UNDERSTANDING THE IMPACT OF BEAD TYPE ON PAINT AND THERMOPLASTIC PAVEMENT MARKINGS

THESIS

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Abstract

Each year the United States spends approximately two billion dollars maintaining pavement markings. Additionally, an impending Federal policy establishing a minimum retroreflectivity value for pavement markings has driven asset managers to develop performance models in order to effectively and efficiently manage these high quantity, low cost assets. Research over the past decade has sought to identify and understand the many factors influencing pavement marking degradation. Despite the fact that reflective glass beads are foundational to pavement marking retroreflectivity, little research has specifically considered the impacts of bead type. The purpose of this study is to quantify the impact that bead type has on the degradation rate of paint and thermoplastic pavement markings in North Carolina. The results of an average value analysis and Wilcoxon rank sum test support the inclusion of bead type as a significant variable in future degradation models and the following two key findings. First, there is a statistically significant difference in the rate of retroreflectivity degradation between standard beads and large beads for both thermoplastic and paint pavement markings. Second, thermoplastic pavement markings with standard beads are more economical than those with large beads in areas that experience snow plow operations.

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To the One who has done immeasurably more than I could have hoped for or imagined, Thank You! It is through You alone that I have life, and it is through the life, death, and resurrection of Your son, Jesus Christ, that I find the way to life, the purpose in life, and the beauty of life. Without Your faithful sustainment and mercy I am incapable of doing anything that honors You. S*oli Deo Gloria!*

To my wife, the one who walks beside me through this life, I love you. You bring me more joy than I could ever have asked for, and you are a faithful friend. I will never forget the late night ice cream runs or the early morning coffee surprises. You have loved and supported me even when I didn’t deserve it. You are truly my crown.

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I. Introduction

Background

In 2009, the Federal Highway Administration estimated the highway infrastructure of the United States to consist of over 8.5 million lane-miles of public roads (U.S. Department of Transportation, 2011). The magnitude of this figure is indicative of the challenge associated with managing such an infrastructure network. Traffic control devices such as road signs, barriers, and pavement markings abound in the transportation infrastructure of the United States, and they exist to encourage highway safety and efficiency (Federal Highway Administration, 2009). Asset managers consider traffic control devices to be High-Quantity, Low-Cost Assets (Rasdorf, Hummer, Zhang, & Sitzabee, 2009). The resources required for monitoring and maintaining these assets, particularly pavement markings, on a small scale may be minimal, but the aggregated impact can be quite large. Current asset management practices are not sufficient to meet the demands of an ever-growing infrastructure, and new tools and techniques are needed to improve highway safety, comply with federal regulations, and reduce pavement marking maintenance costs.

It is estimated that 60% of all highway fatalities result from lane departures (Carlson, Park, & Andersen, 2009). Pavement markings are critical in establishing lane awareness and decreasing lane departures. Nighttime operations are of particular concern due to reduced visibility. In order to improve nighttime visibility, glass beads are embedded in pavement marking material to increase the amount of light originating from vehicle headlights that is returned to the driver. This property of pavement markings is known as retroreflectivity. As the retroreflectivity of the marking decreases, the marking becomes more difficult to distinguish, and the chance of lane departure increases. This condition has prompted the need to develop national standards to govern pavement markings on public roads.

In 1993, Congress directed the Federal Highway Administration (FHWA) to establish minimum standards for retroreflectivity of highway signs and pavement markings (Vereen, Hummer, & Rasdorf, 2003). In 2008, the FHWA updated the Manual on Uniform Traffic Control Devices (MUTCD) to include minimum retroreflectivity standards for traffic signs, and in 2010, the FHWA released the proposed guidance that will regulate pavement markings. However, the official ruling for pavement markings remains open (Federal Highway Administration, 2011). The proposed regulation establishes minimum retroreflectivity standards and requires agencies to implement a management plan for pavement markings. Pending any significant changes or events, the standards will be put into effect in the very near future (Federal Highway Administration, 2010). Departments of Transportation (DOTs) across the nation will be required to establish management plans to ensure pavement markings remain in acceptable condition. Undoubtedly, the manpower and resources required to carry out the directive will increase and the financial impact will be substantial.

A report by the Transportation Review Board estimated the national, annual cost of maintaining pavement markings to total approximately two billion dollars in 2007 (Carlson, Park, & Andersen, 2009). DOTs nation-wide spend more money than necessary on pavement markings due to substandard management practices. For example, the North Carolina Department of Transportation (NCDOT) manages paint pavement markings on an annual basis under the assumption that the service life is approximately one year. However, recent research suggests that paint pavement markings may have a service life of two years or more (Sitzabee, Hummer, & Rasdorf, 2009). Consequently, the NCDOT has the potential to cut pavement marking maintenance costs in half. This consideration combined with the financial impracticality of manually measuring the retroreflectivity of every square inch of pavement markings has forced asset managers to find a better way to estimate pavement marking service life.

Degradation models allow asset managers to predict the life-cycle of various pavement marking types in an effort to improve highway safety, comply with federal regulations, and reduce roadway maintenance costs. Over the past decade, several research efforts have focused on developing pavement marking degradation models, but disparities between the different models still exist (Sitzabee, Hummer, & Rasdorf, 2009). These disparities challenge the validity of such models, and additional research is necessary to refine existing models.

One particular area for additional research is the impact of bead type on pavement marking degradation. Despite the fact that reflective glass beads are foundational to retroreflectivity in pavement markings, little research has specifically considered the impact of bead type on pavement markings. One study considers the impact of bead density on retroreflectivity (Zhang, Hummer, & Rasdorf, 2010), and only one other study considers the impact of bead type specifically. Research conducted at the Air Force Institute of Technology reveals that bead type does impact the degradation rate of polyurea pavement markings, and future research should consider the impact of bead type on other pavement marking materials (Needham, 2011).

Problem Statement

The objective of this study is to quantify the impact of bead type on the degradation of paint and thermoplastic pavement markings. This research answers the following question: "Does bead type impact the degradation rate of paint and thermoplastic pavement markings?" Furthermore, this work seeks to answer the following questions:

1. Do thermoplastic pavement markings with standard beads degrade differently than those with large beads?
2. Do paint pavement markings with standard beads degrade differently than those with large beads?
3. Should bead type be considered a significant variable in future degradation models?

Scope and Approach

The scope of this research is limited to paint and thermoplastic longitudinal pavement markings in North Carolina. Data for over 30,000 road segments in North Carolina were collected between 2001 and 2010. The data set includes a variety of characteristics for each road segment to include initial and annual retroreflectivity values, installation date, marking material type, marking color, region within the state, type of marking, location on the roadway, and bead type. First, an average value analysis is used as an exploratory technique to determine whether or not a difference may exist between paint pavement markings with standard beads and those with large beads. Next, the Wilcoxon rank sum test is used to determine if a statistically significant difference exists between the degradation rate of paint pavement markings with standard beads and paint pavement markings with large beads. An identical analysis is performed on thermoplastic pavement markings. Finally, linear regression is used to develop a performance model for thermoplastic pavement markings that incorporates bead type as a significant variable.

Significance

This research establishes the impact that bead type has on degradation models for paint and thermoplastic pavement markings. With reflective glass beads at the foundation of pavement marking retroreflectivity, it is expected that bead type does impact pavement marking degradation. A better understanding of the impact of bead type on degradation rate can improve the validity and reliability of future pavement marking degradation models. Reliable pavement marking degradation models equip asset managers with the tools needed to effectively and efficiently monitor and maintain pavement markings to improve highway safety, comply with federal regulations, and cut maintenance costs.

Overview of Subsequent Chapters

The remainder of this document is organized into four chapters. Chapter 2 introduces and discusses the literature which forms the foundation for this research effort. It delves into the terms and concepts essential to understanding pavement markings such as pavement marking types, retroreflectivity, and the regulations that govern pavement markings. It also highlights some of the key findings and limitations of previous studies on pavement marking degradation modeling. Chapter 3 describes the methodology used to conduct the research. It explains the reasons for using an average value analysis and Wilcoxon rank sum test in this study, and it discusses the process of implementing these tools. Chapter 4 provides the results for each phase of the research. Chapter 5 provides a discussion of the results and limitations of the study, and it concludes with future research opportunities identified during the study.

II. Literature Review

The purpose of this chapter is to present the existing literature essential to understanding pavement marking degradation models. The first section provides a brief definition and description of Asset Management. The second section provides an overview of pavement marking materials to include discussions on waterborne paints, thermoplastics, retroreflectivity, the minimum retroreflectivity standards, and reflective glass beads. The final section summarizes the previous research on pavement marking degradation modeling and identifies gaps in the research that led to the current research.

Asset Management

According to the Department of Transportation, Asset Management is "a systematic process of maintaining, upgrading, and operating physical assets cost-effectively." Asset Management has been rapidly gaining support of federal and state agencies over the last few decades. As the transportation infrastructure grows, the resource demands heavily outweigh the resource availability in both personnel and budget. There simply are not enough resources to maintain, update, and operate transportation assets without a shift in management practices. Additionally, the government has an obligation to its constituents to effectively and efficiently manage the limited resources. Consequently, government agencies are focusing efforts on understanding the life-cycle of various transportation assets in order to allocate resources at the right time and the right place. The life-cycle cost of pavement markings can vary greatly depending on a number of factors such as the materials used, environment, and performance requirements. By understanding the factors that impact the life-cycle of transportation assets, transportation managers can identify the practices that will provide the most benefit for the least cost (Federal Highway Administration, 1999).

Pavement Marking Materials

Over the years, a variety of materials have been developed to function as adequate pavement markings, ranging from paint to polyester to tape. At the broadest level, pavement markings are classified into two distinct categories: durable and non-durable. Durable markings describe materials that have an expected service life of more than one year. Non-durable markings describe materials that have an expected service life of less than one year. In general, paint-based materials are considered non-durable; all other materials are classified as durable (Rasdorf, Hummer, Zhang, & Sitzabee, 2009). In a 2002 synthesis of pavement marking materials, Migletz and Graham identified the sixteen most prevalent pavement marking materials nation-wide. Although there are many material types, the sixteen listed in Table 1 comprise over 95% of the pavement markings (Migletz & Graham, 2002). The four materials highlighted in Table 1 are the four material types contained in the data set used in this research. As Table 1 illustrates, waterborne paints and thermoplastics are, by far, the most commonly used pavement marking materials. Consequently, this research will focus on these two material types.

