder system. Various ingredients and additives are incorporated to obtain certain desired properties. A liquid (water or solvent) is added to the mixture to produce a material that is pliable by application equipment [VDOT 2008]. Water-based paint is more environment friendly than solvent borne paint. Water-based paint is currently the most commonly used pavement marking material.
Paint markings are typically 15 to 25 mils (0.015 to 0.025 inch) in thickness when applied. Paint drying time depends on the thickness and its composition as defined in the paragraph above. As a rule of thumb, a paint truck speed of 10-12 mph will result in a paint thickness of 15-18 wet mils without beads. Glass beads are usually dropped (using a mechanical pressurized means) into the wet paint as the paint is applied to roads [NCDOT 2006].

5.3.3 Paint Marking Application

Paint marking thicknesses and glass bead application rates are specified in the FP-03. However, thickness and application rate are very hard to control in the field during the paint marking application process. The quality of the markings generally depends on the experience of the paint crew.

Immediately after application, paint crew technicians examine the paint surface glass beads with a magnifier. If the glass beads are found to be too dense or too sparse (determined by a superintendent via visual inspection), the technicians will adjust the pressure in the glass bead tank or the glass bead dispenser until they obtain a satisfactory glass bead density. This paint truck calibration process is conducted on a test road to ensure that the applied markings have good qualities as determined by visual inspection. In the field, the paint crew normally cleans the bead guns and adjusts the bead tank pressure every morning before the paint application.

Paint crews also calibrate the bead guns using a kit form the bead manufacturers. The basic idea is that if we know how long it takes the truck to apply a gallon of paint, then hold a container under the bead guns and measure the volume of the beads after 10 seconds to get the number of pounds per gallon for glass beads. This can be used to compare with the specified values, 6 lb/gal or 12 lb/gal for waterborne paints, depending on the type of glass bead used [FHWA 2003].
5.4 Methodology

The methodology used in this study was to collect field retroreflectivity values with a handheld retroreflectometer and photograph the marking surface using a digital camera. The digital images were analyzed and a bead density value was generated for each pavement marking line. Then, we analyzed the impact of bead density on paint pavement marking retroreflectivity.

5.4.1 Field Data Collection

We first describe the site selection and layout process. Then, we discuss how we collected marking retroreflectivity data and how we captured glass bead images in the field.

5.4.1.1 Site Selection and Layout

The paint data were collected on 40 secondary road sites in four highway divisions in NC. The sites were selected randomly on a set of two lane highways. The selected sites were deemed to be typical. These roads generally have low traffic volumes whose annual average daily traffic (AADT) is at or below 4000 vehicles per day. All measured roads were two-lane highways with asphalt pavement surfaces (chip sealed or plant mixed asphalt). The $R_L$ measurements for each line were collected within a roadway section that was about 10 feet long. The date of marking installation was known for all sites. An example site layout is illustrated in Figure 5.1.

5.4.1.2 Retroreflectivity Measurement

The research team used a handheld LTL 2000 retroreflectometer for data collection. This retroreflectometer uses 30-meter geometry, which is the geometry required by ASTM Specification E 1710-05 [ASTM 2005]. The standard operating procedure in the instrument manual was strictly followed during field data collection. Field calibration of the LTL 2000 was conducted at each site prior to the start of data collection.
Three measurements were collected for each white edge marking line in the direction of vehicle travel. For the yellow center lines, three measurements were collected in each direction because a previous study found that centerline retroreflectivity values measured in the direction of paint application are significantly higher than the values measured in the opposite direction [Rasdorf et. al. 2009]. Thus, six measurements for each yellow center line were collected. The average of the three measurements for white edge lines and the average of the six measurements for yellow center lines were used as the line retroreflectivity.

![Figure 5.1. Field Data Collection Site Layout](image)

Three measurements were collected for each white edge marking line in the direction of vehicle travel. For the yellow center lines, three measurements were collected in each direction because a previous study found that centerline retroreflectivity values measured in the direction of paint application are significantly higher than the values measured in the opposite direction [Rasdorf et. al. 2009]. Thus, six measurements for each yellow center line were collected. The average of the three measurements for white edge lines and the average of the six measurements for yellow center lines were used as the line retroreflectivity.

### 5.4.1.3 Image Acquisition

We photographed five to eight marking images with a digital camera in the same segment of the road as the \( R_L \) measurements were taken (Figure 5.1). The glass bead images were
obtained using the macro zoom mode of a Canon SD camera. This camera enabled us to collect high-resolution images without a specialized digital image capturing device. Totally, about 1,000 glass bead images were collected over our entire study area of 40 sites. From these we selected 9 sites comprising 108 images. These sites were selected because they contained plant mixed asphalt surfaces rather than bituminous surface treatment pavements.

5.4.2 Bead Density Determination

Figure 5.2 shows an example of a good quality glass bead image (a 14 month old marking) collected in the field. One can clearly see that there are three primary elements on all images (as well as all of the other images): glass beads, paint background, and holes (voids) left by the glass beads when they are worn away.

Recall that both the Rich [2002] and Mizera [2009] studies were conducted on newly applied pavement markings. Such new markings do not typically have obvious glass bead loss. Few to no holes appear in them. Figure 5.3 shows an image of a newly applied pavement marking. Not a single bead is found to be worn away on the marking surface. Intuitively, we speculate that when time and traffic pass by, more glass beads are worn away and more holes are created (resulting in Figure 5.2, for example). The percentage of glass beads decreases while the percentage of holes increases with time. This is the primary cause of pavement marking retroreflectivity degradation over time – a reduction in bead density.

In the following sections, the manual, automated, and semi-automated methods used to determine glass bead density are presented.
5.4.2.1 Counting – A Completely Manual Method

Mizera’s manual counting method provides one way to calculate glass bead density. Using images of a predefined area (such as 2 inches by 2 inches) on the marking surface one can count the number of the beads in the area. If the average bead size (diameter) is known, the
The total surface area of all glass beads can be estimated. Then, the total area of glass beads is divided by the total marking area to determine the bead density.

We assume that the pavement markings in our study contained standard Type I glass beads. (The graduation of glass beads used in NC is actually different from AASHTO Type I beads). From Table 5.1, we can determine that the median diameter of a Type I glass bead is same as the size of a No. 40 Sieve, which is 425 μm or 0.0165 inch. Thus, the median area of a Type I glass bead is $0.214 \times 10^{-3}$ inch$^2$. The mean size is estimated to be 455 μm using the gradation of Type I glass beads.

Thus, it is possible to manually determine the bead density of an image (using the above procedure and the estimated median area of a Type I glass bead) by counting the number of visible beads. However, the estimated bead density values using this approach are not accurate. The reason for this is evident by a close inspection of Figure 5.4 which illustrates three typical cases of glass bead embedment. When more than half of a glass bead is embedded in the paint binding material it is most secure and is least subject to being dislodged. The second and third types of embedment (half of the glass bead, and less than half of the glass bead) result in beads that are much more easily worn off, especially when the markings are exposed to traffic for longer periods of time. Most glass beads that remain in older markings are embedded more than half way. Thus, most images (and most pavement markings) contain more deeply embedded beads only. Clearly, the surface area of a bead embedded this way is actually smaller than the estimated median area outlined in the procedure above because the true area is established by the chord length $C$ rather than by the bead diameter $D$ (Figure 5.4). Thus, $C < D$ and the area of type 1 embedment is smaller than the area of types 2 and 3. Thus, the estimated bead densities from the counting method are higher than the actual values. It should be noted that one could convert an estimation of diameter $D$ to chord length $C$ by employing an assumption of the average percentage of a bead that is embedded. However, the assumption may be erroneous. Without an assumption of the average percentage of the bead that is embedded, the manual counting method can
accurately produce a glass bead count (and perhaps an initial density) but not an accurate glass bead density for older pavement markings.

5.4.2.2 Automated Image Processing

The ideal solution for determining glass bead density is to find an image segmentation algorithm and use a computer to automatically process the glass bead images. To explore this approach we studied several image segmentation methods including global thresholding, region growth, and marker-controlled watershed segmentation. Unfortunately, we found that none of these methods works reliably and none can produce an accurate estimation of the bead density. We discuss those methods in the following sections.

5.4.2.3 Global Thresholding

Thresholding is based on the grayscale histogram of an image. The histogram shows, for each gray level, the number of pixels in the image that have that gray level. Figure 5.5 shows the grayscale histogram of Figure 5.2. The x-axis quantifies the gray scale levels which represent pixel intensity. Pixel intensity has 256 levels where level 0 represents black and level 256 represents white. The y-axis represents the number of pixels or the frequency of occurrence of a pixel intensity level. Thus, Figure 5.5 shows that (in Figure 5.2) there are about 2,500 pixels of intensity level 150 and about 15,000 pixels of intensity level 210.
An analysis of the Figure 5.2 image reveals that there are three primarily elements of interest—beads, voids, and background. In Figure 5.5 it is seen that the element with gray level range of approximately 60-120 represents darkness (holes) in the image. The element with a gray level range of approximately 120-170 represents the glass beads. The element with a gray level greater than 170 represents very light grayscale—the background paint. The threshold which separates the holes from the glass beads is somewhere between 110 and 130. The threshold which separate the glass beads from background paint is somewhere between 160 and 180. But where exactly and how can this be determined? There is no clear answer.

