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DEGRADATION MODELING OF POLYUREA PAVEMENT MARKINGS

THESIS

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AFIT/GEM/ENV/11-M05

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AFIT/GEM/ENV/11-M05

DEGRADATION MODELING OF POLYUREA PAVEMENT MARKINGS

THESIS

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DEGRADATION MODELING OF POLYUREA PAVEMENT MARKINGS

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Abstract

Polyurea is a long-life pavement marking material used for assets requiring long periods of uninterrupted accessibility. Knowing the performance characteristics of such markings is critical to asset management planning focused on maximizing marking material life-cycles. This paper presents the performance characteristics of polyurea pavement markings in North Carolina using linear regression models. This research constructed performance models for polyurea based on the independent variables of time, initial retroreflectivity, and lateral line location. The models generated by this research provide pavement marking managers with tools to better allocate limited manpower and resources in order to optimize budgets while meeting newly proposed pavement marking retroreflectivity levels of service as proposed by the Federal Highway Administration. Using the models generated by this research, the pavement marking manager can predict the level of service and remaining life of a given pavement marking. A key finding of this paper is that polyurea pavement marking degradation is significantly impacted by the type of glass bead inserted into the marking.

Acknowledgements

I would like to express my sincere appreciation to my research advisor, Lt Col William Sitzabee for his support and expertise throughout this thesis effort. His guidance and knowledge of this subject matter was instrumental in the completion of this research. I would also like to thank the North Carolina Department of Transportation for their sponsorship and generous provision of the data used in this research, without which this research would have not been possible.

I am also indebted to Dr. Edward White for his willingness to repeatedly explain the processes involved in statistical modeling as well as Dr. Al Thal for his professionalism and assistance in the construction of this document.

Jonathan D. Needham

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Chapter 1: Introduction

Introduction

Departments of Transportation (DOTs) across the United States are engaged in a perpetual cycle of removal and replacement of pavement markings. These everyday assets within our nation's infrastructure are often overlooked and taken for granted by the general public. However, this oversight and lack of awareness by the average citizen does not make these assets any less important. The quality of these pavement markings is absolutely critical in keeping the efficiency and safety of our public road system at its peak performance and is based on pavement marking retroreflectivity. In order to meet the goals of efficiency and safety set by each DOT, a proper management plan must be in place by which this cycle of removal and replacement is made most effective, both cost-wise and safety-wise.

Retroreflectivity, commonly abbreviated as R_L, degradation models are the basis of performance-based modeling and critical to predicting the life-cycles of various types of pavement markings. Knowing when a particular marking material is likely to fall below proposed minimum accepted R_L standards will allow DOTs to create a plan to replace the material at the proper time. Without degradation models, it is simply a subjective approach as to when a given marking needs to be replaced.

The North Carolina Department of Transportation (NCDOT) has taken an active approach to satisfy the need for degradation models by sponsoring research in this area. NCDOT collected an extensive eight year data set containing thousands of retroreflectivity data points. This research effort will be a continuation of ongoing research, further utilizing this extensive data set.

The degradation models presented in this thesis can readily be used by pavement marking managers to better allocate resources and manage pavement parking plans. DOTs, military installations, or other organizations wishing to further their understanding of pavement marking degradation can quickly and easily gain insight through the analysis of the results presented here. While the models directly relate only to polyurea pavement markings, the methodology applies to pavement markings of every type.

Background

Through review of relative literature, it was made clear that construction of degradation models can greatly assist in the management of pavement markings (Sasidharan, Vishesh, and Donnell 2009; Sitzabee, Hummer, and Rasdorf 2009). Through continued research, dating back to 1988, many variables have been identified as significantly impacting pavement marking degradation (Lee, Maleck, and Taylor 1999; J. Migletz et al. 2001; Sitzabee, Hummer, and Rasdorf 2009). Each study examined in this thesis effort provided insight into the nature of pavement marking degradation and encouraged future research in this area. While the significance of this research has yet to be fully realized, the application of this research in asset management programs has tremendous potential. By constructing a degradation model for polyurea pavement markings, this research will add a tool to the field of pavement marking management.