Table 1: Pavement Marking Materials Across the United States and North Carolina

	Pavement Marking Material Type	Percentage of Use
1	Waterborne paint	59.9
2	Thermoplastics	22.7
3	Conventional solvent paint	6.5
4	Polyester	3.8
5	Epoxy	2.7
6	Preformed tape - flat	< 1.0
7	Preformed tape - profiled	< 1.0
8	Methyl methacrylate	< 1.0
9	Thermoplastics profiled	< 1.0
10	Polyurea	< 1.0
11	Cold applied plastics	< 1.0
12	Experimental	< 1.0
13	Green lite powder	< 1.0
14	Polyester profiled	< 1.0
15	Tape removable	< 1.0
16	HD-21	< 1.0

(Adapted from Migletz, 2002)

Waterborne Paints

Waterborne paints are the most pervasive material type used for longitudinal pavement markings. In North Carolina, they account for 60% of all pavement markings (Sitzabee, Hummer, & Rasdorf, 2009). Waterborne paints are used in the majority of applications due to the ease and relatively low cost of application. Waterborne paints are quick drying, and they can be used on both Portland cement concrete and bituminous pavement types. The minimum initial retroreflectivity values for waterborne paints should be between 180 and 275 mcd/m^2/lux (Montebello & Schroeder, 2000). The biggest drawback of using waterborne paint as a pavement marking material is the short service life. Waterborne paint is considered a non-durable material and is typically not expected to last beyond one year; however, research does support a longer or shorter service life depending on a variety of factors (Mull & Sitzabee, 2011; Sitzabee, Hummer,

& Rasdorf, 2009). The service life can be even shorter under high traffic volume conditions. Migletz suggests that waterborne paints are more cost effective than most durable marking materials when the average annual daily traffic count is less than 10,000 vehicles per day (2002).

Thermoplastics

Thermoplastics are the second-most frequently used material. For example, they account for 23% of the pavement marking materials in the NCDOT inventory (Sitzabee, Hummer, & Rasdorf, 2009). Thermoplastics are considered durable materials, and they are expected to have an extended service life. The application of thermoplastics is more difficult than waterborne paints, and the installation cost is typically $0.04 to $0.65 higher per linear foot (Migletz & Graham, 2002). However, the extended service life of thermoplastics balances out the higher installation costs. Research suggests that under heavy traffic conditions, thermoplastics become a cost-effective alternative material to the cheaper, non-durable paint pavement markings (Migletz & Graham, 2002). Thermoplastics can be applied to both Portland cement concrete and bituminous pavement types, but the environmental conditions, such as temperature and moisture, affect the ability for the material to adhere to the pavement surface. The initial retroreflectivity values for thermoplastics are typically 150 to 200 mcd/m^2/lux higher than that of paint markings (Sitzabee, Hummer, & Rasdorf, 2009). Thermoplastics are also susceptible to significant damage during snow plow operations (Mull & Sitzabee, 2011). Despite the challenging application process and higher costs, thermoplastics are still widely used, most likely due to their extended service life. In 2009, Sitzabee et al estimated the average service life of thermoplastics to be between 5.4 to 8.5 years depending on the lateral location of the line.

Retroreflectivity

Retroreflectivity is critical to the visibility of pavement markings during nighttime operations. The MUTCD defines retroreflectivity as, “a property of a surface that allows a large portion of the light coming from a point source to be returned directly back to a point near its origin” (Federal Highway Administration, 2009). For pavement markings, retroreflectivity is achieved by partially embedding reflective glass beads into the marking material during installation. When light originating from vehicle headlights enters the bead, it undergoes a series of refractions and reflections and is returned at a different angle toward the vehicle operator. Retroreflectivity for pavement markings is quantified with the coefficient of retroreflected luminance (R_L), which is measured in millicandelas per meter squared of luminance ($mcd/m^2/lux$). The American Society for Testing Materials (ASTM) standard number E 808 specifies that a specific type of geometry, known as the 30-meter geometry, be used for pavement markings (2009). This geometry measures the retroreflectivity of a point that is 30 meters in front of the light source, as illustrated in Figure 1.

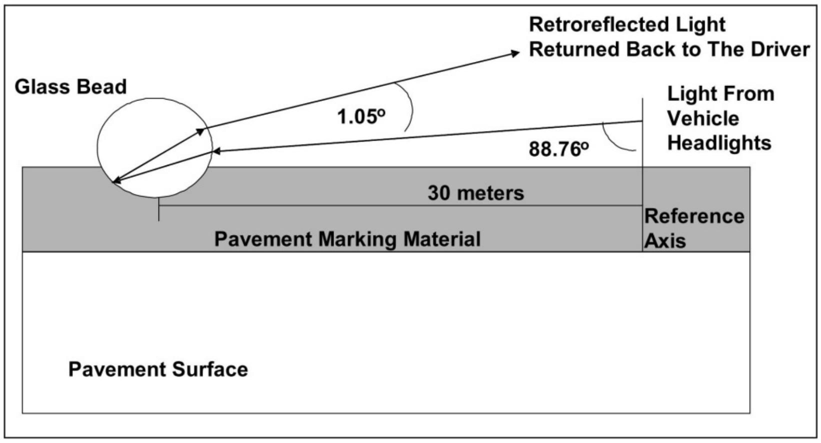


Figure 1: Pavement Marking Retroreflectivity

Minimum Retroreflectivity Standard for Pavement Markings

In 1993, congress directed the FHWA to establish minimum standards for retroreflectivity of pavement markings (Vereen, Hummer, & Rasdorf, 2003). In 2010, the FHWA released the proposed guidance that will regulate pavement markings. The proposed regulation establishes minimum retroreflectivity standards for transportation agencies across the nations. Until the FHWA released the proposed minimum retroreflectivity standards for pavement markings, researchers used a wide range of minimum retroreflectivity values for modeling purposes. There is significant variation between the estimated service life estimates, because each study used a different retroreflectivity value to determine the point at which pavement markings exceed their useful life. Now, researchers can use the proposed standards released by the FHWA to establish the point where pavement markings are considered unusable. Table 2 shows the minimum retroreflectivity values that have been proposed by the FHWA for incorporation into the MUTCD.

Table 2: Minimum Retroreflectivity Values for Longitudinal Pavement Markings

	Posted Speed (mph)		
	≤ 30	35-50	≥ 55
Two-lane roads with center line markings only	n/a	100	250
All other roads	n/a	50	100

measured at standard 30-m geometry in units of mcd/m² /lux

Reflective Glass Beads

Reflective glass beads are critical to achieving the appropriate level of retroreflectivity in pavement markings. Factors such as size, shape, roundness, chemical and physical composition, depth of embedment, and density all influence the retroreflectivity of the beads (Zhang, Hummer, & Rasdorf, 2010). The *Standard Specifications for Construction of Roads and Bridges on Federal Highway Projects* classifies pavement marking beads into five different types based on size and gradation (Federal Highway Administration, 1996). In general, Type I and Type II beads are considered "standard beads" while the remaining types are considered to be "large beads." It is important to note that the beads within each type are not of the same diameter. Each bead type has a specific distribution of beads with varying diameters as listed in Table 3 and displayed in Figure 2. This gradation allows the pavement marking to achieve a higher bead density and the proper depth of embedment.

Table 3: Gradations of Glass Bead Types (FHWA, 1996)

US Sieve Size	Sieve Size in	Mass Percent Passing				
		Type I	Type II	Type III	Type IV	Type V
No. 8	0.0937	-	-	-	-	100
No. 10	0.0787	-	-	-	100	95-100
No. 12	0.0661	-	-	100	95-100	80-95
No. 14	0.0555	-	-	95-100	80-95	10-40
No. 16	0.0469	100	-	80-95	10-40	0-5
No. 18	0.0394	-	-	10-40	0-5	0-2
No. 20	0.0334	95-100	-	0-5	0-2	-
No. 25	0.0278	-	-	0-2	-	-
No. 30	0.0234	75-95	100	-	-	-
No. 40	0.0165	-	90-100	-	-	-
No. 50	0.0117	15-35	50-75	-	-	-
No. 80	0.0070	-	0-5	-	-	-
No. 100	0.0059	0-5	-	-	-	-

Adapted from FP-03 (FHWA, 1996)

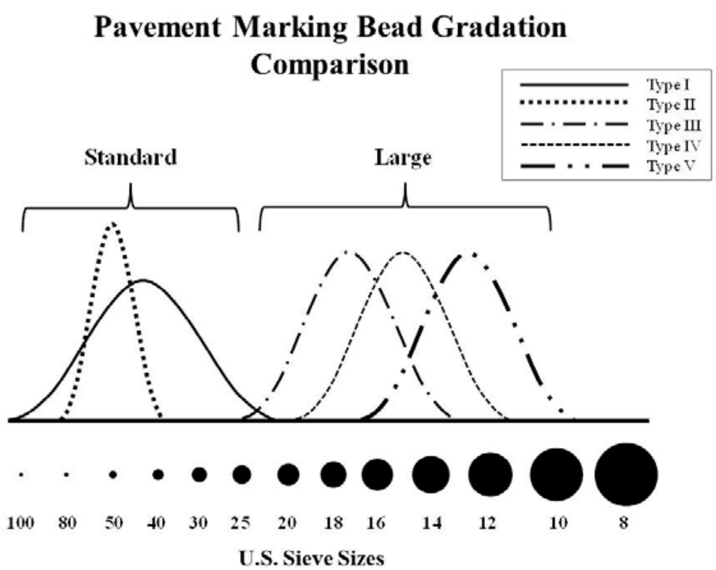


Figure 2: Pavement Marking Bead Type Gradation Comparison

Bead Density

Zhang et al. defined bead density as “the surface percentage of glass beads that are exposed above the marking binding material,” and the results of their study indicate a positive correlation between bead density and the retroreflectivity of the pavement marking (2010). As mentioned earlier, the gradation of pavement marking beads helps to increase bead density by increasing the number of beads that are able to fit within a segment of pavement marking material. The smaller beads are able to fill the gaps that exist between the larger beads, as illustrated in Figure 3.

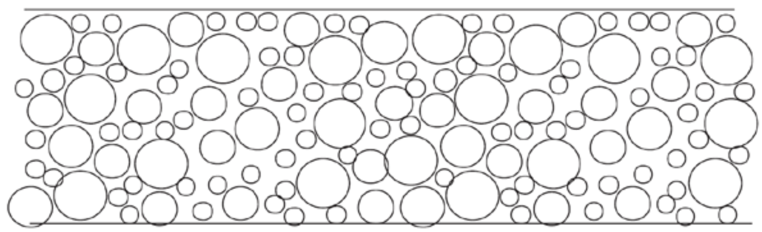
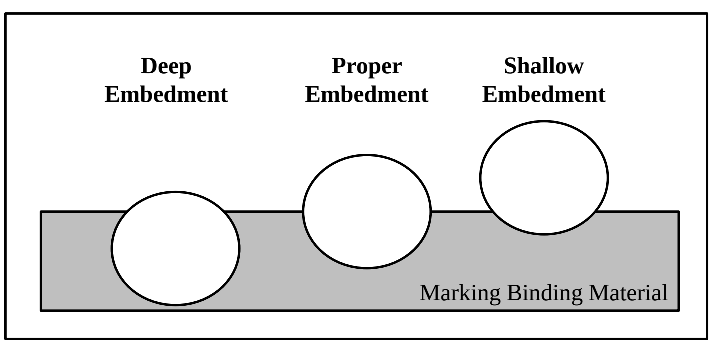


Figure 3: Proper Bead Distribution (VDOT, 2011)

Bead Embedment

Another reason for the gradation of pavement marking beads is to ensure that an adequate number of beads achieve the proper depth of embedment. The optimum embedment depth is between 40% and 60% (Zhang, Hummer, & Rasdorf, 2010). An embedment depth less than 40% (shallow) can reduce the longevity of the bead, and an embedment depth of more than 60% (deep) can reduce the retroreflectivity of the marking. Figure 4 illustrates the varying degrees of bead embedment.