![Figure 5.5. Histogram of the Grayscale Image of Figure 5.2](image)

Still, if the thresholds were able to be determined this way one could then calculate the hole density and bead density by analyzing the binary images in an automated fashion. The number of pixels in any of the three critical areas divided by the total number of pixels would yield the required density.
However, the global thresholding method has serious drawbacks. First, the bead and hole density values are too sensitive to the thresholds. For example, if we select 120 as the threshold separating holes and beads for the image with the histogram shown in Figure 5.5, a selection of 165, 170, or 175 as the threshold separating beads and backgrounds would result in bead density values of 17.4, 20.0, and 22.7%. Thus, a change in threshold value from 165 to 175 results in as much as a 5 to 6% difference in bead density.

Finally, Figure 5.5 represents one of the best histograms we obtained. Figure 5.6 illustrates another valid histogram of our images. The reader can clearly see that discernable break points between beads, voids, and background are not in evidence. Thus, after having processed hundreds of images using this approach we did not find it to be fruitful.

Figure 5.6. Randomly Selected Histogram
5.4.2.4 Region Growth

Region growing is a procedure that groups pixels or sub-regions into larger regions based on predefined criteria. The basic approach is to start with a set of “seed” points and from these grow regions by appending to each seed those neighboring pixels that have properties similar to the seed [Gonzalez and Woods, 2003]. For the images with histograms similar to Figure 5.5, the starting points were set to be the pixels with grayscale levels less than a threshold (such as 100 for Figure 5.5).

The difficulty of the region growth method is twofold — first, what is the threshold and second, what is the formulation of a stopping rule? Both of these problems have to do with finding the cutoff points (boundaries or thresholds) between the beads, voids, and background and neither method enables us to do so satisfactorily.

5.4.2.5 Marker Controlled Watershed Segmentation

The watershed segmentation method has been used to find drainage basins and watershed ridge lines in an image by treating the image as a surface where light pixels are at high elevations and dark pixels are at low elevations. Watershed segmentation often produces more stable segmentation results than other methods. The concept of watershed segmentation and its algorithms are described in detail by Gonzalez and Woods (2003). Our findings are that directly applying the watershed segmentation method to a glass bead image leads to over-segmentation, which means the image is segmented into too many regions. We did consider an approach used to control segmentation that is based on the concept of a marker [Gonzalez and Woods 2003]. We applied the marker controlled watershed segmentation to our bead images. The glass bead density values produced by the watershed segmentation method were either unreasonably high or low. The method was not considered to be accurate or reliable.
5.4.2.6 Computer-Aided Counting – A Semi-automated Method

All of the manual counting and automated image processing methods we investigated or considered failed to satisfactorily generate the desired bead density values for a large range of images. Thus, we considered combining the two methods and created an approach we refer to as computer-aided counting.

Glass beads are generally round in shape. Thus, we can determine the center and the radius of a glass bead by knowing the coordinates of three points in its circumference. If two of the three known points and the center point of the circle are in a line, the center and the radius of the glass bead (circle) can be determined by using only the two points on the circumference.

We developed a bead density analysis program (BDAP) to take this into account. The program requires two mouse clicks to select a glass bead on an image. The positions of the two clicks must be at the two end points of a diameter. If the coordinates of the two mouse clicks are \((x_1, y_1)\) and \((x_2, y_2)\), the center of the glass bead then is \(((x_1+x_2)/2, (y_1+y_2)/2)\) and the diameter of the glass bead is \(D = \sqrt{(x_1-x_2)^2 + (y_1-y_2)^2}\). If the entire glass bead is contained within the image (as is Bead 1 in Figure 5.7) the area of the bead is

\[
A = \pi \times (D/2)^2
\]

If a small portion of the glass bead is outside of the image (such as Bead 2 in Figure 5.7), the area of the bead is

\[
A = \pi \times (D / 2)^2 - \alpha(D / 2)^2 + d(D / 2) \sin \alpha
\]

Where,

\[
d = \text{Distance from the center of the bead to the edge of the image}
\]

\[
\alpha = \text{The angle } \arccos(2d / D) \text{ in radius}
\]

If more than half of a glass bead is outside of the image (such as Bead 3 in Figure 5.7), the program user needs to imagine the point outside the image (point 2 of Bead 3 in Figure 5.7). Then, the area of the bead is calculated as:

\[
A = \alpha(D / 2)^2 - d(D / 2) \sin \alpha
\]
Where the D and $\alpha$ have the same meaning as in the previous equation.

The overall area of an image is calculated by multiplying the image width and image height. The area of the beads is the sum of the areas of each glass bead. The bead density is then obtained by dividing the total bead area by the overall area of the image.

**Figure 5.7. Glass Bead Area Calculation**

The flowchart of the computer aided counting method algorithm is shown in Figure 5.8. The first steps include loading the image, calculating the image size, and enlarging the image according to a user input ratio that supports good visualization. The user can then select a bead with two mouse clicks. The program calculates the bead area and updates variables representing the total area of beads (BeadArea) and the number of beads counted (BeadNum). The beads are selected one by one until they have all been measured. The program outputs the cumulative bead density and the number of beads contained within the
image. The program could also be used to determine hole density and the number of the holes in the image.

Figure 5.9 illustrates the bead selection process described by the algorithm. When a bead is selected (two mouse clicks), the program graphically circles and numbers the bead. Figure 5.9 shows that 15 beads have been selected so far. The total area of selected glass beads is 7,208 image pixels. The total area of the image is 480,000 (800 × 600) pixels. The calculated bead density for these 15 beads is 1.9%. The selecting process should continue until the last bead is selected and all beads are cumulatively tallied.

The computer-aided counting method works well on the field collected images. Because it is (regrettably) only a partially automated method, about 10 minutes are needed to analyze each image. While not ideal this is not unreasonable given the value of the results that can be obtained.

5.5 Results

It is important to note that the quality of the images collected from plant mixed asphalt pavement is much better than the images from chip sealed pavement. Images from 9 sites (with markings applied on plant mixed asphalt pavement) were processed. Each site has four marking lines. We processed three images for each line resulting in a total of 108 images processed.

The three bead density values for each pavement marking line were averaged to determine the bead density for the marking line. Doing so accounted for keep variations in point density values. Table 5.2 shows the bead density and retroreflectivity values at one measurement location (Site 11). The values in the column titled “Line Density” and the column titled “Line $R_L$” are used in the correlation analysis.
Table 5.2. Bead Density and Retroreflectivity Values at Site 11

<table>
<thead>
<tr>
<th>Image Name</th>
<th>Color</th>
<th>Bead Density in Percentage</th>
<th>R_L in mcd/m2/lux</th>
<th>R_L in mcd/m2/lux</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Color</td>
<td>Bead Density in Percentage</td>
<td>R_L in mcd/m2/lux</td>
<td>R_L in mcd/m2/lux</td>
</tr>
<tr>
<td>No11-SR1613-03.JPG</td>
<td>White</td>
<td>16.9</td>
<td>18.6</td>
<td>294</td>
</tr>
<tr>
<td>No11-SR1613-04.JPG</td>
<td>White</td>
<td>19.6</td>
<td></td>
<td>306</td>
</tr>
<tr>
<td>No11-SR1613-06.JPG</td>
<td>White</td>
<td>19.3</td>
<td></td>
<td>333</td>
</tr>
<tr>
<td>No11-SR1613-10.JPG</td>
<td>Yellow</td>
<td>14.3</td>
<td>14.7</td>
<td>122</td>
</tr>
<tr>
<td>No11-SR1613-11.JPG</td>
<td>Yellow</td>
<td>15.6</td>
<td>14.7</td>
<td>132</td>
</tr>
<tr>
<td>No11-SR1613-12.JPG</td>
<td>Yellow</td>
<td>14.3</td>
<td></td>
<td>149</td>
</tr>
<tr>
<td>No11-SR1613-19.JPG</td>
<td>Yellow</td>
<td>14.2</td>
<td>13.5</td>
<td>122</td>
</tr>
<tr>
<td>No11-SR1613-20.JPG</td>
<td>Yellow</td>
<td>13.9</td>
<td></td>
<td>134</td>
</tr>
<tr>
<td>No11-SR1613-21.JPG</td>
<td>Yellow</td>
<td>12.4</td>
<td></td>
<td>129</td>
</tr>
<tr>
<td>No11-SR1613-28.JPG</td>
<td>White</td>
<td>14.9</td>
<td>14.7</td>
<td>260</td>
</tr>
<tr>
<td>No11-SR1613-29.JPG</td>
<td>White</td>
<td>14.7</td>
<td></td>
<td>265</td>
</tr>
<tr>
<td>No11-SR1613-30.JPG</td>
<td>White</td>
<td>14.5</td>
<td></td>
<td>295</td>
</tr>
</tbody>
</table>

Three white edge markings had bead density values of 26.1%, 27.9%, and 30.7%. The glass beads on those roads are especially dense. Figure 5.10 (b) shows one of the images from the marking lines with a bead density of 30.7%.

The 9-24% bead density range is comparable to Rich’s research results [Rich et. al. 2002]. Rich’s study measured three paint sample sites and the approximate bead densities of these paint markings were 8, 18, and 20%. The 18% and 20% bead densities are in the range of 9-24%. A bead density of 8% is very close to this range.