Objective and Scope

Degradation models currently exist for waterborne paint and thermoplastic pavement markings, which make up the majority, but not all, of pavement markings nationwide (Sitzabee et al. 2009, Sarasua et al. 2003). Other materials, such as polyurea and epoxy, are common yet do not have acceptable degradation models which can accurately predict their life-cycles. This research focuses on polyurea, the fourth most common material used in North Carolina, after waterborne paint, thermoplastics, and epoxy (Sitzabee, Hummer, and Rasdorf 2009).

This research will take an extensive data set collected in the state of North Carolina and construct a degradation model from that data for polyurea. This model, coupled with the thermoplastic and paint models constructed by Sitzabee et al. (2009) will provide NCDOT with more complete information with which to construct effective pavement marking asset management plans. The use of this additional model will potentially save thousands of taxpayer dollars while maintaining or exceeding current NCDOT minimum safety standards. Specifically, this research will:

- Formulate a service life degradation model for polyurea
- Provide examples of how the resulting models can be used by asset managers

Methodology Overview

The data for this thesis effort will be collected using a mobile retroreflectometer. Computer software will be used in conjunction with the retroreflectometer to input the data into a spreadsheet, thereby eliminating human entry error. Once the data is collected, a manual data mining operation will be completed in order to glean the applicable information relating to this research. The resulting mined data set will then be analyzed using JMP® statistical software. This software will be used to construct a linear regression model describing the degradation rate of polyurea pavement markings and will be based on independent variables identified as statistically significant to the model. Once the model is constructed, it will be validated using the Mean Absolute Percentage Error method.

Retroreflectivity

Retroreflectivity is the key indicator of pavement marking performance. It is the amount of light from a vehicle headlight reflected from a pavement marking back to the driver (ASTM 2005). When pavement markings are placed, glass beads are mixed into the marking and protrude from the surface of the marking, thereby allowing light to pass through the bead. The light then refracts, bounces off the marking, and reflects the color of the marking back to the driver (See Figure 1-1). The value of the intensity of the reflection is measured in millicandelas per meter squared of luminance (mcd/m^2/lux) and is known as the retroreflectivity value. This value is typically represented by the abbreviation R_L.

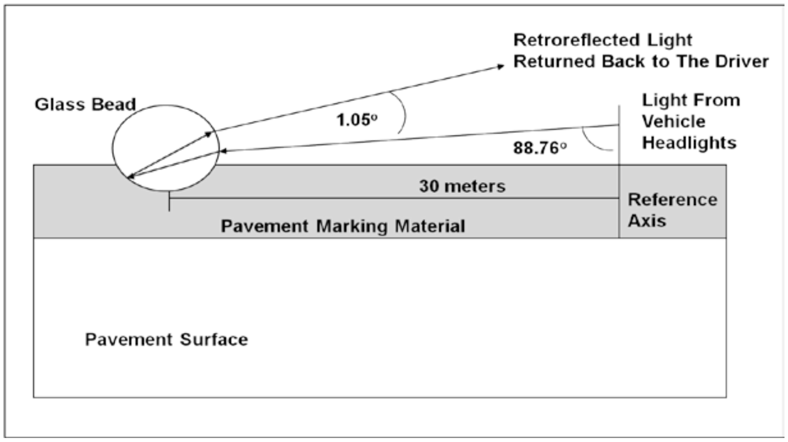

Figure 1-1: Retroreflectivity Illustration

ASTM standard E1710-05 specifies the entrance angle of the light to be 88.76^o, measured from a reference axis perpendicular to the pavement surface. The observation angle is specified to be 1.05^o from the pavement. These specifications are based on the headlight being positioned 0.65m above the pavement and an eye height of 1.2m above the pavement. The eye position height is based on the vertical distance traveled by the light over a horizontal distance of 30m from the reflection point and an angle of 1.05^o (ASTM, 2005). All measurements taken by the retroreflectometer used in this research were calibrated to this standard of 30m geometry.