Adapted from (Zhang, 2010)

Figure 4: Varying Degrees of Embedment

The thickness of the pavement marking material will vary with material type, environmental conditions, and experience of the application team. Well graded beads ensure that an adequate number of beads reach the optimum depth of embedment as the pavement marking thickness fluctuates. One bead size may achieve better embedment in one material over another due to the thickness of the material or temperature during application. The typical thickness of paint markings is between 15 and 25 mils, which is equivalent to 0.015 to 0.025 inches (Zhang, Hummer, & Rasdorf, 2010). Thermoplastics, however, typically have a thickness range of 90-120 mils (Migletz & Graham, 2002). Table 3 shows that the average diameter of a large bead is approximately 50 mils. Consequently, large beads may not be able to achieve the same depth of embedment on paint markings compared with thermoplastic markings as illustrated in Figure 5. The temperature of thermoplastics during bead application may also influence the quality of bead embedment. Thermoplastics are more pliable at higher temperatures which will allow beads to sink deeper into the material upon application. As the temperature cools and the material becomes less pliable, the beads may not achieve the same depth of embedment. Both thickness and application temperature influence the depth of bead embedment.

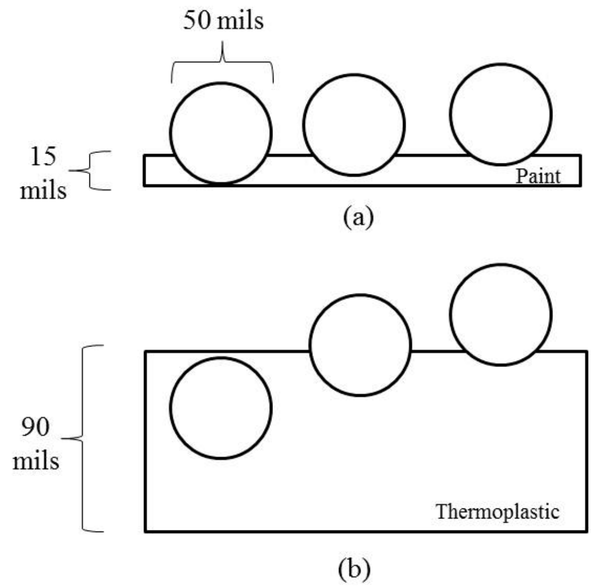


Figure 5: Impact of Material Thickness on Bead Embedment

Previous Studies

Over the past decade, numerous studies have been conducted to understand the degradation rates of pavement markings. Many of the studies have been sponsored by DOTs around the country, and there is considerable variety between both the variables considered for the model and the modeling approaches. This section discusses the key studies listed in Table 4 which have influenced the course of this research.

Table 4: Summary of Literature

Year	Author	Key Findings
1999	Lee et al.	- Paint is the most cost effective marking in Michigan - Snow removal operations impact degradation rate - All marking materials have a short life span (< 24 months) - Variables: AADT, speed limit, commercial traffic %
2001	Migletz et al.	- Large variation in the shape of degradation curves - Average life of waterborne paint is 10.4 months - Average life of thermoplastics is 26.2 months - Average life of polyurea is 25.7 months - Variables: material, lateral location, color, type of roadway
2007	Craig et al.	- Lateral line location impacts thermoplastic pavement marking degradation rates - Use of Average Value Analysis and ANOVA
2009	Rasdorf et al.	- Direction has a statistically significant impact on retroreflectivity
2009	Sitzabee et al.	- Regression models for paint and thermoplastics - Average life of thermoplastics is 5.4 to 8.5 years - Average life of waterborne paint is 2.2 to 2.6 years - Variables: time, traffic volume, color, lateral location
2010	Previti et al.	- Pilots reported no difference in ease of detection between Type I and Type III beads
2010	Zhang et al.	- Bead density is positively correlated with retroreflectivity
2011	Needham	- Bead type impacts the degradation of polyurea pavement markings - Variables: time, lateral location, bead type
2011	Nepal et al.	- Depth of surface texture negatively correlated with retroreflectivity

Migletz et al., 2001

In 2001, under the National Cooperative Highway Research Program, Migletz and Graham compiled a synthesis of long-term pavement marking practices. The synthesis summarized long-term pavement marking practices and research from sixty-one governmental agencies and private companies from the United States and Canada. The purpose of the effort was to highlight the current and best practices for pavement markings and to identify future needs. The work identified two major challenges facing transportation agencies as nighttime visibility in rain and fog and quality control when markings are installed. It also identified several shortfalls in current pavement marking management practices such as the lack of a minimum federal retroreflectivity standard and poor retroreflectivity performance under wet pavement conditions. The synthesis identified the sixteen material types that are most used for longitudinal pavement markings.

The work also summarized the factors that have been shown to impact pavement marking service life such as line color, pavement surface type, material, and traffic volume. Their results showed that white lines have a service life that is typically 42% greater than yellow lines. Also, lines on asphalt have a 27% greater service life than lines on Portland cement concrete. In order for most durable markings to be cost-effective, they must be applied to roads with an average daily traffic count of at least 10,000 vehicles per day per lane.

Craig et al., 2007

In 2007, Craig et al. researched the effect of lateral line location on pavement marking retroreflectivity degradation. Data were collected over a 5-year period on North Carolina roadways, and the scope of the research was limited to yellow and white thermoplastic markings on an asphalt surface. A weighted average analysis and an unweighted average analysis suggested a possible difference in degradation rates based on lateral line location. An Analysis of Variance (ANOVA) established a statistically significant difference between the degradation rate of edge lines and the degradation rate of centerlines for both yellow and white thermoplastic pavement markings. The work of Craig et al. forms the methodological framework for which this current research is based.

Rasdorf et al., 2009

In 2009, a research team from North Carolina State University led by William Rasdorf conducted a study to statistically validate the assumption that pavement marking retroreflectivity has a directional component to it. In theory, when glass beads are applied to pavement markings, they enter the binder material at a perfectly vertical angle. In reality, the beads have a horizontal velocity which causes the beads to enter the binder material at an angle causing the material to form in an asymmetric manner around the beads as seen in Figure 6. To validate this theory, the research team collected retroreflectivity values in both directions for centerlines at six different sites. An initial reading was taken shortly after installation, and a follow-up reading was accomplished four months after installation. The retroreflectivity values taken in the same direction of striping were consistently 40 – 90 mcd/m^2/lux higher than the retroreflectivity values taken in the opposite direction of striping. Further analysis confirmed the difference to be statistically significant.

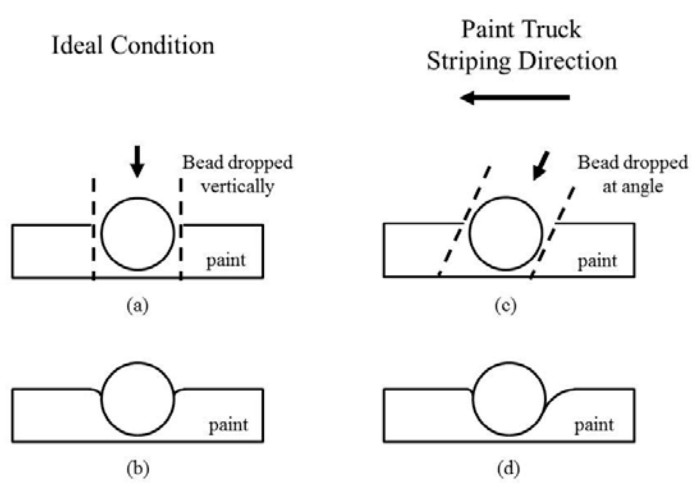


Figure 6: Directionality of Bead Embedment (Rasdorf, 2009)

Sitzabee et al., 2009

In 2009, a research team from North Carolina State University worked to determine the performance characteristics of thermoplastic and paint pavement markings. The team considered the variables known to have an impact on service life such as time, traffic volume, and color. The team also included lateral line location as a key variable in the model. The team used linear regression to model the degradation rates of thermoplastic and paint pavement markings. The findings suggest that the service lives of both types are greater than originally expected. For the data that were analyzed, the service life of thermoplastics on asphalt with an AADT of 10,000 vehicles per day ranges from 5.4 years to 8.5 years depending on the lateral location of the line. Paints considered in the study had a service life just above two years. The researchers recommended that future research explore other variables that are suspected to impact degradation rates.

Previti et al., 2010

The Federal Aviation Administration Airport Safety Technology Research and Development Sub-Team worked to determine the relative conspicuity, from aircraft approach, of Type I and Type III retroreflective beads. The research was conducted at two different airports with the same marking types. One airport had identical pavement markings with different bead types at each end of the runway. The second airport had the pavement markings with the two types of beads installed side by side. Subjective data were collected from pilots in the form of questionnaires. All but one of the subjects reported that there was no difference in ease of detection between the two bead types.

These findings can have significant impacts on the management decisions associated with pavement markings.

Zhang et al., 2010

In 2010, Zhang et al. studied the relationship between bead density and retroreflectivity in paint pavement markings. The retroreflectivity data used in the study represented 40 segments of two-lane highways in North Carolina. Numerous digital images were taken of each roadway segment, and a computer-aided counting method was used to calculate the density of pavement marking beads in each segment. A correlation study was performed on bead density and retroreflectivity. The outcome of the study was two-fold. First, the study presented a new method for determining bead density that is more robust and more efficient than previous methods. Second, Zhang et al. found that the calculated bead density values were positively correlated with retroreflectivity.

Needham, 2011

In 2011, Needham conducted research on polyurea pavement markings in North Carolina. The purpose of the study was to construct performance models and quantify the degradation rate of polyurea pavement markings in North Carolina. The effort resulted in two different performance models for polyurea pavement markings. The first performance model describes polyurea markings containing standard beads. The second performance model describes polyurea markings containing highly reflective elements. Both performance models considered the variables of time, initial retroreflectivity, and lateral line location. One of the key findings of the study was that bead type significantly impacts the degradation rate of polyurea pavement markings. Figure 7 shows that polyurea pavement markings with highly reflective elements had a much higher initial retroreflectivity value than those with standard beads. It also shows that polyurea markings with highly reflective elements degrade in a nonlinear manner that is much faster than polyurea markings with standard beads. Needham demonstrated the impact of bead type on polyurea markings, but future research should explore the impact of bead type on other marking materials. These findings are foundational to the purpose behind the current research effort.

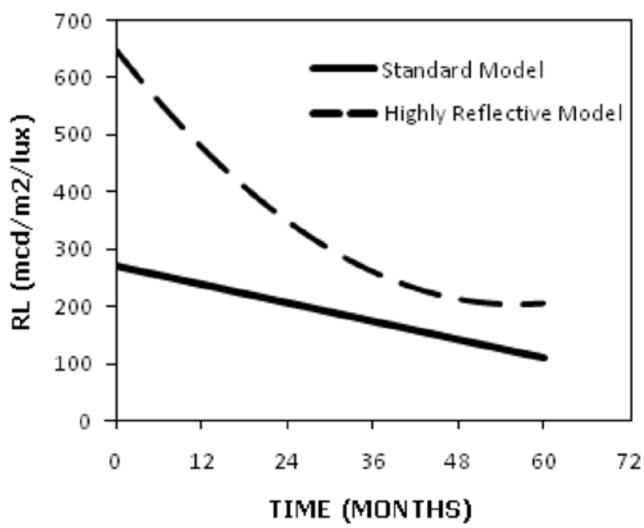


Figure 7: Bead Performance Over Time for Polyurea (Needham, 2011)

Nepal and Lahtinen, 2011

Nepal and Lahtinen assessed the state of pavement markings in southeast Queensland and investigated the implementation issues associated with a new mobile data collection platform. An ECODYN retroreflectometer was mounted on a mobile platform and used to collect retroreflectivity data of white centerlines on roads with various surface types and traffic volumes. The mean retroreflectivity values for the different roads were compared and analyzed for variance. The results show that retroreflectivity values are lower for deeper texture depths. The authors suggest that this is due to glass bead embedment being too deep in the "valleys" and too shallow at the "peaks."