Figure 5.11 clearly shows that bead density values have a positive correlation with the marking retroreflectivity readings. The linear regression equations for the white edge markings and yellow center markings are:

\[
R_L \text{ (white)} = 90.0 + 9.50 \times \text{Density} \quad (R^2 = 0.73)
\]

\[
R_L \text{ (yellow)} = 52.7 + 6.11 \times \text{Density} \quad (R^2 = 0.61)
\]

Where:

\[ R_L \] = Retroreflectivity of pavement markings in mcd/m2/lux

\[ \text{Density} \] = Bead density in percentage
Figure 5.8. Computer Aided Counting Method Algorithm
Figure 5.9. Computer Aided Counting Process

Figure 5.10. Marking Images with Very Low and Very High Bead Densities
The values of 9.50 and 6.11 are the slopes of the regression lines. The positive signs of the two values indicate that retroreflectivity readings increase as bead density increases. The coefficient of determination, $R^2$, is the proportion of the variability in the response explained by the regression model, which can be used to determine how well the regression line approximates the real data. The $R^2$ values of 0.73 and 0.61 for white edge lines and yellow center lines indicate the regression lines fit the data reasonable well. We also fitted the data using a quadratic curve and found the result was slightly better. Given the small sample size of the study (18 points for each type of markings), a linear regression fit is considered to be satisfactory.

![Figure 5.11. Bead Density and Retroreflectivity Relationship](image)

Notice also that the regression line for white edge markings is significantly higher than the regression line for yellow center markings. Thus, white edge markings have higher retroreflectivity values than yellow markings when the bead density values are same. For
example, when the bead density is 15%, white markings have a retroreflectivity value of 233 mcd/m$^2$/lux while yellow markings have retroreflectivity value of 144 mcd/m$^2$/lux. This is approximately 60% more $R_L$ for white lines. This research result is consistent with the findings of a previous study by Craig et. al [2007] showing that white edge lines generally have higher retroreflectivity values than yellow center lines.

Table 5.3 summarizes the relationship between bead density and retroreflectivity. If a bead density value is in the range of 9-15%, white edge lines and yellow centerline markings have retroreflectivity values between 175-232 mcd/m$^2$/lux and 107-144 mcd/m$^2$/lux, respectively.

Table 5.3. Bead Densities and Retroreflectivity Values

<table>
<thead>
<tr>
<th>Bead Density in Percent</th>
<th>White Edge Line $R_L$</th>
<th>Yellow Center Line $R_L$</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;9</td>
<td>&lt;175</td>
<td>&lt;107</td>
</tr>
<tr>
<td>9-15</td>
<td>175-232</td>
<td>107-144</td>
</tr>
<tr>
<td>15-20</td>
<td>232-280</td>
<td>144-174</td>
</tr>
<tr>
<td>20-25</td>
<td>280-327</td>
<td>174-205</td>
</tr>
<tr>
<td>&gt;25</td>
<td>&gt;327</td>
<td>&gt;205</td>
</tr>
</tbody>
</table>

The FHWA and other transportation agencies are working together to establish a minimum retroreflectivity standard for pavement markings. A recent FHWA publication proposed recommendations for the minimum levels of pavement marking retroreflectivity which were based on the results of a Target Visibility Predictor (TARVIP) computer model [FHWA 2007]. If the paint truck speed is in the ranges of less than 50 mi/hr, 50-70 mi/hr, or greater than 70 mi/hr, the recommended minimums are 40, 60, or 90 mcd/m$^2$/lux for fully marked roadways (with edge lines) where retroreflected raised pavement markers (RRPMs) are not provided. Our study shows that for pavement markings with a 10% bead density, white edge lines and yellow center lines have predicted retroreflectivity values of 185 mcd/m$^2$/lux and 114 mcd/m$^2$/lux respectively. Generally speaking, this is more than enough retroreflectivity for drivers and it is well above the recommended minimum.
5.6 Conclusions

The image processing techniques we studied did not satisfactorily enable us to determine bead density. The bead density results from the complete manual counting method tend to be higher than the actual values. None of the three automated methods (global thresholding, region growth, and marker control watershed segmentation) yielded reliable and satisfactory bead densities for the field collected images.

However, we did find a semi-automated compromise that can satisfactorily be used to obtain bead density values from paint pavement marking images. The method is easy to use and has a relatively low cost. Most importantly, it is quite accurate. The bead density values obtained from multiple tests of the same image are normally very close to each other (typically within a range of ±1%). The method can also be applied to other types of markings.

Our findings clearly indicate that glass bead density has a significant impact on marking retroreflectivity. Higher glass bead density leads to higher marking retroreflectivity. Furthermore, white edge markings have conclusively higher retroreflectivity values than do yellow center markings when the bead density values are the same.

The bead density values in the tested NC pavement markings are most normally in the range of 9-24 percent of the paint marking surface. Markings with bead density values lower than 9% are considered to have too few glass beads on the marking surface to provide acceptable retroreflectivity. This knowledge could be used by state DOTs to select a suitable and desirable bead density and then monitor the glass bead application process to ensure the achievement of the desired density.

5.7 Recommendations

It is recommended that a similar study be conducted for other types of pavement markings, especially thermoplastics. This study focused on paints because they comprise the majority
of markings. Additionally, the traffic control required for data collection was much easier on two-lane highways than on other types of highways. Other types of pavement markings are expected to have a similar correlation between retroreflectivity and bead density values, but the regression lines are expected to have different intercepts and slopes.

A similar study on different types of pavement surface materials (such as chip sealed asphalt surface, concrete pavement) is also recommended. A study should also be conducted in different climate zones, especially in a northern area where weather and temperature are more severe than in NC.

This study was conducted on two-lane highways with low traffic volumes. A similar study could be initiated to evaluate bead density differences on high traffic volume roads. We also recommend conducting a similar study using larger glass beads. Such a study could evaluate whether markings with large glass beads provide better retroreflectivity than markings with standard glass beads if the bead densities are same.

The retroreflectivity values have an obvious variation when the bead density is in the range of 10-15 percent as indicated in Figure 5.11 especially for white edge lines. The colors of the markings are observed to vary for both white edge and yellow center markings. The marking color (within white or within yellow) is speculated to be another factor with a significant impact on marking retroreflectivity. Thus, we recommend conducting a chromatography study to determine whether or not marking color plays a role in determining marking retroreflectivity.

Finally, it would be interesting to study how the bead density values change over time. Our images showed that some old markings have a high hole density. It would be possible to determine when the holes are formed (the glass beads are worn away) if we know the marking bead density values over time. By conducting such a study, we could know more about the physical process of pavement marking retroreflectivity degradation over time.
Thus, we could determine an optimal initial bead density range for new paint striping in order to achieve good $R_L$ performance for the whole life cycle of paint markings.
Pavement markings control traffic and encourage safe and efficient vehicle operation [AASHTO 2004]. The *Manual on Uniform Traffic Devices for Streets and Highways (MUTCD)* is the most important document guiding pavement marking use in the United States. It specifies where centerline, lane line, and edge line markings are to be provided based on the type of roadway, the width of the road, and the annual average daily traffic (AADT) [FHWAa 2003].

During daytime, drivers discern pavement markings mainly by the color contrast between the marking and the pavement surface. Alternatively, nighttime visibility of pavement markings is generally determined by the retroreflectivity of the pavement marking. Retroreflectivity describes the amount of light returned back to a driver from a vehicle’s headlight as it is reflected back from the markings. The reflected light provides the driver with roadway information and enables a safer drive at night. Retroreflectivity is represented by a measure referred to as the coefficient of retroreflected luminance ($R_L$) and is expressed in units of millicandels per square meter per lux (mcd/m$^2$/lux) [ASTM 2001]. This chapter discusses how to model paint marking retroreflectivity degradation over time.

Retroreflectometers are used to measure pavement marking retroreflectivity. These instruments can be divided into two categories, handheld and mobile. A handheld retroreflectometer is a portable instrument that can be operated by a technician. It is used to test locations on the pavement marking one at a time. A mobile retroreflectometer, on the other hand, is mounted on a vehicle and can measure pavement marking retroreflectivity continuously at normal driving speed. The American Society for Testing Materials (ASTM) has published a specification for using handheld retroreflectometers, while the specification for mobile instruments is still under development [ASTM 2005].
Pavement markings can reach the end of their service lives because of bead loss (resulting in poor retroreflectivity), loss of the marking material, marking color change, or loss of contrast between marking and pavement. Daytime visibility and nighttime visibility are normally related to each other. When markings are chipped or abraded by traffic there typically is not only a loss of marking material (which decreases the daytime visibility of the markings) but also a loss of beads (which reduces the nighttime retroreflectivity of the markings) [Migletz and Graham 2002].

Many factors may have impacts on the rate of pavement marking retroreflectivity degradation including, but not limited to:

- Traffic volume (AADT), type of traffic, heavy vehicle percentages, and road speed limit.
- Age of markings, type of pavement marking material, marking color, glass beads type, glass beads density, and quality control during installation.
- Type of pavement and roadway geometry.
- Weather and climate, snowplowing, salt and sand use, and studded tires.

However, it is impossible to incorporate all of these factors into a mathematical model to predict pavement marking performance because not all of them can be accurately measured and recorded over time. Normally a pavement marking degradation model includes a limited number of parameters from the above list.

6.1 Scope

The scope of this research is on waterborne paint pavement marking retroreflectivity. Waterborne paint is currently the most commonly used pavement marking material in the US. Paint is used on almost 60% of the total national pavement marking mileage [Migletz and Graham 2002]. In NC, however, waterborne paint markings are reported to make up more than 80% of the total marking mileage [NCDOT 2008]. Thus, a model for paint pavement marking performance is critical.
The data collection efforts undertaken for this study were made on two-lane highways because these roads comprise the majority of the highway system. Additionally, traffic control for data collection (for safety) was much easier on two-lane highways than on other types of highways. In NC, 74,015 of the total 79,042 roadway miles (93.6%) are two-lane highways [NCDOT 2007]. This research does not address paint pavement markings on multi-lane roads or divided highways, but in NC these types of roads often get a different and more durable type of markings anyway.