Chapter 2: Summary of Literature

Literature Review

Construction of degradation models greatly assists in the development of asset management plans. Each year, DOTs spend millions of dollars in pavement marking expenditures alone. Not only is the cost of marking materials included in that price, but thousands of man-hours must also be paid in the execution of management plans; and this cost does not include the intangible cost of worker safety. The issue of safety generates another significant area of DOT cost and includes that of worker and equipment safety. The more workers present on busy highways, the greater the opportunity for a mishap. With a better understanding of the life-cycle of a given marking material, both monetary and intangible costs can be minimized while maximizing retroreflectivity performance. Table 1-1, and the descriptions that follow, summarize the current body of knowledge on the subject with regard to degradation modeling.

Table 1-1: Summary of Literature

Sponsor	Year	Authors	Model Type	R^2	Marking Material
MSU	1999	Lee et al.	Linear	0.14	Thermoplastic
TRB	2001	Migletz et al.	Linear	N/A	Durable
VDOT	2007	Fitch et al.	Logarithmic	0.53-0.86	Polyurea
NCSU	2009	Hummer et al.	Mixed Effects	0.68	Paint
NCSU	2009	Sitzabee et al.	Linear	0.60	Thermoplastic

Lee, Maleck, and Taylor (1999)

In the mid 1990s, Michigan State University contracted with the Michigan Department of Transportation (MDOT) for a four-year evaluation of various pavement marking materials. The purpose of the study was to identify the most cost effective marking material to be used in the state of Michigan. Fifty test sites were used and were geographically separated to include all regions of Michigan. Marking materials tested included water-borne paint, polyester, thermoplastics, and tapes. Three to eight locations within each test site were randomly selected and retroreflectivity readings were taken at each location at scheduled intervals using a Mirolux 12 retroreflectometer by Miro-Brand Assembles Inc. The authors noted the readings from this device had a high degree of variability and suggested future research be accomplished with a different data collection device as well as different collection methods.

From the collected data, linear regression models were constructed for each type of marking material. Due to the high variability within measurements, the coefficient of determination (R^2) value of each linear model was relatively low (0.14). Based on these results, the authors concluded all materials have a short lifespan (< 24 months), with a R_L value of <100 mcd/m^2/lux being considered a failure. Additionally, the authors concluded water-borne paints are the most cost effective material.

Variables considered in the models were average annual daily traffic (AADT), speed limit, and commercial traffic percentage; none of these variables were found to have a significant impact on R_L degradation. However, as a side note, the authors noted that pavement markings exposed to frequent snow removal operations also experienced higher degradation rates and suggested snow removal be added as a variable in future models.

Migletz, Graham, Harwood, and Bauer (2001)

This study was comprised of 85 sites in 19 states and focused on linear regression models to determine the degradation rate of various durable pavement marking materials in multiple regions of the United States. The test sites selected were a mixture of two-lane, multi-lane, freeway, and non-freeway roads in order to analyze retroreflectivity behavior over time under a diverse set of conditions. The variables considered in this study were marking material, lateral location, marking color, and type of roadway. Severity of winter climate was also assessed but found to be of no correlation to the service life of the markings.

For each test site, retroreflectivity readings were taken using a Laserlux mobile retroreflectometer in 0.01 mile intervals and averaged to produce one reading for that entire site. Retroreflectivity measurements were taken every six months over the specified time period with time zero being within sixty days of the marking installment. This methodology was used at all 85 sites, which totaled to 362 marking lines and more than 2.6 million readings.

The statistical software package SAS was used to construct regression models for each type of pavement marking. Plots of both Retroreflectivity vs Cumulative Traffic Passes (CTP) and Retroreflectivity vs Time (in months) produced very similar results. Since CTP included both average daily traffic and elapsed time, it was decided to build the regression models based on CTP rather than time alone. While each model produced a good fit, no two models were the same; the service life of each marking varied substantially from site to site. These variations were attributed to type and quality of pavement, quality control during installation, brand of beads used, and winter maintenance.