Summary of Literature

One common theme throughout all of the literature is the emphasis of the need for a greater understanding of the various factors that influence pavement marking degradation. Research has shown that pavement marking retroreflectivity is impacted by time, type of material, color, lateral line location, traffic volume, and pavement surface type. However, there is a significant gap in literature related to retroreflective beads, despite their centrality to the retroreflectivity of pavement markings. Zhang et al. found retroreflectivity to be positively correlated with the bead density of the marking. Needham demonstrated that bead type does impact the degradation of polyurea pavement markings, but no research has been conducted to investigate the impact of bead type on paint and thermoplastic pavement markings. With paint and thermoplastics accounting for a majority of the pavement markings in the United States it is important to consider the impact that bead type has on the degradation of these pavement markings.

III. Methodology

The purpose of this chapter is to present the data collection and analysis methods used in this study. The chapter begins with an overview of the data set to include the data collection procedure. The steps taken to reduce the original data to a usable data set that is applicable to this particular study are explained. The next section explains the initial investigative efforts which consist of an average value analysis and an analysis of the variance using the Wilcoxon rank sum test. The final section describes how linear regression was used to model the data to include bead type as a significant variable.

Data Collection

The data used in this research were collected for the NCDOT by an independent contractor. The collection effort and procedures are summarized in the doctoral work of Dr. William Sitzabee (2008). The purpose of the effort was to collect retroreflectivity values on specified routes throughout the state of North Carolina to assist quality control. Consequently, the data have limitations due to the inherent bias that is introduced with field data. One primary source of bias is a result of the replacement cycle of the markings under investigation. Markings of a poor quality were replaced earlier than markings of a higher quality. Therefore, markings with a full compliment of data are, naturally, of higher quality than markings with only 6 to 12 months of data. This can skew the results to favor a better performance of the markings. The markings under consideration were installed under normal field conditions, which can lead to a large amount of variance in the quality of installation of the individual markings. While this fact could prove to be problematic for research focused on understanding pavement markings under ideal conditions, it does not have significant implications to this research effort. From an asset management perspective, the data used in this research are more representative of realistic scenarios encountered by asset managers.

It is common to collect retroreflectivity data with a handheld retroreflectometer or a mobile retroreflectometer platform, but handheld units typically have less variability. However, collecting data with a handheld unit has two areas of concern: safety and efficiency. Ideally, the safest way to collect roadway data is to close the road. However, this option is impractical for large data collection efforts due to the negative impacts associated with closing roadways during data collection. With traffic still moving on the roadways of interest, the data collection crew is exposed to a high level of risk. A collection effort of this magnitude would require an inordinate amount of time for a collection crew to cover 30,000 lane miles of pavement markings on foot.

These two concerns were addressed by using a mobile platform which consisted of a modified Laserlux mobile retroreflectometer (model LLR5) mounted on a Chevrolet Suburban. This mobile data collection platform allowed one operator to collect a large amount of data in a safe and efficient manner. The LTL-2000 handheld retroreflectometer was used to collect an accurate data sample in accordance with the standard 30-meter geometry prescribed by ASTM E 1710-97 (1997). Those data were used to calibrate the LLR5 before each run to reduce some of the variance associated with the mobile platform.

The LLR5 continuously collected R_L values along the road segments at a rate of 100 readings per minute when traveling at 60 miles per hour. An on-board computer recorded the data which eliminated operator input error. The computer was set to only record R_L values within a given range which allowed for unusually low readings, as typical of bare pavement surfaces, and unusually high readings, as typical of raised reflectors, to be rejected. The continuously recorded R_L values that were within the accepted range were averaged over each tenth of a mile increment. Those values were averaged over the entire length of the segment to establish one R_L value representative of the entire road segment of interest.

Data Reduction

The original data set includes thousands of data points representing over 30,000 lane miles of North Carolina roadway markings. The data were collected over a 9 year period and include a variety of information ranging from material type and color to traffic volume to the contact information of the snow plow operators. An extensive data mining effort was conducted to strip the data set of erroneous information. Initially, all data associated with polyurea and epoxy pavement markings were removed to reduce the data set to include only records with paint and thermoplastic pavement markings. Additionally, the data set only includes records of pavement markings applied on an asphalt concrete surface. Finally, the data set was refined to different levels of specificity depending on the stage and purpose of analysis. The details for each specific data set used in the various levels of analysis are presented in the appropriate sections of Chapter 4.

Average Value Analysis

An average value analysis is selected to initially investigate whether or not bead type appears to have an impact on the degradation rate of both paint and thermoplastic pavement markings. Average value analysis is a very basic technique that is suitable for a preliminary investigation because of its simplicity. An average value is calculated for each bead type using the following equation:

$$RL_{ave} = \frac{\sum RL_i}{N_t}$$

where

RL_{ave}	=	average retroreflectivity for each time period in mcd/m^2/lux
RL_i	=	measured retroreflectivity of road segment *i* in mcd/m^2/lux
N_t	=	Number of road segments measured for each category & time period

The average value for retroreflectivity (RL_{ave}) for each bead type is then compared at each time interval to determine whether or not there appears to be a difference based on bead type. The difference between the two population RL_{ave} values (delta) is calculated and plotted to investigate a potential difference in degradation rates. An increase or decrease in the delta over time indicates a possible difference in the degradation rates of the two populations.

While an average value analysis is easy to conduct, the results are only capable of identifying a possible interaction between bead type and retroreflectivity degradation. A more certain technique is needed to statistically validate the results. Two techniques were considered for this research: the standard Analysis of Variance (ANOVA) Test and the Wilcoxon rank sum Test. The following sections explain both techniques.

Analysis of Variance (ANOVA)

Analysis of Variance (ANOVA) is a statistical tool that is used to establish whether or not there is a statistical difference between the means of multiple populations. When comparing population means, some part of the difference is attributed to normal variance within and between the two populations. The ANOVA determines whether or not the difference between the means is attributed to normal variance or if it is attributed to a true difference between the two populations.

The first type of variance that is addressed with the ANOVA is "within-group variance." This is the variance between the observations from the same populations. With an ANOVA, this variance is assumed to be equal for each population. The second type of variance that is addressed is "between-group variance." This is the variance between the means of each population in the comparison. A ratio of the "between-group variance" to the "within group variance" close to one would indicate that the two types of variance are equal. This makes it difficult to determine whether or not the difference between the means is attributed to a true difference. As the ratio gets smaller, the likelihood of a true difference between the two population means increases (Newbold, Carlson, & Thorne, 2010).

The null hypothesis (H_o) states that the difference between the standard bead mean and the large bead mean is statistically insignificant. The alternative hypothesis (H_a) states that the difference between the standard bead mean and the large bead mean is statistically significant. This research establishes the significance level at $\alpha=0.05$. A probability value less than 0.05 indicates that the null hypothesis (H_o) should be rejected and the alternative hypothesis (H_a) should be accepted. In other words, a probability value less than 0.05 indicates that the researcher can be 95% confident that the difference between the sample means is due to a true difference between the populations.

The ANOVA procedure is parametric in nature. As such, the validity of the procedure is dependent upon the assumption that the data come from a particular probability distribution. In the case of the ANOVA, the assumption is that the data come from the normal probability distribution. If this assumption is not met, the results of the ANOVA are not valid and an alternative procedure to the ANOVA must be explored.

Wilcoxon Rank Sum Test

The Wilcoxon rank sum test is a non-parametric alternative to the ANOVA. In contrast to parametric tests, non-parametric test do not require assumptions that the data come from a particular probability distribution. Thus, this particular test is extremely useful when the data do not fit a normal distribution. In addition, non-parametric tests are considered more conservative than parametric tests due to the robustness against the influence of outliers (Newbold, Carlson, & Thorne, 2010).

In the Wilcoxon rank sum test, all observations from both samples are arranged in ascending order. A rank is assigned to each observation with the smallest observation receiving the rank of “1.” Ties are assigned the average of the next available ranks. Consequently, the sample median is used to describe the central tendency of the data rather than the mean. This is the key difference between the ANOVA and the Wilcoxon rank sum test. The ANOVA compares sample means while the Wilcoxon rank sum test compares sample medians (Newbold, Carlson, & Thorne, 2010).

The hypothesis test of the Wilcoxon rank sum test is similar to the hypothesis test of the ANOVA. The null hypothesis (H_o) states that the difference between the standard bead median and the large bead median is statistically insignificant. The alternative hypothesis (H_a) states that the difference between the standard bead median and the large bead median is statistically significant. This research establishes the significance level at $\alpha = 0.05$. A probability value less than 0.05 indicates that the null hypothesis (H_o) should be rejected and the alternative hypothesis (H_a) should be accepted. In other words, a probability value less than 0.05 allows the researcher to be 95% confident that the difference between the sample medians is due to a true difference between the populations.

Linear Regression Model

Linear regression was chosen to develop a performance model for thermoplastic pavement markings. The model was built using a statistical software package used primarily by practicing statisticians called JMP®. This particular software is accepted as an appropriate tool for pavement marking performance modeling (Sitzabee, Hummer, & Rasdorf, 2009; Mull & Sitzabee, 2011; Needham, 2011). The linear regression model is a simple model that is easy to construct, and it is easily understood by managers and practitioners alike. Additionally, several previous research efforts used linear regression to develop pavement marking performance models that are both accurate and useful (Mull & Sitzabee, 2011; Needham, 2011). The model is presented in the following basic form:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 \ldots + \beta_\rho x_\rho + \varepsilon$$

where,

y	=	Response variable
β_i	=	Regression coefficients
i	=	0, 1, 2, …, ρ
x_j	=	Regression variables
j	=	0, 1, 2, …, ρ
ε	=	Random error

In order for a linear regression model to be useful, three assumptions must be met. First, the model residuals of the dependent variable must be independent. Second, the model residuals of the dependent variable must be normally distributed. Third, the residual variances of the dependent variable must be equally distributed about the mean. The Shapiro-Wilk test and the Breusch-Pagan test were used to confirm whether or not the model residuals satisfy the latter two of these. The Shapiro-Wilk test was performed using JMP®, and the Breusch-Pagan test was performed using a Microsoft Excel® macro.