6.2 Objective

The objective of this research was to develop an accurate paint pavement marking retroreflectivity performance prediction model to be used as a key component in an overall pavement marking management system. An accurate prediction model can help pavement marking managers optimize restriping programs, thereby providing motorists with roadways that have better markings while saving money.

Other researchers have used several forms of degradation models on pavement marking retroreflectivity data, but none of them can predict marking performance satisfactorily at an individual road level. Linear mixed effects models (LMEMs) have been used to predict individual conditions of a transportation asset [Yu et. al. 2007]. The results of work by others in using LMEMs show that they have significantly higher accuracy than other prediction models. One element of the study reported herein was to investigate whether LMEMs can be used to model pavement marking retroreflectivity data and to determine if LMEMs provide more accurate prediction than existing forms of marking retroreflectivity degradation models.
6.3 Literature Review

In this section, we divide degradation models into three categories and analyze their characteristics. We compare the reported modeling methods and point out their advantages and disadvantages.

6.3.1 Linear Regression Model

A simple linear regression model assumes a linear relationship between the mean response and the value of a single independent variable. It can be expressed as follows:

\[ Y = \alpha + \beta X + e \]

Where:

- \( Y \) = Response variable, normally the \( R_L \) value in mcd/m\(^2\)/lux
- \( X \) = Predicting or independent variable, normally the time in months or days since installation
- \( \alpha, \beta \) = Regression coefficients, usually estimated from a set of data
- \( e \) = Random error which is a random variable with mean 0

Lee et. al. [1999] evaluated the performance of several types of pavement marking materials in Michigan. The research objective was to determine the degradation rates for the various materials. The study used 50 sample sites throughout Michigan. The data were collected during a 40-month period from March 1994 to July 1997 using a 15-meter geometry device, a Mirolux 12 (as opposed to the 30-meter devices that are standard now). Simple linear regression models were established for polyester, paint, and thermoplastic pavement markings. The coefficients of determination (\( R^2 \) values) were in the range of 0.14-0.18, which is low.

Sarasua, et. al. [2003] conducted a modeling study using field data collected from 149 sample sites on interstate routes in SC. The data were collected during a 28-month period...
from May 1999 to September 2001. Each sample site was measured six times at approximately four to six month intervals. Data used for analysis were collected with an LTL 2000, a 30-meter instrument. The marking materials examined in the study included epoxy, thermoplastic, and preformed plastics tape. The response variable in the simple linear model was the difference between their current measurement and their first data collection measurement. The R² values were in the range of 0.21-0.78.

The degradation rates in Sarasua’s study were not consistent with Lee’s results. For example, the degradation rates of thermoplastics were found to be -0.03 mcd/m²/lux per day and -0.06 mcd/m²/lux per day for yellow and white markings in Sarasua’s study. The rate was -0.36 mcd/m²/lux per day in Lee’s study. The inconsistency of the research results between the two studies may be attributed to geographic differences (MI vs. SC), measurement instrument differences (Mirolux 12 vs. LTL 2000), and marking material differences (materials were from different vendors). In any case it is a significant difference.

The advantage of simple linear regression is that the model is easy to understand and easy to use. The disadvantage of the simple linear regression model is that only one factor, marking age, is included in the model.

In most situations, the response variable can be predicted more accurately on the basis of a collection of independent variables rather than on one variable as in the simple linear regression model. In a multiple linear regression model, the response variable Y is related to k independent variables:

\[ Y = \beta_0 + \beta_1 X_1 + \cdots + \beta_k X_k + e \]

Where:

- \( Y \) = Response variable, normally the R_L value in mcd/m²/lux
- \( X_i \) = Predicting variables, which could be time, AADT, color, initial R_L, and other factors (i = 1, 2, …, k)
\[ \beta_i \quad \text{Regression coefficients, usually estimated from a set of data (i = 0, 1, \ldots, k)} \]

\[ e \quad \text{Random error which is a random variable with mean 0} \]

Sitzabee et. al. [2009a] established multiple linear regression models for thermoplastics and paints using a large retroreflectivity dataset collected in NC. The data were collected over a seven-year period. The data collection instrument was a Laserlux mobile retroreflectometer. They developed a number of multiple linear regression models that had three independent variables (time, initial \( R_L \), and AADT). The initial \( R_L \) variable reflected the quality of the initial installation of the markings on a specific road. The \( R^2 \) values were in the range of 0.38-0.60.

When including the initial \( R_L \) as an independent variable, multiple linear regression models can increase the accuracy of predicting future \( R_L \) values for a specific road. However, all linear regression models have an assumption that data collected at different time intervals on the same pavement marking are independent of each other. This assumption is not true for data collected through repeated measurements on the same site. This will be discussed further in the marking retroreflectivity data characteristic section below.

6.3.2 Exponential and Logarithmic Models

Linear regression models assume that pavement marking \( R_L \) values deteriorate linearly with time meaning that the degradation curve is a line and the degradation rate is a constant. However, pavement marking \( R_L \) values are generally recognized to degrade faster in the first few months after installation. The degradation rates then generally decrease with time. Both exponential and logarithmic models can reflect this degradation trend. Therefore, it is worthwhile to investigate them. The exponential or logarithmic model can be described as:

\[ Y = \alpha + \beta \ln X + e \]

or

\[ Y = \alpha + \beta e^X + e \]

Where:

\[ Y \quad \text{Response variable, normally the } R_L \text{ value in mcd/m}^2/\text{lux} \]
\[X = \text{Predicting or independent variable, normally the time in months or days}\]

\[\alpha, \beta = \text{Regression coefficients, usually estimated from a set of data}\]

\[e = \text{Random error which is a random variable with mean 0}\]

Andrady [1997] proposed a logarithmic degradation model in NCHRP Report 372, though the main objective was to assess the environmental friendliness of pavement marking materials. The model is similar to a simple linear regression model except that the logarithmic transform of time is used as an independent variable. The data used in the study were from AASHTO Alabama and Pennsylvania test decks. No goodness of fitness values were published for the model.

Perrin et. al. [1998] established an exponential degradation model based on the data collected by a mobile retroreflectometer in Utah. The retroreflectivity data were collected in five days on markings of various ages. The exponential model for preformed plastics (tapes) achieved an \(R^2\) value of 0.58. However, the models for paint and epoxy markings had very low \(R^2\) values of 0.005 and 0.03, respectively.

The logarithmic model proposed by Abboud and Bowman [2002] multiplies the AADT and time and uses the result to estimate vehicle exposure. Vehicle exposure is the estimated total number of vehicles that have passed along the road since the installation of the new pavement markings. The model assumes that the retroreflectivity value is a function of vehicle exposure. Normally time (age of marking) is used as the independent variable in most other models. A Mirolux 12 was used to collect the retroreflectivity data. A total of 4,518 retroreflectivity measurements were collected at 827 test sites along 520 miles of rural highways in Alabama. The \(R^2\) values were 0.58 and 0.31 for thermoplastics and paints, respectively.

The disadvantage of the exponential and logarithmic models is similar to that of a simple linear regression model. These models include only one factor, either marking age or vehicle...
exposure. The established models discussed so far only reflect the average marking performance at a population level. However, the model predictions at an individual road level are not necessarily accurate.

6.3.3 Other Models

A number of other types of models have recently been developed using pavement marking retroreflectivity data. Those models are relatively new compared with the two types of models discussed above.

Zhang and Wu [2005] used smoothing spline and time series to model pavement marking retroreflectivity changes over time. Data from the 2002 National Transportation Product Evaluation Program (NTPEP) were used for model development and model validation. The study concluded that both models performed well and that both models can predict the retroreflectivity of a pavement marking material for the next 6 months with very good accuracies [Zhang and Wu, 2005]. The authors pointed out that the data from NTPEP test decks may not be truly representative of actual field installed longitudinal edge lines or skip lines. Readers should also be aware that most marking lines are transversely installed on NTPEP test decks. The performance of those markings could be quite different from the longitudinal markings actually installed on the roads.

Sathyanarayanan et. al. [2008] used the Weibull analysis method to model pavement marking retroreflectivity degradation in Pennsylvania. Weibull analysis is a method typically used in reliability engineering. The model was based on paint data collected from the Pennsylvania NTPEP test deck from July 2002 to July 2005. The established model is similar to an exponential model and includes only time as the predicting variable. This Weibull analysis method predicts a survival probability of pavement markings instead of producing a future retroreflectivity value. The probability result is reasonable from an engineering point of view.
The Sathyanarayanan and Zhang and Wu studies mentioned above possess a common limitation. It has to be recognized that the NTPEP test decks differ significantly from field installed roadways and exposure conditions. As a consequence, the research results cannot necessarily be deemed to be directly applicable. This leaves the research community in a position of choosing between NTPEP data and initiating costly field data collection efforts independently. The authors again call for an evaluation of the NTPEP program to see if changes could be made to better serve the research community and, ultimately, to attain safer roadways.

6.3.4 LMEM

Researchers have developed linear mixed effects models (LMEMs) for predicting individual pavement conditions [Yu et. al. 2007]. This type of model may apply well to pavement marking data. Pavement marking retroreflectivity data are similar to pavement condition data. The data are in the form of repeated measurements on the same road over time. In statistics, data in the form of repeated measurements on the same unit (road) over time are called longitudinal data [Davidian 2005]. The pavement marking retroreflectivity data collected in this study are typical longitudinal data and, therefore, longitudinal data analysis techniques (LMEM is one of these) are applicable and most well suited to the marking retroreflectivity data we collected. In the following sections, we discuss the nature of pavement marking retroreflectivity data, show when LMEMs are suitable models, and develop LMEMs for the marking data.