Fitch (2007)

Between the years of 2002 and 2005, data were collected and analyzed from 25 newly constructed projects in the state of Vermont. The purpose of this unpublished study was to determine the retroreflectivity resilience and resistance to wear of several pavement marking types. This effort analyzed numerous pavement marking materials in various regions of the state and constructed degradation models for each material.

Data collection was accomplished using an LTL 2000 Retroreflectometer in accordance with ASTM E 1710-97, "Standard Test Method for Measurement of Retroreflective Pavement Marking Materials with CEN-Prescribed Geometry Using a Portable Retroreflectometer." Care was taken to ensure data collection was accomplished within the bounds of this standard; however, there were two notable exceptions. First, data collection occurred when temperatures dropped below 40^{o} F, which is outside of ASTM E 1710-97 standards. It is unknown what effect, if any, this had on data collection.

The most noteworthy flaw in the data collection was the *cleaning* of the pavement marking before a measurement was taken. In some instances, the technicians *cleaned* the marking with a mixture of water and windshield washer fluid and then thoroughly dried it with a towel. This practice introduced variables not taken into account in the modeling process and are not typical in the field

While the modeling was not accomplished with a statistical software package, the use of an Excel spreadsheet yielded results that are of interest. The variables considered in the model were age, traffic volume, regional placement, seasonal application, winter maintenance, and depth the marking was recessed into the pavement. Due to the high snow volumes in Vermont, winter maintenance was found to have the greatest impact on retroreflectivity degradation.

This study suggests a degradation of over 100 mcd/m^2/lux, directly correlated to snow plowing operations, during the first winter after application. It was also observed that thermoplastic markings showed an increase in retroreflectivity during the following spring and early summer with average annual daily traffic (AADT) being suggested as the reason for this increase. Theoretically, since thermoplastic degrades at a faster rate than the glass beads, wear from traffic volume exposes and polishes more of the glass beads thus increasing the R_L value. Conversely, this study suggested the hardness of polyurea does not allow this rebound of retroreflectivity. This study concluded that, depending on the region, various marking types should be used in order to have a more effective pavement marking system.

Hummer, Rasdorf, and Zhang (2009)

From 2007-2009, data were collected on 25 two-lane rural highways in North Carolina. From this data, multiple degradation models were created for paint pavement markings and compared for accuracy. Specifically, this study compared a simple linear regression model with a Linear Mixed Effects Model (LMEM). The purpose of this study was to develop an accurate paint pavement marking retroreflectivity performance model to be used as a key component in an overall pavement marking management plan.

The data were collected using a handheld LTL 2000 retroreflectometer based on 30m geometry. All roads in this study were asphalt pavement with an AADT of less than 4000. NCDOT provided the installation dates of the pavement markings before the collection effort began.

Previous research had developed linear mixed effects models for predicting individual pavement conditions and this study expanded this method to predict retroreflectivity conditions at the individual road level. LMEMs were established for white edge and yellow centerline paint markings and compared to simple regression models constructed from the same data set. While both models include similar (and in some cases exact) variables, each model had unique characteristics. The key difference between the two modeling techniques is that of assumptions.

The most commonly used models in pavement marking research, linear regression models, assume data collected at different time intervals on the same pavement marking are independent of each other. This assumption holding true is the key to an accurate regression model. The authors argue this assumption does not hold for retroreflectivity models based on a positive correlation between multiple R_L measurements (over time on the same marking) when displayed graphically on a scatterplot. This scatterplot is the basis for the argument for using LMEMs rather than simple linear regression models. The LMEM models in this research did indeed provide more accurate models for the individual road level of analysis; however, they are more cumbersome and difficult to use.