Summary of Three-Phase Methodology

This effort utilizes a three-phase approach to answer the questions of interest. First, an average value analysis is performed on paint and thermoplastic pavement markings. The intent of this phase is strictly to determine whether or not further investigation of the subject is beneficial. Second, the Wilcoxon rank sum test is performed on both paint and thermoplastic pavement markings to provide a valid statistical basis for the conclusions. The Wilcoxon rank sum test is used, rather than the standard ANOVA test, because of the ability to provide valid results for data originating from various population distributions. The significance level for the research is set at α = 0.05. Finally, an attempt is made to develop a degradation model for thermoplastic pavement markings that includes bead type as a significant variable. A linear regression model is constructed using JMP® statistical software package, and the model residual assumptions of normality and constant variance are tested using the Shapiro-Wilk and Breusch-Pagan tests. The results of each phase of the analysis are presented in Chapter 4.

IV. Results

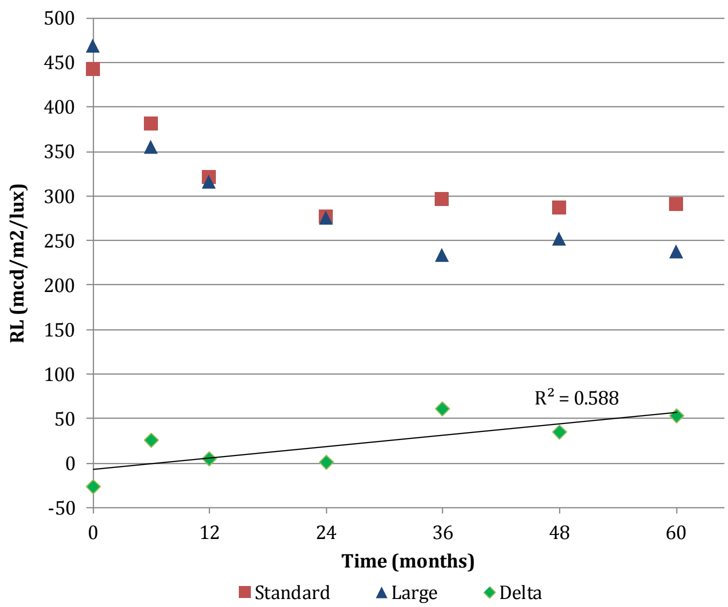
The purpose of this chapter is to present the results of this study. The chapter is organized into the three main phases of analysis: Average Value Analysis, Wilcoxon Rank Sum Test, and Proposed Performance model. The results of the average value analysis and Wilcoxon rank sum test are subsequently divided into the two marking material types of interest, thermoplastic and paint. Finally, the proposed performance model for thermoplastic pavement markings is described. The development of the model underwent two iterations, and the results of both attempts are presented.

Average Value Analysis

Thermoplastic

The data used to conduct the average value analysis consisted of all white thermoplastic markings on asphalt with a full compliment of data through 60 months. The resulting data set consisted of 20 records with large beads and 104 records with standard beads. A record consists of a continuous segment of roadway that is homogenous with respect to pavement marking material, material color, and road surface. Several records also contained retroreflectivity values for time intervals beyond 60 months. In order to achieve an appropriate sample size, an average retroreflectivity value was calculated and input into a "60+ months" category for each record. Consequently the sample size was consistent for each time interval for large beads and standard beads at 20 and 104, respectively.

Figure 8 shows the results from the average value analysis for thermoplastic markings. The average retroreflected luminance values at each time interval are plotted for thermoplastic markings with standard beads (squares) and large beads (triangles). The difference (delta) between the two values at each time interval is also plotted (diamonds). As expected, the retroreflected luminance values for both samples drop considerably over the first two years before leveling out around 250 mcd/m^2/lux for large beads and 300 mcd/m^2/lux for standard beads. The trend line shows the delta between the two populations to be increasing over time, indicating a potential for thermoplastic markings with large beads to degrade at a faster rate than thermoplastic markings with standard beads.



Time (months)	*0*	*6*	*12*	*24*	*36*	*48*	*60*
Standard	441	380	320	276	296	287	290
Large	468	355	315	275	234	252	237
Delta	-27	25	5	1	62	35	53

Notes:

1) Values given in mcd/m^2/lux

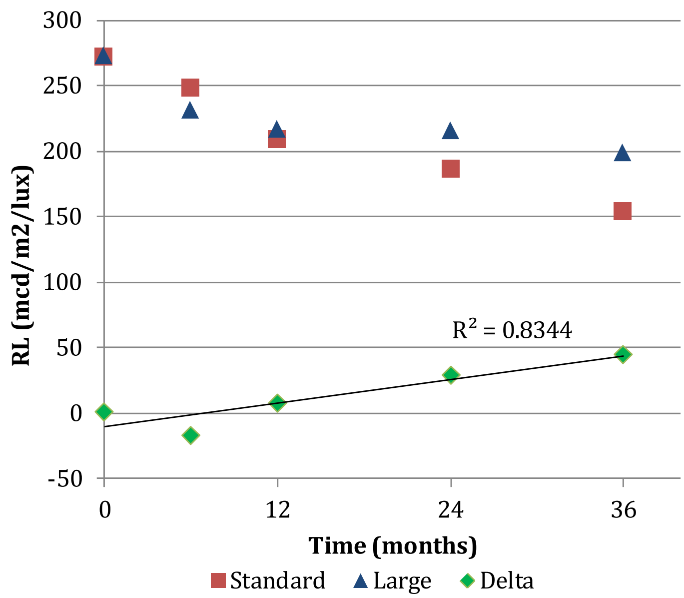
2) Values at 60 months represent 60+ months

Figure 8: Average Retroreflected Luminance (R_L) Values Over Time of Thermoplastic Pavement Markings

Paint

The data used to conduct the average value analysis consisted of all white paint markings on asphalt with a full compliment of data through 36 months. The resulting data set consisted of 12 records with large beads and 12 records with standard beads. Several records also contained retroreflectivity values for time intervals beyond 36 months. Previous research suggests that paint markings do not typically last much beyond three years (Sitzabee, Hummer, & Rasdorf, 2009). As such, an average retroreflectivity value was calculated and input into a "36+ months" category for each record. Consequently the sample size was consistent for each time interval for large beads and standard beads at 12.

Figure 9 shows the results from the Average Value Analysis for paint pavement markings. The average retroreflected luminance values at each time interval are plotted for paint markings with standard beads (squares) and large beads (triangles). The difference (delta) between the two values at each time interval is also plotted (diamonds). The trend line shows the delta between the two populations to be increasing over time, indicating a potential for paint markings with standard beads to degrade at a faster rate than paint markings with large beads.



Time (months)	*0*	*6*	*12*	*24*	*36*
Standard	271	248	208	186	154
Large	272	231	216	215	198
Delta	1	-17	8	29	44

Notes:

1) Values given in mcd/m^2/lux

2) Values at 36 months represent 36+ months

Figure 9: Average Retroreflected Luminance (R_L) Values Over Time of Paint Pavement Markings

The results of the average value analysis for both thermoplastic and paint pavement markings indicate that bead type may influence the degradation rate. However, further analysis is required to determine whether or not the difference is statistically significant. Initially, the standard ANOVA test was chosen to statistically validate the results; however, the assumption of normality was violated. Consequently, the Wilcoxon rank sum test was used to statistically validate the results derived from the average value analysis.

Wilcoxon Rank Sum Test

The Wilcoxon rank sum test was performed with the following null and alternative hypotheses:

- H_o Null Hypothesis: The difference between the standard bead median and the large bead median is statistically insignificant for all time periods;
- H_a Alternative Hypothesis: The difference between the standard bead median and the large bead median is statistically significant for all time periods.

If the p-value from the analysis is less than or equal to the level of significance of $\alpha=0.05$, there is sufficient statistical proof to reject the null hypothesis and accept the alternative hypothesis.

The data used in this research are field data. As such, there are several limitations that must be considered. One primary limitation is the disparity between the number of records with standard beads and those with large beads. A large majority of the data come from pavement markings with standard beads. Consequently, the analysis is limited by the amount and type of data drawn from pavement markings with large beads. For example, all the data representing thermoplastic pavement markings with large beads are drawn from areas that experience snow plow operations. However, the data representing thermoplastic markings with standard beads are drawn from areas that experience snow plow operations and areas that do not. Including records from both categories would not be a fair comparison. This limitation was considered and addressed for the analysis of both thermoplastic and paint pavement markings, and the details are presented in the respective sections.

Thermoplastic

Before performing the Wilcoxon rank sum test on thermoplastic markings, the data set was refined to only include records with the following four characteristics:

Color:	White
Snow Plow Area:	Yes
Thickness:	90/120 mil
Surface Material:	Asphalt

Color is known to significantly influence retroreflected luminance values (Migletz & Graham, 2002). White markings were used in the analysis due to a larger sample size. For thermoplastic markings with large beads, data were only recorded for markings with a thickness of 90/120 mil, on an asphalt surface, and located in areas that experience snow plow operations. Therefore, the standard bead data set was limited to only include records with similar characteristics. Table 5 shows the summary statistics for the data set used in the analysis.

Table 5: Summary Statistics for Thermoplastic Pavement Markings

Time (Months)	Mean (mcd/m^2/lux)		Median (mcd/m^2/lux)		SD (mcd/m^2/lux)		Range of Values (mcd/m2/lux)		Sample Size	
	Standard	*Large*	*Standard*	*Large*	*Standard*	*Large*	*Standard*	*Large*	*Standard*	*Large*
0	432	462	442	473	81	54	224 - 614	328 - 563	269	22
6	401	371	387	370	103	69	199 - 662	242 - 528	186	34
12	352	328	342	334	115	59	151 - 622	215 - 433	159	30
24	299	257	296	233	69	59	162 - 498	193 - 443	157	30
36	306	223	298	204	61	61	184 - 482	127 - 383	141	28
48	319	244	321	234	73	47	127 - 457	169 - 364	119	24
60	313	237	319	209	62	73	164 - 407	170 - 414	74	24
72	296	244	309	229	60	35	192 - 375	206 - 313	30	12

The analysis compares the median retroreflected luminance values for thermoplastic pavement markings with large beads and those with standard beads at each of the following time intervals: 0, 6, 12, 24, 36, 48, and 60 months. As shown in Table 5, the sample size for thermoplastic pavement markings with large beads at 72 months is only twelve. Consequently, data for the 72 month time interval is not sufficient to draw conclusive results, and it was removed from the analysis.

Figure 10 shows the behavior trends of thermoplastic pavement markings over time. The median retroreflected luminance value at each time interval is plotted for thermoplastic markings with standard beads (squares) and large beads (triangles). The difference (delta) between the two values at each time interval is also plotted (diamonds).