6.4 Pavement Marking Retroreflectivity Data

In this section, we first discuss the field data collection and the data sampling method. Then, we use paint marking data on two lane highways to illustrate the characteristics of retroreflectivity data for pavement markings.
6.4.1 Data Sampling Method

ASTM Specification E 1710-05 provides a method of measuring pavement marking retroreflectivity using a handheld retroreflectometer that can be placed on the road marking [ASTM 2005] to obtain $R_L$ measurements. However, it does not specify the sampling method to be employed when using a handheld unit to measure retroreflectivity values. Instead, the number of measurements to be taken at each test location and the spacing between test locations is to be determined by the user. ASTM E 1710 recommends use of the sampling method in ASTM Specification D 6359 [ASTM 2005]. However, the ASTM D 6359-99 specification was withdrawn in December 2006 because the sampling methods were not being used [ASTM 2009]. Thus, there is no current specified standard sampling method when using a handheld instrument to measure retroreflectivity values. For this study, we generally followed or exceeded the precedent set in Iowa, one of the leaders in pavement marking management in the US. Iowa researchers collected retroreflectivity samples once every 5 miles along a road unless conditions changed. Each sample consisted of an average of 5 measurements over a minimum segment length of 160 feet [Hawkins et. al. 2006].

The purpose of the data collection activity in this study was to provide a sample with which we could evaluate field paint marking performance. The research team first selected sections of the road to be measured. Test locations were not selected where there were sharp horizontal or vertical curves, but were otherwise randomly chosen. Test locations were about 200 feet long. Twenty measurements, approximately evenly distributed along each 200 feet segment (at approximately 10 feet intervals), were taken for each white edge pavement marking line.

A previous study found that that paint centerline retroreflectivity values measured in the direction of paint striping are significantly higher than values measured in the opposite direction [Rasdorf et. al. 2009]. Thus, centerlines were measured in both directions of traffic and their values (2 lines, 2 directions) were averaged to obtain a final $R_L$ for both lines. The centerlines on two lane highways could be either solid or skip lines. A total of 20
measurements for solid lines and 10 measurements for skip lines were taken in each direction for each yellow centerline.

6.4.2 Data Collection Procedure

The study described herein used a handheld LTL 2000 retroreflectometer for data collection. The LTL 2000 retroreflectometer uses 30-meter geometry, which is the geometry required by ASTM Specification E 1710-05. The researchers followed the standard operating procedure in the instrument manual strictly during field data collection. Field calibration of the LTL 2000 was conducted before measurements were taken. The calibration was performed at each site prior to the start of data collection. We used a Global Position System (GPS) device to record the coordinates of the starting and ending points on each test location. Measurement sections were marked with spray paint on the pavement (their boundaries were marked) so that future measurements were taken in the same road section.

We collected paint retroreflectivity data on secondary roads in four divisions of the NCDOT. Those roads have low traffic volumes, with annual average daily traffic (AADT) on most roads less than 4000 vehicles per day. All measured roads were two-lane rural highways with asphalt pavement surfaces (both chip sealed and plant mixed pavement). Included in the study were 25 roads which were painted in September and October 2007 and measured four times in November 2007, May 2008, November 2008, and May 2009. A two-person team carried out the data collection and each round of data collection lasted about two weeks. NCDOT provided the paint marking installation dates before the field data collection effort was undertaken.

6.4.3 Paint Retroreflectivity Data

The data for the two white edge lines (or two yellow centerlines) located on a single road were averaged to a single value (20 measurements in 200 feet along each line). That value represents the retroreflectivity of both white edge lines on the measured road section. The data from one white edge line (or one yellow centerline) were not considered to be an
independent sample because the retroreflectivity values of the two white edge lines (or the two yellow centerlines) on the same road were related to each other. All markings on a road section were normally striped using the same paint truck and the same material batch on the same day by the same marking crew. Columns 2-9 in Tables 6.1 and 6.2 show the retroreflectivity measurements and marking ages for white edge and yellow center markings on the 25 roads, respectively.

Figure 6.1 shows the plots of the retroreflectivity data on the 25 sample roads for white edge and yellow center markings. Plots like Figure 6.1 are called spaghetti plots in a longitudinal data analysis context [Davidian 2005]. The horizontal axis represents the age of the markings in days. The vertical axis represents the retroreflectivity values on a sample road section. The thin lines represent pavement marking retroreflectivity trajectories for individual roads. The bold line represents the average retroreflectivity of all measurements.

Figure 6.1 indicates that each sample marking has its own trajectory. The performances of each marking are quite different from each other. Figure 6.3 shows the retroreflectivity performances of two specific roads (roads 11 and 23 from Figure 6.1) and the population average of the 25 roads. The retroreflectivity measurements on road 11 are consistently higher than the population average. The measurements on road 23 are consistently lower than the average. The $R_L$ measurements on road 11 are more than double the measurements on road 23.
Table 6.1. White Edge Pavement Marking R\textsubscript{L} Data

<table>
<thead>
<tr>
<th>No.</th>
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<th>Third Round</th>
<th>Fourth Round</th>
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* Data are missing due to pavement resurfacing and marking restriping.
# Circumstances prevented the collection of these data.
R\textsubscript{L} and Intercept values are in the unit of mcd/m\(^2\)/lux.
Slope values are in the unit of mcd/m\(^2\)/lux per day.
Shadowed cells are used as an example in the description.
Table 6.2. Yellow Center Pavement Marking R₄L Data

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Mean: 62 141 234 123 431 120 227 103 143 -0.069

* Data are missing due to pavement resurfacing and marking restriping.
# Circumstances prevented the collection of these data.
R₄L and Intercept values are in the unit of mcd/m²/lux.
Slope values are in the unit of mcd/m²/lux per day.
Shadowed cell is used as an example in the description.
Figure 6.1. Paint Pavement Marking Retroreflectivity Plots
The marking performance differences are due to several reasons. First, we found that the bead densities of the markings were in a wide range [Zhang et. al. 2009]. Second, the markings were installed by four different crews using different paint trucks. The paint thicknesses were believed to be different. Third, the pavement surface type may have an impact on the marking retroreflectivity. Generally speaking, markings on plant mixed pavement have higher retroreflectivity measurements than markings on bituminous surface treatment (chip sealed) pavement. Other factors mentioned in the Introduction Section may also have impacts on the markings performances.

Figure 6.1 also indicates that the measurements of white edge markings are obviously different from yellow center markings. The range of white edge marking measurements was 80-430 mcd/m²/lux. The range of yellow center markings was 70-220 mcd/m²/lux. Thus, it is clear that the yellow markings were significantly less reflective than white markings. The two bold lines in the Figure 6.1 show the average marking retroreflectivity values on the 25 roads over time. The average measurements of white edge markings were 303, 249, 227, and 184 mcd/m²/lux for the four rounds (decreasing over 2 years) of measurements, while the average measurements of yellow centerline markings were 141, 123, 120, and 103 mcd/m²/lux. The average degradation rate of white edge markings was $-0.225$ mcd/m²/lux per day which was much faster than the average degradation rate of $-0.072$ mcd/m²/lux per day of yellow centerline markings.

6.4.4 Marking Retroreflectivity Data Characteristic

Figure 6.1 shows, as expected, that each pavement marking on a specific road has its own trajectory of retroreflectivity as a function of time. For each road, the trajectory looks roughly like a straight line. Therefore, in this study, we assume that retroreflectivity values of particular paint pavement markings degrade in a linear form. Reader should note that nonlinear models can also be used to fit longitudinal data as was previously discussed.
To assess paint retroreflectivity data, we used $i \ (i = 1, \ldots, m)$ as the subscript indexing different roads (units) and $j \ (j = 1, \ldots, n)$ as the subscript indexing measurements in time order within each road (unit). The character $m$ denotes the total number of roads and $n$ denotes the total rounds of data collections. $Y_{ij}$ is a random variable representing all $R_L$ measurements on road $i$ at time $t_j$ [Davidian 2005]. $y_{ij}$ is used to represent an individual $R_L$ measurement.

The natural estimator for the mean $\mu_j \ (j = 1, \ldots, n)$ at the $j$th time point $t_j$ is the sample mean [Davidian 2005]:

$$\bar{y}_j = \frac{1}{m} \sum_{i=1}^{m} y_{ij}$$

For example, $\bar{y} = (303, 249, 227, 184)$ for white edge new markings. The natural estimator for $\sigma_j^2$ is the sample variance at time $j$:

$$S_j^2 = (m-1)^{-1} \sum_{i=1}^{m} (y_{ij} - \bar{y}_j)^2$$

For each pair of times $t_j$ and $t_k$, if we graph the observed data values $(y_{ij}, y_{ik})$ for all $i = 1, \ldots, m$ roads (units), the observed pattern might be suggestive of the nature of the association among responses at times $t_j$ and $t_k$. However, since the means $\mu_j$ and $\mu_k$ and variances $\sigma_j^2$ and $\sigma_k^2$ are not the same, it would be better to plot the centered and scaled version of these pairs [Davidian 2005]:

$$\left(\frac{y_{ij} - \mu_j}{\sigma_j}, \frac{y_{ik} - \mu_k}{\sigma_k}\right)$$

Because we do not know the $\mu_j$ or $\sigma_j$, a natural strategy is to replace these by estimates and plot the pairs:
Such a graphical display of the observed data is known as a scatterplot matrix [Davidian 2005]. Figure 6.2 shows the scatterplot matrix for the white edge new markings in our sample. The scatterplot matrix for yellow center new markings shows a similar pattern as in Figure 6.2. The subplot in the first row, second column shows the standardized data from the first round (y-axis) and data from the second round of data collection (x-axis). The subplot in the first row, third column shows the standardized data from the first round of data collection (y-axis) and the data from the third round of data collection (x-axis), and so on. The trend for all plots in Figure 6.2 is from lower left to upper right, which means large centered and scaled measurements at one time correspond to large ones at another time. The plots, therefore, indicate that the correlation is strong and positive for each pair of measurements.