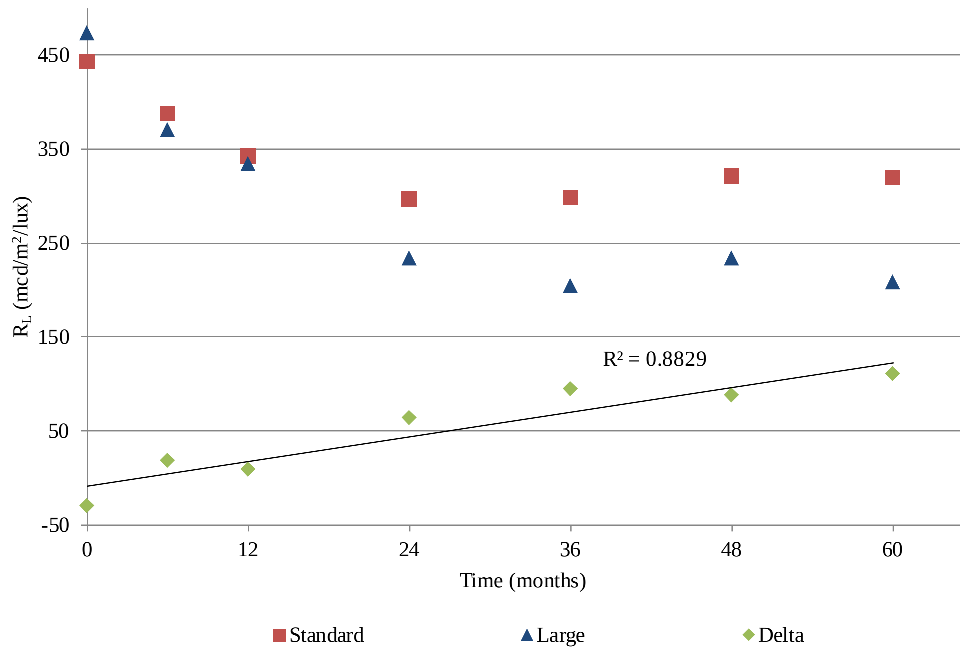


Figure 10: Median Retroreflected Luminance (R_L) Values Over Time of Thermoplastic Pavement Markings

Table 6 shows the results of the Wilcoxon rank sum test for thermoplastic pavement markings. Values that are highlighted in black meet or exceed the confidence level of 95% and indicate a statistically significant difference between the two population medians at the given time interval. Values that are highlighted in grey do not indicate a statistically significant difference between the two population medians at a confidence level of 95%, but they do indicate a statistically significant difference between the two population medians at a confidence level of 90%. Values that are not highlighted indicate that the difference between the two population medians is statistically insignificant.

Table 6: Wilcoxon Rank Sum Test Results for Thermoplastic Pavement Markings

		0	6	12	24	36	48	60
Standard	**Median**	442.0	387.0	342.0	296.0	298.0	321.0	318.5
	n	*269*	*186*	*159*	*157*	*141*	*119*	*74*
Large	**Median**	472.5	369.5	333.5	233.0	204.0	234.0	208.5
	n	*22*	*34*	*30*	*30*	*28*	*24*	*24*
	Delta	-30.5	17.5	8.5	63.0	94.0	87.0	110.0
	P-value	0.0956	0.1261	0.4502	0.0005	0.0001	0.0001	0.0001

Notes:
1) H_o: R_L of standard beads = R_L of large beads
2) H_a: R_L of standard beads ≠ R_L of large beads
3) p-values below 0.05 are highlighted in black
4) p-values between 0.05 and 0.10 are highlighted in grey

The results indicate that thermoplastic markings with large beads degrade differently than thermoplastic markings with standard beads. We are 90% confident that, initially, thermoplastic pavement markings with large beads perform better than those with standard beads. However, when the markings reach 6 to 12 months, the performance between large beads and standard beads is essentially the same. Once the markings reach 24 months and beyond, we are 99% confident that markings with standard beads begin to out-perform those with large beads.

Paint

Before performing the Wilcoxon rank sum test on paint markings, the data set was refined to only include records with the following four characteristics:

Color:	White
Snow Plow Area:	No
Thickness:	15-16 mil
Surface Material:	Asphalt

Color is known to significantly influence retroreflected luminance values (Migletz & Graham, 2002). White markings were used in the analysis due to a larger sample size. For paint markings with large beads, data were only recorded for markings with a thickness of 15-16 mil, on an asphalt surface, and located in areas that do not experience snow plow operations. Therefore, the standard bead data set was limited to only include records with similar characteristics. Table 7 shows the summary statistics for the data set used in the analysis.

Table 7: Summary Statistics for Paint Pavement Markings

Time (Months)	Mean ($mcd/m^2/lux$)		Median ($mcd/m^2/lux$)		SD ($mcd/m^2/lux$)		Range of Values (mcd/m2/lux)		Sample Size	
	Standard	*Large*	*Standard*	*Large*	*Standard*	*Large*	*Standard*	*Large*	*Standard*	*Large*
0	332	317	318	316	68	61	153 - 509	140 - 424	141	71
6	244	245	241	230	44	49	177 - 325	176 - 332	20	16
12	205	221	203	204	51	55	136 - 323	166 - 364	18	14
24	172	215	175	198	40	54	104 - 239	157 - 334	16	10
36	144	209	128	200	44	46	77 - 205	142 - 291	10	8
48	N/A	219	N/A	212	N/A	85	N/A	107 - 332	0	6

The analysis compares the median retroreflected luminance values for paint pavement markings with large beads and those with standard beads at each of the following time intervals: 0, 6, 12, 24, and 36 months. As shown in Table 7, the sample size for paint pavement markings with standard beads at 48 months is zero. This is to be expected due to previous research showing the average service life of paint pavement markings to be slightly beyond two years (Sitzabee, Hummer, & Rasdorf, 2009). Consequently, the analysis was limited to 36 months.

Figure 11 shows the behavior trends of paint pavement markings over time. The median retroreflected luminance value at each time interval is plotted for paint markings with standard beads (squares) and large beads (triangles). The difference (delta) between the two values at each time interval is also plotted (diamonds).

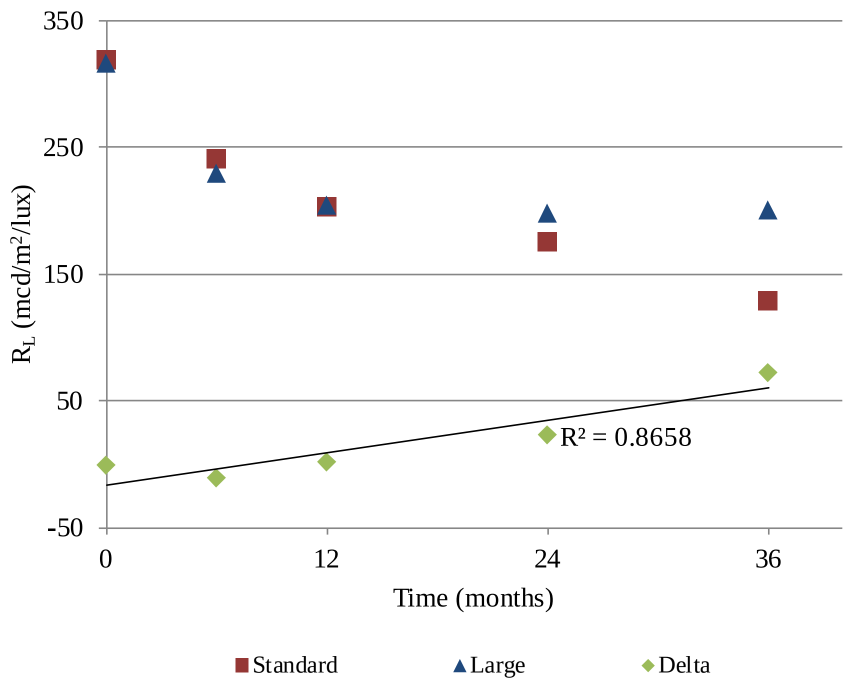


Figure 11: Median Retroreflected Luminance (R_L) Values Over Time of Paint Pavement Markings

Table 8 shows the results of the Wilcoxon rank sum test for paint pavement markings. Values that are highlighted in black meet or exceed the confidence level of 95% and indicate a statistically significant difference between the two population medians at the given time interval. Values that are highlighted in grey do not indicate a statistically significant difference between the two population medians at a confidence level of 95%, but they do indicate a statistically significant difference between the two population medians at a confidence level of 90%. Values that are not highlighted indicate that the difference between the two population medians is statistically insignificant.

Table 8: Wilcoxon Rank Sum Test Results for Paint Pavement Markings

		0	6	12	24	36
Standard	**Median**	318.0	240.5	202.5	175.0	128.0
	n	*141*	*20*	*18*	*16*	*10*
Large	**Median**	316.0	229.5	203.5	198.0	199.5
	n	*71*	*16*	*14*	*10*	*8*
	Delta	-2.0	-11.0	1.0	23.0	71.5
	P-value	0.1872	0.9619	0.6079	0.0543	0.0208

Notes:
1) H_o: R_L of standard beads = R_L of large beads
2) H_a: R_L of standard beads ≠ R_L of large beads
3) p-values below 0.05 are highlighted in black
4) p-values between 0.05 and 0.10 are highlighted in grey

The results indicate that paint markings with large beads degrade differently than paint markings with standard beads after the first year. The difference between the two population medians is statistically insignificant during the first 12 months. However, we are 90% confident that paint pavement markings with large beads begin to perform better than those with standard beads at 24 months. Once the markings reach 36 months, we are nearly 98% confident that markings with large beads continue to out-perform those with standard beads. Although the strength of the results is decreased due to sample sizes less than 20, the results are strong enough to conclude that bead type does have some impact on paint pavement markings.

Thermoplastic Performance Model

Based on the results of the Wilcoxon rank sum test for thermoplastic pavement markings, an attempt was made to construct a regression model for thermoplastics that accounts for bead type. The average value analysis and Wilcoxon rank sum test also indicate that bead type may impact the degradation rate of paint pavement markings. However, a degradation model for paint pavement markings was not developed in this research due to limitations of the data.

The data used to construct the model consist of 482 road segments totaling 2,700 lane miles of thermoplastic pavement markings on an asphalt concrete surface. Previous research suggests that snow plow operations impact degradation rate, and this data set only includes large bead pavement markings located in areas that experience snow plow operations (Mull & Sitzabee, 2011). Consequently, the data is limited to pavement markings located in areas that experience snow plow operations. Additionally, the data consist of 67% white markings and 33% yellow markings; 60% edge lines and 40% center lines.

The proposed variables to be included in the model were AADT, bead type, color, initial R_L value, lateral line placement, and time. A stepwise insertion of the variables was deemed unnecessary due to previous research that found each of the variables to be significant variables. Table 9 provides a definition of each proposed variable.

Table 9: Varible Definitions

Variable	Definition
AADT	Average Annual Daily Traffic: estimation of how many vehicle passes will be on a section of road
Bead type	Standard Beads vs. Large Beads
Color	White vs. Yellow
Initial RL value	Initial retroreflectivity value calculated within 30 days of marking installation
Lateral line placement	Position of marking on road; edge line vs. center line
Time	Number of months since marking installation

AADT

The AADT values contained in this data set ranged from less than 10,000 passes per day to more than 100,000 passes per day, Previous research concludes that the retroreflectivity of a marking will degrade faster as the number of vehicle passes increase (Migletz & Graham, 2002). AADT was entered into the model as a continuous variable, and it was found to be significant with a p-value <0.0001.

Bead Type

This data set consisted of either standard beads or large beads. The previous results of this research support the inclusion of this variable into the model for thermoplastics. As such, bead type was entered into the model as a dummy variable where large beads receive a “one” and standard beads receive a “zero.” It was found to be significant with a p-value <0.0001.

Color

The pavement markings of interest are either yellow or white. Previous research shows that white markings typically have a higher retroreflectivity value than yellow markings when all other factors are the same (Migletz & Graham, 2002). Color was entered into the model as a dummy variable where yellow markings received a “one” and white markings received a “zero.” It was found to be significant with a p-value <0.0001. However, the results indicated possible multicollinearity between color and initial RL value. This is expected because the initial RL value of white markings is known to be significantly higher than the initial RL value of yellow markings (Sarasua, Clarke, & Davis, 2003). Removing color from the model fixed the multicollinearity issues, but the predictability of the model decreased. Because the variable did not exceed our level of tolerance for multicollinearity, color remained in the model.

Initial R_L Value

Initial R_L Value represents the retroreflectivity value taken within 30 days of the marking’s installation. Previous research shows that a marking with a higher initial R_L value will typically result in a higher R_L value at some given time (Migletz & Graham, 2002). It was entered into the model as a continuous variable, and it was found to be statistically significant with a p-value <0.0001.

Lateral Line Placement

Lateral line placement represents the lateral position of the marking on the road segment. The marking is either an edge line or a center line. Previous research suggests that center lines degrade faster than edge lines (Craig, Sitzabee, Rasdorf, William, & Hummer, 2007). Lateral Line Placement was entered into the model as a dummy variable where edge lines received a “one” and center lines received a “zero.” It was found to be statistically significant with a p-value <0.0001.

Time

Time represents the number of months that have passed since installation. While time itself does not directly impact degradation models, it does act as a surrogate variable for UV radiation, hail damage, and other environmental exposure factors. Time was entered into the model as a continuous variable, and it was found to be statistically significant with a p-value <0.0001.

Initial Model

The data set included 1,364 observations, and all proposed variables were found to be statistically significant. Table 10 lists the parameter estimates for each of the significant variables. The resulting regression model had an adjusted R^2 of 0.50 and is presented below:

$$R_L = 244.9 - 0.0006 * AADT - 55.10 * Bead_{DV} - 71.17 * Color_{DV}$$

$$+0.28 * Initial\ R_L + 44.06 * LP_{DV} - 1.28 * Time$$

where,

R_L	=	Retroreflectivity level in mcd/m^2/lux
AADT	=	Average Annual Daily Traffic count
$Bead_{DV}$	=	Bead Type [1=large; 0 = standard]
$Color_{DV}$		Marking color [1 = yellow; 0 = white]
Initial R_L		Initial retroreflectivity level in mcd/m^2/lux
LP_{DV}		Lateral line location [1 = edge line; 0 = center line]
Time	=	Number of months since installation

Table 10: Parameter Estimates for Initial Model

Variable	Significance	β Estimate	t Ratio	Std Beta	Influence	VIF
Intercept	*< 0.0001*	*244.8500*	*16.64*	*0.000*		
Color	< 0.0001	-71.1747	-10.06	-0.338	22%	3.096
Initial RL value	< 0.0001	0.2798	8.52	-0.292	19%	3.231
Time	< 0.0001	-1.2794	-13.62	-0.262	17%	1.018
Lateral line placement	< 0.0001	44.0616	11.41	0.218	14%	1.002
AADT	< 0.0001	-0.0006	-10.29	-0.204	13%	1.075
Bead type	< 0.0001	-55.0953	-10.06	-0.198	13%	1.067

The Shapiro-Wilk test returned a p-value of < 0.0001 causing us to reject the null hypothesis that the residuals are normally distributed. However, visual inspection of a normal curve fitted to the distribution of residuals supports the decision to accept the null hypothesis that the data are from a normally distributed population. Additionally, the Q-Q plot of the residuals fits a relatively straight line except for a slight trailing in the tail. Consequently, the failed Shapiro-Wilk test is most likely due to an algorithm that causes the software to treat the large sample of data as a population. Any deviation from the normal distribution would cause the software to reject the null hypothesis. Recognizing data from the field are subject to more deviation a slight deviation from normality of the model is accepted. Figure 12 shows the distribution and Q-Q plot of the residuals for the initial model.

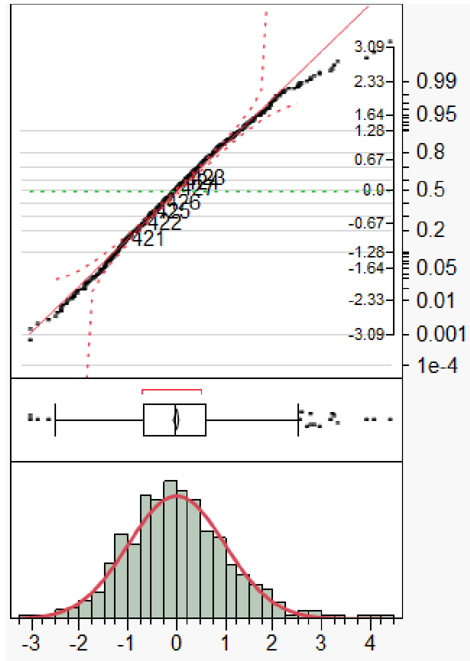


Figure 12: Distribution and Q-Q Plot of Residuals - Initial Model

The model was also subjected to the Breusch-Pagan test for constant variance. The result was a p-value < 0.0001 causing us to reject the null hypothesis that the data have constant variance. If the model does have constant variance, the residuals should be evenly distributed about the mean. The fanlike shape shown in Figure 13 of the Residuals versus Predicted Plot confirms that the model does not have constant variance.

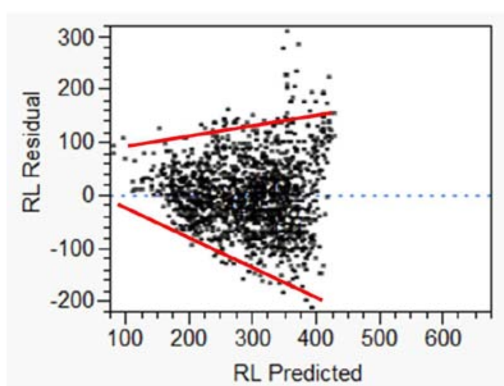


Figure 13: Residuals vs. Predicted Plot – Initial Model

Overall, the model included six variables and produced an adjusted $R^2 = 0.50$. However, previous thermoplastic degradation models produced similar adjusted R^2 values with fewer variables (Abboud & Bowman, 2002; Sitzabee, Hummer, & Rasdorf, 2009). When two models with a similar predictive characteristics are compared, the model with fewer variables is often more useful. While other models may be better suited for generic predictions of thermoplastic markings, none of the previous models distinguish between bead types. This model is useful for quantifying the impact that bead type has on thermoplastic pavement markings. Although the model's ability to consider bead type does make it useful for comparing pavement markings with different types of beads, it does not meet the assumption of constant variance.

Final Model

Upon further examination of the initial model, it was decided to perform a transformation of the response using the natural log function. Rather than using the actual retroreflectivity values, the natural log is taken for each value of R_L. The natural log transformation is a common technique used to make linear regression models with normality and constant variance problems more useful, but it does introduce some limitations during the back transformation. The process of transforming the natural log of the predicted values back to the original form causes the confidence interval to expand. Despite this limitation, the model is still more useful than a model that does not meet the assumptions of normality and constant variance.

The data set was not altered in any way, and the model included 1,364 observations. All proposed variables were found to be statistically significant, and Table

11 lists the parameter estimates for each of the significant variables. The resulting regression model had an adjusted R^2 of 0.53 and is presented below:

$$\ln (R_L) = 5.5002 - 0.000002 * AADT - 0.1861 * Bead_{DV} - 0.2975 * Color_{DV}$$
$$+0.0008 * Initial\ R_L + 0.1528 * LP_{DV} - 0.0039 * Time$$

where,

R_L	=	Retroreflectivity level in mcd/m^2/lux
AADT	=	Average Annual Daily Traffic count
$Bead_{DV}$	=	Bead Type [1=large; 0 = standard]
$Color_{DV}$		Marking color [1 = yellow; 0 = white]
Initial R_L		Initial retroreflectivity level in mcd/m^2/lux
LP_{DV}		Lateral line location [1 = edge line; 0 = center line]
Time	=	Number of months since installation

Table 11: Parameter Estimates for Final Model

Variable	Significance	β Estimate	t Ratio	Std Beta	Influence	VIF
Intercept	*< 0.0001*	*5.500E+00*	*112.57*	*0.000*		
Color	< 0.0001	-2.975E-01	-12.66	-0.412	28%	3.096
Initial RL value	< 0.0001	8.292E-04	7.60	0.253	17%	3.231
Time	< 0.0001	-3.930E-03	-12.60	-0.235	16%	1.018
Lateral line placement	< 0.0001	1.528E-01	11.92	0.221	15%	1.002
Bead type	< 0.0001	-1.861E-01	-10.23	-0.196	13%	1.067
AADT	< 0.0001	-1.874E-06	-9.03	-0.173	12%	1.075

Again, the Shapiro-Wilk test returned a p-value <0.0001 causing us to reject the null hypothesis that the residuals are normally distributed. However, as previously mentioned, this is due to the software treating the large sample size as a population. A visual inspection of the distribution of the residuals was performed. Furthermore, an examination of the Q-Q plot of the residuals reveals a relatively good fit of the data to a straight line. A visual inspection of the two tools in Figure 14 validates the assumption of normality for the model.

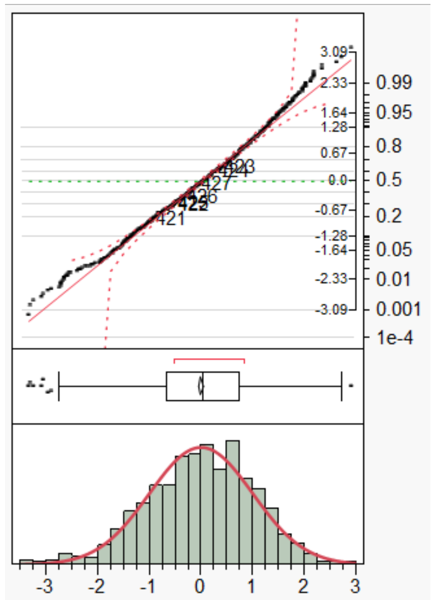


Figure 14: Distribution and Q-Q Plot of Residuals - Final Model

The Breusch-Pagan test for constant variance also returned a p-value <0.0001 causing us to reject the null hypothesis that data have constant variance. However, a visual inspection of the Residuals versus Predicted Plot in Figure 15 supports a decision to accept the null hypothesis that the data have constant variance. Note that the fanlike plot seen in Figure 13 has been replaced with an even distribution of the residuals about the mean, thus confirming the null hypothesis that the data have constant variance.

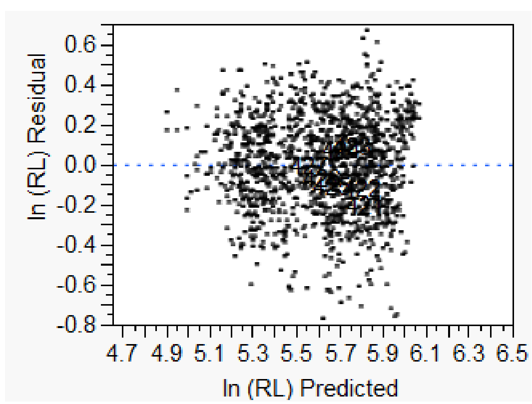


Figure 15: Residuals vs. Predicted Plot - Final Model

Overall, the final model included six variables and produced an adjusted R^2 = 0.53. The final model is slightly more predictive than the initial model, and it satisfies both assumptions of normality and constant variance. However, the final model is limited by the transformation of the predicted retroreflectivity values back to the original form. Additionally, the final model still does not compete with previously developed degradation models that contain fewer variables and are equally as predictive (Abboud & Bowman, 2002; Sitzabee, Hummer, & Rasdorf, 2009). However, existing thermoplastic degradation models do not consider bead type as a significant variable, and they do not assist in understanding the impact that bead type has on degradation models. Thus, the final model is a valid and useful for the purposes of this research.