The scatterplot matrix shows that $R_L$ measurements on the same marking are positively correlated. The correlation is positive and significant. However, a linear regression model assumes that $R_L$ data collected at different time intervals on the same pavement marking are independent of each other and the correlation to be zero. The linear mixed effects model, on the other hand, can take this correlation into account. Thus, a linear mixed effects model could produce more accurate predictions than a linear regression model with data such as those collected in this study.

6.5 Methodology

In the following discussion, LMEMs are established based on the paint retroreflectivity data described above. Then, we compare model prediction accuracy between LMEMs and linear regression models. We also show how to use the models at the end of this section.
6.5.1 Linear Mixed Effects Model

We present the development of the linear mixed effects model (it is developed in two stages) in the following paragraphs. We begin the analysis by considering that markings on each road have their own underlying straight line inherent trend. The intercept and slope for a specific road are $\beta_{0i}$ and $\beta_{1i}$ ($i=1,2,\ldots,m$), which determine the linear trend.

![Figure 6.2. Scatterplot Matrix for White Edge Markings](image)

Figure 6.2. Scatterplot Matrix for White Edge Markings
The first stage is at the individual road level. We write a model for the random variables \( Y_{i1}, Y_{i2}, \ldots, Y_{in} \) for the \( i \)th road (unit) taken at the time points \( t_{i1}, t_{i2}, \ldots, t_{in} \). The model for road (or unit) \( i \) \((i = 1, 2, \ldots, m)\) is:

\[
Y_{ij} = \beta_{0i} + \beta_{1i}t_{ij} + e_{ij}, \quad j = 1, 2, \ldots, n_i
\]

(1)

Where:

- \( Y_{ij} \) = Response variable
- \( \beta_{0i}, \beta_{1i} \) = Intercept and slope for a specific road (unit)
- \( e_{ij} \) = Random error
- \( i \) = The subscript indexing units, \( i = 1, \ldots, m \) (\( m \) denotes total number of units)
- \( j \) = The subscript indexing responses in time order within units \( j = 1, \ldots, n_i \)
- \( n_i \) = Total rounds of data collected for road (unit) \( i \)

If we write the parameters in a matrix form, let:

\[
\beta_i = \begin{pmatrix} \beta_{0i} \\ \beta_{1i} \end{pmatrix}, \quad Z_i = \begin{pmatrix} 1 & t_{i1} \\ 1 & t_{i2} \\ \vdots & \vdots \\ 1 & t_{in} \end{pmatrix}, \quad Y_i = \begin{pmatrix} Y_{i1} \\ Y_{i2} \\ \vdots \\ Y_{in} \end{pmatrix}, \quad e_i = \begin{pmatrix} e_{i1} \\ e_{i2} \\ \vdots \\ e_{in} \end{pmatrix}
\]

The model can be expressed as follows:

\[
Y_i = Z_i \beta_i + e_i, \quad i = 1, \ldots, m, \quad e_i \sim N_{n_i}(0, R_i)
\]

(2)

The factor \( e_i \) in equation 2 represents the variation within an individual road (unit); \( R_i \) is the covariance matrix.

The second stage is at the population level. Let \( \beta_0 \) and \( \beta_i \) represent the mean values of the intercept and slope. We define \( \beta \) as the mean vector of the population of all \( \beta_i \). Then we can write:

\[
\beta_{0i} = \beta_0 + b_{0i}, \quad \beta_{1i} = \beta_1 + b_{1i}
\]
Where $b_{bi}$ and $b_{bi}$ are random effects describing how the intercept and slope for the $i$th road (unit) deviate from the mean values. Then, we can write the above two equations in a matrix form:

$$\beta_i = \beta + b_i, \quad \beta = \begin{pmatrix} \beta_0 \\ \beta_1 \end{pmatrix}, \quad b_i = \begin{pmatrix} b_{bi} \\ b_{bi} \end{pmatrix}$$

(3)

We use matrix $A_i$ to represent information such as group membership, allowing the mean of $\beta_i$ to be different for different groups, so equation 3 can be rewritten as:

$$\beta_i = A_i \beta + b_i, \quad b_i \sim N_h(0, D)$$

In this expression $b_i$ represents the variation among roads (units) with a covariance matrix $D$.

When two parts of the model are combined into a single representation, letting $X_i = Z_i A_i$, the linear effects model is:

$$Y_i = Z_i (A_i \beta + b_i) + e_i = (Z_i A_i) \beta + Z_i b_i + e_i = X_i \beta + Z_i b_i + e_i$$

(4)

The coefficient $\beta$ in equation 4 can be estimated using a maximum likelihood method. The generalized least squares estimator for $\beta$ is:

$$\hat{\beta} = \left( \sum_{i=1}^{m} X_i \hat{\Sigma}_i^{-1} X_i \right)^{-1} \sum_{i=1}^{m} X_i \hat{\Sigma}_i^{-1} Y_i$$

(5)

$\hat{\Sigma}_i$ is the estimator of $\Sigma_i$ and the covariance of $Y_i$ ($\Sigma_i$) is:

$$\Sigma_i = Z_i D Z_i' + R_i$$

The best linear unbiased predictor for $b_i$ is:

$$\hat{b}_i = \hat{D} Z_i \hat{\Sigma}_i^{-1} (Y_i - X_i \hat{\beta})$$

(6)

When an LMEM is used to model pavement marking retroreflectivity data, the $\beta$ in equation 3 represents the fixed effects and the $b_i$ represent the random effects. We use two variables
(fintercept and fslope) to represent the fixed intercept and fixed slope, which are characteristics of the population. We also use rintercept\_i and rslope\_i to represent the random intercepts and random slopes, which are unique to each marking on a specific road. The $\beta$ and $b_i$ in equation 3 can be expressed as:

$$\beta = \begin{pmatrix} fintercept \\ fslope \end{pmatrix}, \quad b_i = \begin{pmatrix} rintercept\_i \\ rslope\_i \end{pmatrix}$$

(7)

Then, the linear mixed effects model (4) can be expressed as:

$$R_L = (fintercept + rintercept\_i) + (fslope + rslope\_i) \times Days + error$$

(8)

The coefficients $\beta$ and $b_i$ in equation 7 (fintercept, fslope, rintercept\_i, and rslope\_i in equation 8) can be estimated by equations 5 and 6 using SAS statistical software [Davidian 2005]. The fintercept and fslope coefficients in equation 8 represent the average marking performance, which are same for all markings. The rintercept\_i and rslope\_i (i=1, 2, ..., 25 for the data collected in this study) coefficients reflect individual marking performance, which are different for each marking. Thus, each road has its own model. For example, the linear mixed effects model for road 11 can be expressed as:

$$R_L = (fintercept + rintercept\_{11}) + (fslope + rslope\_{11}) \times Days + error$$

(9)

Where:

- $R_L$ = Retroreflectivity in mcd/m$^2$/lux
- Days = Days since installation

The estimated coefficients (fintercept, rintercept\_{11}, fslope, and rslope\_{11}) for road 11 are reported in the LMEM Results Section.

The white edge and yellow center paint marking retroreflectivity data are modeled separately. The data reported in Tables 6.1 and 6.2 were organized into a format that can be imported into SAS. The SAS procedure PROC MIXED was used to model the data [Davidian 2005]. The results of the LMEMs are described in the following section.
6.5.2 LMEM Results

White edge and yellow center paint marking retroreflectivity measurements are significantly different from each other. Thus, their data were modeled separately. The results are also reported separately for white edge and yellow center markings.

For white edge markings, the fixed intercept \( f_{\text{intercept}} \) and slope \( f_{\text{slope}} \) are estimated to be 310 mcd/m\(^2\)/lux and -0.204 mcd/m\(^2\)/lux per day (or -75 mcd/m\(^2\)/lux per year), respectively. These values represent the average retroreflectivity performance of white edge markings. These values represent the bold line in Figure 6.3. The confidence interval of the fixed intercept is [287, 333]. The confidence interval of the slope is [-0.238, -0.174].

![Image: White Edge Markings](image)

**Figure 6.3.** Population Average and Subject Specific Retroreflectivity Performance
Columns 10 and 11 of Table 6.1 show the combined intercepts and slopes for white edge markings on each road. The combined intercept is the sum of fixed intercept ($f_{\text{intercept}}$) and random intercept ($r_{\text{intercept}}$) for each road and the combined slope is the sum of fixed slope ($f_{\text{slope}}$) and random slope ($r_{\text{slope}}$) for each road. The combined intercepts are in the range of 161 to 415 mcd/m$^2$/lux and the combined slopes are in the range -0.105 to -0.295 mcd/m$^2$/lux per day (-38 to -108 mcd/m$^2$/lux per year).

Each road has its own combined intercept and slope. For example, the combined intercept and slope for white edge markings on road 11 is 415 mcd/m$^2$/lux and -0.295 mcd/m$^2$/lux per day (shadowed cells in Table 6.1). The estimated coefficients $f_{\text{intercept}}$ and $r_{\text{intercept}}$, for road 11, are 310 and 105 mcd/m$^2$/lux, $f_{\text{slope}}$ and $r_{\text{slope}}$, for road 11, are -0.204 and -0.091 mcd/m$^2$/lux per day. The linear mixed effects model for road 11 is:

$$R_L = 415 - 0.295 \times \text{Days}$$

The line is also shown in Figure 6.3.