Summary of Results

The results of the Average Value Analysis and Wilcoxon rank sum test confirm that there is a statistically significant difference in the rate of retroreflectivity degradation between standard beads and large beads for both thermoplastic and paint pavement markings. For thermoplastic markings, the Wilcoxon rank sum test indicates that there is at least a 90% chance that standard bead markings are outperformed by large bead markings initially. However, the analysis indicates that there is a 99% chance that standard bead markings outperform large bead markings from the second year on. For paint markings, the Wilcoxon rank sum test indicates that there is at least a 90% chance that large bead markings outperform standard bead markings at two years and beyond. However, previous research suggests that paint markings are non-durable markings that, in general, are not expected to last much more than two years (Sitzabee, Hummer, &

Rasdorf, 2009). Further research that observes paint markings at more frequent intervals may provide more conclusive results.

The results for thermoplastics merited further investigation on how to incorporate bead type as a significant variable into degradation models. The regression analysis found the following variables to be significant: AADT, bead type, color, initial R_L value, lateral line placement, and time. The initial model produced an adjusted R^2 value of 0.50 and violated the assumption of constant variance. Further investigation led to a second model which used the natural log transformation. The final model produced an adjusted R^2 value of 0.53 and satisfied both assumptions of normality and constant variance. The ability of the final model to accurately predict retroreflectivity is somewhat reduced when the predicted retroreflectivity values are transformed back to the original form, but it remains superior to the initial performance model that violated the assumption of constant variance. Additionally, existing thermoplastic degradation models use fewer variables and are equally as predictive, but they do not consider bead type as significant variable (Abboud & Bowman, 2002; Sitzabee, Hummer, & Rasdorf, 2009). The final performance model presented in this research is valid and useful for the purposes of this research.

V. Conclusions

The purpose of this chapter is to present the conclusions of this research effort. The chapter is organized into three main sections: Research Questions, Significant Findings for Asset Managers, and Future Research. The first section demonstrates how the results of the study specifically satisfy the research questions presented in Chapter 1. The second section presents the significant findings of this research that are particularly applicable to asset managers. The final section highlights the limitations of this research in order to identify areas for future research.

Research Questions

The primary thrust behind this research effort is to answer the question, "Does bead type impact the degradation rate of paint and thermoplastic pavement markings?" As expected, this research provides significant statistical evidence that bead type does impact the degradation rate of both paint and thermoplastic pavement markings. Specifically, the research sought to answer the following three questions which are answered in further detail:

1. Do thermoplastic pavement markings with standard beads degrade differently than those with large beads?
2. Do paint pavement markings with standard beads degrade differently than those with large beads?
3. Should bead type be considered a significant variable in future degradation models?

Research Question #1

This research suggests that thermoplastic markings with large beads degrade faster than those with standard beads in areas that experience routine snow plow operations. We are 90% confident that markings with large beads are, generally, more retroreflective than markings with standard beads during the first six months. This coincides with the theory that large beads provide more retroreflectance than standard beads due to a higher bead profile. However, this research suggests that the retroreflectivity of large bead markings degrades at a faster rate than that of standard bead markings. Once thermoplastic markings reach a service life of 24 months, we are 99% confident that markings with standard beads are more retroreflective than markings with large beads. The most plausible explanation for this phenomenon is that the higher profile of large beads increases the chances of beads becoming dislodged during traffic passes and snow plow operations. Consequently, this research suggests that, in areas that routinely experience snow plow operations, thermoplastic markings with standard beads have a longer service life than those with large beads.

Research Question #2

This research suggests that, in areas that do not experience snow plow operations, paint markings with standard beads degrade faster than those with large beads. Paint markings with large beads perform identical to markings with standard beads during the first 12 months of service life. Once paint markings reach a service life of 24 months, we are 90% confident that markings with large beads are more retroreflective than markings with standard beads. However, paint markings are typically near the end of their service life by 24 months (Sitzabee, Hummer, & Rasdorf, 2009). Therefore, for all intents and purposes, the impact that bead type has on the degradation rate of paint markings is negligible in areas that do not experience snow plow operations.

Research Question #3

This research provides statistically significant evidence that bead type should be included as a significant variable in future degradation models for thermoplastic markings. The average value analysis and Wilcoxon rank sum test both confirm the hypothesis that bead type does impact the degradation rate of thermoplastic markings. Furthermore, bead type was found to be a significant variable in the proposed performance model. Although the model itself is not as useful as existing models in predicting the degradation rate of thermoplastic markings, it does provide sufficient evidence to merit the inclusion of bead type as a significant variable in future models. Due to limitations in the field data, this research effort does not conclusively answer this question for paint markings. There is statistical evidence that bead type does impact the degradation rate of paint markings, but the extent of the impact is not fully understood. Further details regarding this limitation are discussed in Future Research.

Significant Findings for Asset Managers

This research concludes that thermoplastic markings with standard beads outperform those with large beads in areas that experience snow plow operations. Cost data from the NCDOT indicate that 4” thermoplastic pavement markings with standard beads are approximately $0.10 cheaper than those with large beads (Howard, 2012). Clearly, it is more economical to use thermoplastic markings with standard beads which cost less and perform better. Consider the impact of this finding for a best case and worst case scenario in North Carolina.

The NCDOT ensure the quality of pavement markings by designating a minimum initial retroreflectivity value depending on color. White markings require an initial retroreflectivity value of 375 mcd/m^2/lux. Yellow markings require an initial retroreflectivity value of 250 mcd/m^2/lux. Using the model presented in this research, the initial retroreflectivity specifications, and the proposed minimum retroreflectivity standards presented in Table 2, one is able to calculate the service life of markings under a variety of conditions. This example will consider two cases. Case A represents yellow thermoplastic center lines that are exposed to high traffic volumes (100,000 veh/day/year). These markings are likely to have the shortest service life. Case B represents white thermoplastic edge lines that are exposed to low traffic volumes (10,000 veh/day/year). These markings typically have longer service lives. In both cases, the minimum retroreflectivity value is set at 100 mcd/m^2/lux. Table 12 highlights the predicted service life for both cases.

Table 12: Thermoplastic Service Life Estimates for Two Cases

	Service Life *(years)*	
Case	**Standard**	**Large**
Case A - Yellow center line, high AADT	13	9
Case B - White edge line, low AADT	28	24

Due to the different service life of each marking type, the initial costs cannot be compared directly. Instead, the installation cost must be evenly distributed across the service life at a given interest rate to compute the Equivalent Annual Cost (EAC) for each pavement marking type. The interest rate is also known as the marginally accepted rate of return (MARR), and for the purposes of this study, it will be established at 10%. The EAC can easily be computed using the following equation:

$$EAC = (Initial\ Installation\ Cost) * \left(\frac{i(1+i)^n}{(1+i)^n - 1}\right)$$

where,

i = Marginally Accepted Rate of Return (MARR)

n = Estimated service life in years rounded down to the nearest integer

The EAC for both cases is displayed in Table 13. The results of this research coupled with the NCDOT installation specifications and the proposed MUTCD minimum retroreflectivity standards indicate a potential savings of $80 to $190 per year per linear mile of pavement marking. The magnitude of this savings is fully realized when applied to the North Carolina roadway system. Thermoplastic markings make up 23% of the 312,000 linear miles of state maintained pavement markings (Sitzabee, Hummer, & Rasdorf, 2009). A savings of $80 to $190 per year per linear mile of pavement marking applied to 72,000 miles of thermoplastic markings results in a potential annual savings of $5.8M to $13.7M for the state of North Carolina.

Table 13: Equivalent Annual Cost Comparison

	Case A *yellow, center, high AADT*		**Case B** *white, edge, low AADT*	
	Standard	**Large**	**Standard**	**Large**
Service Life *(years)*	13	9	28	24
Cost per foot	$0.46	$0.58	$0.46	$0.58
Cost per mile	$2,428.80	$3,062.40	$2,428.80	$3,062.40
EAC	$341.92	$531.76	$260.98	$340.84
Potential Savings	**$190**		**$80**	

MARR = 10%

Future Research

It is noteworthy that the impact of bead type on the two marking materials is drastically different. However, one should be cautious to simply conclude from this research that standard beads are preferred for thermoplastic markings and large beads are preferred for paint markings. Due to the limitations of the field data used in this study, the analysis is limited to thermoplastic markings which are exposed to snow plow operations and paint markings which are not exposed to snow plow operations. This limitation influences the applications of the research conclusions and highlights a need for future research.

Currently, research concerning the impact of bead type on pavement marking degradation is limited to paint, thermoplastics, and polyurea (Needham, 2011). However, little research considers the impact of bead type on other materials such as epoxy and preformed tape. Future research should investigate the impact of bead type on other marking materials. Additionally, similar research efforts should be conducted in other states and regions of the country.

Furthermore, additional research is needed to fully understand the impact of bead type on paint and thermoplastic pavement markings. The data used in this research were limited to thermoplastic markings that experience snow plow operations and paint pavement markings that do not experience snow plow operations. Future research should consider a design of experiments that better isolates the impact of bead type across a variety of environments.

Another limitation of this research, as it relates to paint pavement markings, is the frequency of data collection intervals. Annual data collection for paint pavement markings is insufficient considering the relatively short service life of non-durable pavement markings. More frequent data collection intervals would provide a more complete understanding of paint pavement markings. Future research efforts focused on paint pavement markings should collect data at least semi-annually if not monthly.

Finally, future research should investigate the impact of bead type on pavement markings under wet conditions. Large beads are expected to perform better than standard beads in wet conditions due to the higher profile (Virginia Department of Transportation, 2011). The data used in this research do not specify the weather conditions of the data collection day. Thus, this research effort does not compare the performance of large beads and standard beads under varying conditions of wetness.

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14. ABSTRACT
Each year the United States spends approximately two billion dollars maintaining pavement markings. Additionally, an impending Federal policy establishing a minimum retroreflectivity value for pavement markings has driven asset managers to develop performance models in order to effectively and efficiently manage these high quantity, low cost assets. Research over the past decade has sought to identify and understand the many factors influencing pavement marking degradation. Despite the fact that reflective glass beads are foundational to pavement marking retroreflectivity, little research has specifically considered the impacts of bead type. The purpose of this study is to quantify the impact that bead type has on the degradation rate of paint and thermoplastic pavement markings in North Carolina. The results of an average value analysis and Wilcoxon rank sum test support the inclusion of bead type as a significant variable in future degradation models and the following two key findings. First, there is a statistically significant difference in the rate of retroreflectivity degradation between standard beads and large beads for both thermoplastic and paint pavement markings. Second, thermoplastic pavement markings with standard beads are more economical than those with large beads in areas that experience snow plow operations.

15. SUBJECT TERMS
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