For yellow center markings, the fixed intercept and fixed slope are 143 mcd/m$^2$/lux and -0.069 mcd/m$^2$/lux per day (or -25 mcd/m$^2$/lux per year), respectively. Columns 10 and 11 in Table 6.2 show the combined intercepts and slopes for each yellow center marking. The combined intercept range is 76 to 214 mcd/m$^2$/lux. The slope of road 11 (shadowed cell in Table 6.2) is found to be +0.006, which is abnormal and should be a negative value. Other than the abnormal slope, the combined slope range is -0.0003 to -0.145 mcd/m$^2$/lux per day (-0.1 to -53 mcd/m$^2$/lux per year).

6.5.3 Prediction Accuracy Comparison

The theoretical analysis in the Marking Retroreflectivity Data Characteristics Section showed that LMEMs should produce more accurate prediction than linear regression models because LMEMs consider the correlation among repeated measurements on the same marking. In this section, we compare the prediction accuracy of the LMEMs and linear regression models.
(both simple and multivariable linear regression models) using field marking retroreflectivity data.

The first three rounds of retroreflectivity data (data collected in November 2007, May 2008, and November 2008) were used to estimate the coefficients in the LMEMs and linear regression models. The fourth round of data (data collected in May 2009) was used to compare with the predicted values from the models. The fourth round data were not collected on roads 3 and 12 due to marking restriping. Data from these two roads were excluded from the comparison. We used the white edge marking data as an example in the following discussion.

We first use a simple linear regression model to fit the data. The model for a white edge line is:

\[
R_L = 309 - 0.206 \times \text{Days} \quad (R^2 = 0.315)
\]

Where:

- \( R_L \) = Retroreflectivity in mcd/m\(^2\)/lux
- Days = Days since installation

The predictions of the fourth round of data from the model are shown in the third column of Table 6.3.

In a multiple linear regression model, we use the initial \( R_L \) as one of the independent variables [Sitzabee, 2009a]. The model results are similar to simple linear regression model but each road has a different intercept. The multiple linear regression models, with initial \( R_L \) as an independent variable, for white edge markings is as follows:

\[
R_L = 83 + 0.633 \times \text{Initial}R_L - 0.110 \times \text{Days} \quad \text{(with an } R^2 = 0.682)\]

Where:

- \( \text{Initial}R_L \) = Initial retroreflectivity measurements in mcd/m\(^2\)/lux
The fourth column of Table 6.3 shows the predictions for the fourth round from this model.

The intercepts and slopes for each individual road are shown in columns 5 and 6 of Table 6.3. Each marking on a specific road has its own linear mixed effects model. For example, the intercept and slope for road 11 is 406 mcd/m²/lux and -0.268 mcd/m²/lux per day. Then, the model for road 11 is:

$$RL = 406 - 0.268 \times \text{Days}$$

The last column of Table 6.3 shows the prediction from the LMEM based on these intercepts and slopes.

Figure 6.4 shows the plots of the residuals for these three types of models (actual measurement minus prediction values). The LMEM prediction plot is more aggregated toward zero than the two linear regression plots, which indicates that the LMEM provides more accurate predictions.

We can use the average squared difference of the residuals as an indicator to compare the three types of models. The average squared difference, SS, is defined as:

$$SS = \frac{1}{m} \sum_{i=1}^{m} (\text{actual}_i - \text{prediction}_i)^2$$

In this expression $m$ is total number of road sections, which equals 23 in this case. The average squared difference values from simple linear regression, multiple linear regression, and LMEM are 2536, 2066, and 471, which indicated that the LMEM prediction is significantly better than the linear regression prediction. The multiple linear regression prediction was slightly better than the simple linear regression.

The same procedure was applied on the yellow center line new marking data and similar results were obtained. The average squared difference values from simple linear regression,
multiple linear regression, and LMEM were 1115, 656, and 137. The results confirmed that the LMEM prediction was better than the linear regression prediction.

6.5.4 LMEM Application Examples

Agencies can use the LMEM to predict the $R_L$ of a marking when no data are available, when only initial retroreflectivity data are available, or when multiple prior $R_L$ measurements are available for a specific road. In this section we demonstrate how to use LMEM to predict paint marking performance under these varying data availability conditions.

6.5.4.1 Case 1. No Historical Retroreflectivity Data

If a transportation agency does not have any historical retroreflectivity data for a road, the fixed intercept and slope can be used to make a prediction as long as the marking age is known. In this case, the prediction models for white edge and yellow center markings are:

$$R_L = 310 - 0.205 \times \text{Days} \quad \text{(white edge)}$$  \hspace{1cm} (10)

$$R_L = 143 - 0.069 \times \text{Days} \quad \text{(yellow center)}$$  \hspace{1cm} (11)

These models represent average paint marking retroreflectivity performance over time. If we use 100 and 65 mcd/m$^2$/lux as the minimum acceptable retroreflectivity values for white and yellow waterborne paints (which are the current effective minima in NC per Sitzabee et. al. (2009a)), and extrapolate the model beyond the range of the database, the estimated the white edge pavement marking life is 1025 days (34.2 months) and the yellow center marking life is 1130 days (37.6 months). However, it should be pointed out that the estimated marking lives represent the average marking performance. It means that almost half of the markings would have $R_L$ values lower than the minima at 34.2 months and at 37.6 months, respectively. Thus, it is clear that restriping at approximately two year intervals is reasonable.
Table 6.3. LMEM and Linear Regression Model Prediction Comparison

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<th>No.</th>
<th>Actual $R_L$ Measurements</th>
<th>SLR Prediction*</th>
<th>MLR Prediction*</th>
<th>LMEM</th>
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SLR: Simple Linear Regression.
MLR: Multiple Linear Regression
$R_L$, Intercept, and Prediction values are in the unit of mcd/m²/lux.
Slope values are in the unit of mcd/m²/lux per day.
Figure 6.4. Accuracy Comparison of Actual and Predicted $R_L$. 

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6.5.4.2 Case 2. Initial Retroreflectivity Measurements Available

NCDOT often collects initial retroreflectivity measurements 14-30 days after the installation of a pavement marking for quality assurance purposes. If the initial retroreflectivity measurement data are available for a specific road, in addition to the marking age, the initial $R_L$ can be used as the intercept in the prediction models. The prediction models then become:

$$R_L = \text{Initial}R_L - 0.205 \times \text{Days} \quad \text{white edge} \quad (12)$$

$$R_L = \text{Initial}R_L - 0.069 \times \text{Days} \quad \text{yellow center} \quad (13)$$

For example, if a white marking has an initial $R_L$ measurement of 250 mcd/m$^2$/lux, the estimated service life for the marking is 732 days (24.4 months).

6.5.4.3 Case 3. Multiple Retroreflectivity Measurements Available

If multiple retroreflectivity measurements are collected for a specific road (and we know initial $R_L$ and marking age), we could make a more accurate prediction based on all available data (including data collected on other roads). The model was presented in equation 8. The coefficients ($f_{intercept}$, $f_{slope}$, $r_{intercept}$, and $r_{slope}$) need to be estimated using statistical software.

For example, assume the retroreflectivity measurements on a white edge paint marking are 300, 250, 210, and 170 mcd/m$^2$/lux at 30, 210, 390, and 570 days. The coefficients in equation 8 can be estimated based on the measurements from this road and all available historical measurements from other roads. The coefficients $f_{intercept}$ and $r_{intercept}$ were estimated to be 309 and -10 mcd/m$^2$/lux for our sample of 25 roads, for example. The coefficients $f_{slope}$ and $r_{slope}$ were estimated to be -0.206 and -0.012 mcd/m$^2$/lux per day. The combined intercept and slope were 299 mcd/m$^2$/lux and -0.218 mcd/m$^2$/lux per day for this example. Then, the prediction model for this specific road is

$$R_L = 299 - 0.218 \times \text{Days} \quad \text{White edge, } R^2 = 0.315$$

The estimated service life of this white edge marking is 914 days (30 months).
6.6 Conclusions

LMEMs have three advantages for pavement markings when compared with linear regression models: (1) LMEMs take into account the correlation among repeated measurements on the same marking while linear regression models assume the correlation to be zero; (2) LMEM is flexible and can be applied in different situations; (3) the prediction accuracy of LMEM increases with the amount of historical data available.

Figure 6.2 indicated that the correlation between different rounds of retroreflectivity data was positive and significant. The LMEM considers the correlation while the linear regression models assume the correlation is zero. Thus, the LMEM is more appropriate for pavement marking retroreflectivity data, and likely for other similar data sets, than linear regression models.

LMEM is flexible and can be applied in different situations. In no data are collected on a specific road, prediction equations 10 and 11 are used, which yields results similar to simple linear regression models. If only initial measurement data are available, prediction equations 12 and 13 can be used, which yields results similar to multivariable linear regression models. If more than one measurement is available for the road of interest, the LMEM can use all available data and provide a more accurate prediction than other models.

The prediction accuracy of LMEM increases with the amount of historical data. The estimation of coefficients in equation 8 becomes more accurate if more historical marking retroreflectivity data are available. For a specific road, when more measurements are taken, the performance prediction becomes more accurate.

The LMEM results indicate that paint marking retroreflectivity values vary significantly among different roads. The intercepts and the slopes have wide ranges. To accurately predict the marking performance on a specific road, it is desired to have more than one
retroreflectivity measurement taken on the specific road and use LMEMs to predict the marking performance.

The LMEM results indicate that the retroreflectivity performance of white edge and yellow center paint markings is different. The fixed intercept (initial retroreflectivity) of white markings is 310 mcd/m²/lux comparing to 143 mcd/m²/lux of yellow markings. The white markings are more than twice as reflective as yellow markings at the initial time. But, the fixed slope (degradation rate) of white markings (-75 mcd/m²/lux per year) is about three times faster than yellow markings (-25 mcd/m²/lux per year). This finding is consistent with those of other researchers [Sathyanarayanan et. al. 2008, Sitzabee et. al. 2009a].

The results also indicate that predicted average lifecycles are 34.2 months and 37.6 months for white edge and yellow center markings if we use 100 and 65 mcd/m²/lux as the minimum acceptable retroreflectivity values, respectively. Thus, the currently NCDOT practice of restriping paint markings at approximately two year intervals is reasonable. However, pavement marking managers should attend to the markings with low initial retroreflectivity measurement (200 mcd/m²/lux for white edge and 100 mcd/m²/lux for yellow center markings). The retroreflectivity values of those markings are more likely to fall below the minima than other markings in less than two years.

6.7 Recommendations

Pavement marking managers should consider using LMEMs to predict paint marking performance. The prediction accuracy of LMEMs increases with an increased amount of historical data, which makes LMEMs ideal to be used in a pavement marking management system (PMMS) [Sitzabee et. al. 2009b]. When more and more retroreflectivity data are stored in the PMMS, the prediction accuracy of a LMEM increases over time.

This study used field paint marking retroreflectivity data collected in NC. The estimated coefficients of LMEMs are only applicable to the markings in NC. Transportation agencies
in other states should collect their own data and establish LMEMs using their own data. However, the modeling method describe in this chapter can also be directly used to establish LMEMs.

This study only collected paint marking retroreflectivity data in the first 600 days after marking installation due to the time constraint of the project funding. The time interval did not cover a full lifecycle of paints. Future research should collect retroreflectivity measurements for a period of time longer than 2.5 years to include data on even older markings.

This study only considered LMEMs for paint pavement markings. It is recommended that similar studies be conducted on other types of pavement marking materials such as thermoplastics, polyurea, and preformed plastics. It would be interesting to know if the retroreflectivity degradation trajectories of other materials perform similarly to paint pavement markings and if the curves are of a linear form.
7.0 CONCLUSIONS

This conclusions section is divided into three subsections based on the studies reported in previous chapters. These are factors impacting pavement marking retroreflectivity, bead density, and retroreflectivity degradation models.

7.1 Factors Impacting Pavement Marking Retroreflectivity

The impacts of two important factors – directionality and pavement type – on marking retroreflectivity were evaluated in this study. With a large pavement marking retroreflectivity dataset in hand, we evaluated whether these factors have significant impacts on marking retroreflectivity.

Paint pavement marking centerline retroreflectivity values measured in the direction of paint striping were found to be significantly higher than the values measured in the opposite direction. The differences were normally in the range of 20-50 mcd/m$^2$/lux but the difference can be as large as 95 mcd/m$^2$/lux based on the collected data. The results led us to the recommendation that the lower average retroreflectivity value for a yellow centerline, measured in the opposite direction from the direction of paint striping, should be used to compare with the future FHWA minimum standard to determine whether or not the centerline meets the standard.

The results of the pavement type and roughness impact study indicate that the mean values of the retroreflectivity measurements collected on the plant mixed pavements (137 and 238 mcd/m$^2$/lux for yellow and white markings, respectively) are significantly larger than the values collected on the bituminous surface treatment (BST) chip seal pavements (89 and 180 mcd/m$^2$/lux for yellow and white markings, respectively). The study also found that pavement roughness has an impact on the pavement marking retroreflectivity readings. However, the large variability in the data suggests that pavement roughness is not the major impact factor which determines the paint pavement marking retroreflectivity. The conclusion
of the research is that marking crews should consider applying higher quality paint markings on BST pavements.

7.2 Bead Density

We developed a computer-aided counting method to analyze glass bead images to obtain glass bead density values. Then, we conducted a correlation study between pavement marking retroreflectivity and bead density. The study found that the normal range of bead density we observed was 9-24 percent of the paint marking surface. Bead density had a significant impact on marking retroreflectivity. Higher glass bead density led to higher marking retroreflectivity. Furthermore, white edge markings had conclusively higher retroreflectivity values than yellow center markings when the bead density values were the same. Markings with bead density values lower than 9% are considered to have too few glass beads on the marking surface to provide acceptable retroreflectivity. This knowledge could be used by transportation agencies to select a suitable and desirable bead density at application and then monitor the glass bead application process to ensure the achievement of the desired density.

7.3 Retroreflectivity Degradation Models

This study reviewed previously-established pavement marking retroreflectivity degradation models in the literature. Based on the marking retroreflectivity data collected on the paint markings in NC, we established linear mixed effects models for paint markings.

The LMEM took into account the correlation among repeated measurements of the data set and produced more accurate predictions than other methods. LMEMs were established for white edge and yellow center paint pavement markings. The LMEM results showed that the estimated white edge pavement marking lifecycle is 34.2 months and yellow center marking lifecycle is 37.6 months on average when using 100 and 65 mcd/m²/lux as the minimum acceptable retroreflectivity values for white and yellow paint markings. Thus, the current NCDOT practice of restriping paint markings at approximately two-year intervals is
reasonable and may be relaxed on some roads (those with initial $R_L$ over 300 mcd/m$^2$/lux for white and 150 mcd/m$^2$/lux for yellow markings) without violating the current benchmarks. However, pavement marking managers should attend to the markings with low initial retroreflectivity measurement (200 mcd/m$^2$/lux for white and 100 mcd/m$^2$/lux for yellow markings). The retroreflectivity values of those markings are more likely to fall below the minima than other markings in less than two years.
8.0 RECOMMENDATIONS

The main objectives of the research were to evaluate pavement marking performance in NC and to help transportation agencies meet future FHWA pavement marking minimum $R_L$ requirements. The tasks listed in Section 1.1 have been successfully completed and the objectives have been achieved. The research results can help transportation agencies improve their pavement marking performance.

This chapter is divided into three different subsections which are Pavement Marking Retroreflectivity Data Collection, Glass Bead Density, and Future Research.

8.1 Pavement Marking Retroreflectivity Data Collection

Based on the results of the paint marking directionality study (Chapter 3), bead density study (Chapter 5), and the degradation model study (Chapters 6), the following recommendations are made regarding future retroreflectivity data collection.

First, the retroreflectivity data for paint pavement marking centerlines on two lane highways should be collected in both travel directions. The lower average retroreflectivity value for a yellow centerline, measured in the opposite direction from the direction of paint striping, should be used to compare with the future FHWA minimum standard to determine whether or not the centerline meets the standard.

Second, future studies should consider collecting paint retroreflectivity data for more than 2.5 years to have more accurate pavement marking retroreflectivity degradation curves for an entire lifecycle. We recommend that the NCDOT continue collecting data on the 25 “new” paint sites on which we have collected four rounds of retroreflectivity data for at least two more rounds.
Third, more marking retroreflectivity data should be collected on other types of marking materials such as polyurea and epoxy. This research focused on paints because paints make up a majority of pavement marking mileage, but retroreflectivity readings for other types of materials are limited and there is an important subset of NCDOT roads with these other marking types.

Finally, we highly recommended that the NCDOT records installation date and collects initial retroreflectivity readings for all new pavement markings. The age of the markings and initial $R_L$ readings need to be collected for use in prediction models.

### 8.2 Glass Bead Density

The research results in Chapter 5 clearly indicate that glass bead density has a significant impact on paint marking retroreflectivity. Higher glass bead density leads to higher marking retroreflectivity. By examining the glass bead density, traffic engineers and researchers can understand how and why pavement marking retroreflectivity readings degrade over time.

The research team recommends that the NCDOT and other agencies start using the Matlab program to inspect the glass bead densities of newly applied pavement markings to decide if the bead density values are in a normal range (9-22% for paint markings), especially when the retroreflectivity readings of the markings are found to be lower than desired values. The NCDOT and other agencies can then work with material manufactures and installation crews to insure that bead densities are as high as needed upon installation.

### 8.3 Pavement Marking Degradation Models

We established retroreflectivity degradation model paint pavement markings in Chapters 6. The FHWA is expected to publish pavement marking retroreflectivity minimum standards in the near future. It is impractical for NCDOT to measure all the pavement markings in NC. We recommend that NCDOT start using the degradation models to predict the marking retroreflectivity values on roads it cannot measure. It is also recommended that NCDOT
continue to use a visual inspection process in their management of pavement markings. Visual inspection can be used to verify the condition estimates produced by the models [Siztabee 2009b].

8.4 Future Research

The future research ideas listed below would make more useful information available for pavement marking management.

- The bead density program (BDAP) developed as a part of this study could be improved. The objective of the future research should be to pursue an automatic image recognition program.

- An important result of this research was that the initial retroreflectivity measurement of new markings is an important factor that determines how long markings can last. Future research should be launched to explore how to improve the marking installation process to achieve higher initial retroreflectivity readings.

- This research established paint marking degradation models. Future research should be initiated to develop degradation models for other types of marking materials (such as polyurea on concrete surfaces) when and where more retroreflectivity data are available.

- A successful pavement marking management system can help transportation agencies reduce costs by maximizing marking lifecycle and help transportation agencies meet the pending FHWA minimum requirements. Future research is recommended to focus more on pavement marking management system.
9.0 REFERENCES


48. Texas Department of Transportation (TxDOT) (2004). *Pavement Marking Handbook*. TxDOT, Austin, TX.