Sitzabee, Hummer, and Rasdorf (2009)

Sponsored by NCDOT, this study used regression analysis to model the degradation rate of thermoplastic pavement markings in the state of North Carolina. Additionally, paint pavement markings were modeled for comparison. The objective of this study was to provide pavement marking managers tools that will enable them to better plan the removal and replacement of pavement markings and avoid replacing markings which have significant life remaining.

Data were collected for this study over a 5 year period using a Laserlux mobile retroreflectometer (model LLR5) mounted on a Chevrolet Suburban. This unit used 30m geometry and averaged R_L readings every tenth of a mile via an onboard computer. The data collected for thermoplastic markings included 56 segments and totaled approximately 450 miles of roadway. The data for painted markings included 37 segments and totaled approximately 300 miles of roadway.

The researchers used JMP® statistical software to construct the regression models for both thermoplastic and paint markings. The resulting models included the variables of time, traffic volume, marking color, and lateral line placement. Each of these variables was found to have a significant impact on the model.

The models for both thermoplastic and paint pavement markings showed the life-cycle of each marking was far greater than originally expected with a key finding in this study that lateral line location significantly impacts the degradation rate of the marking. This finding is important in that it assists pavement marking managers better understand degradation rates and develop re-striping plans accordingly.

Summary of Literature

While this literature review did not present an exhaustive study of all pavement marking studies, it did present the existing knowledge base in the field of pavement marking retroreflectivity performance modeling. Migletz and Graham (2002) constructed a synthesis of pavement marking research, dating back to 1988, and includes topics other than degradation modeling. Their endeavour was not repeated here, nor was it appropriate to do so. The focus of this thesis was specifically on the modeling aspect of pavement marking research. The five articles presented were considered key because they not only identified variables with significant impact on pavement marking degradation, but they also identified variables that are of no effect.

With few exceptions, past research has modeled R_L degradation as a linear decay with increasingly good results. The main effects included in each model have progressively become standard as the knowledge base expanded with the most recent addition being that of lateral line location. Thus, it is concluded the main effects of AADT, initial R_L value, marking color, winter maintenance operations (based on region), and lateral line location should be considered, at a minimum, in all future models.

The importance of predicting when R_L values will degrade below specified minimum standards is clearly seen in these five key articles. The effects of proper management of pavement markings coupled with appropriate minimum R_L values is revealed in a study conducted in Pennsylvania which discovered that reducing the minimum R_L from 100mcd/m^2/lux to 75mcd/m^2/lux would save over $70 million over the course of ten years (Sasidharan, Vishesh, and Donnell 2009). This study clearly shows that effective planning can lead to significant cost savings over time. To reinforce this notion, Sitzabee et al.'s (2009) North Carolina study showed that both waterborne paint and thermoplastics "have a far greater life expectancy than originally expected." In this specific case, paints were lasting approximately twice as long as they were expected to. Since paint makes up approximately 60% of markings in North Carolina, this new understanding can significantly reduce the NCDOT budget dedicated to paint re-striping.

While these studies do not explicitly address the worker safety aspect of cost, it is indirectly implied that high quality degradation models, when used properly, can effectively lower risks associated with worker safety. When life-cycles of marking materials are maximized, total man-hours needed are reduced. When man-hours are reduced, safety risks are also reduced. Less exposure of the workforce is a by-product of proper asset management.

Both Sasidharan et al. (2009) and Sitzabee et al. (2009) have a common theme; pavement markings are lasting significantly longer than expected. This is partially due to the fact pavement markings have been in use for several decades now. Historically, re-striping plans have been centered around manual, subjective surveys and rules of thumb practices derived from these surveys. Over the years, these rules of thumb have been accepted as good practices. However, through the years, pavement marking material selection has expanded from exclusive use of paint to the use of other materials such as thermoplastic, epoxy, and polyurea. Furthermore, technology has improved the quality of these materials, thereby rendering these manual, subjective surveys and rules of thumb obsolete. With today's advanced marking materials, and based on previous studies, it is clear that degradation models are needed in order to properly develop asset management plans for pavement markings.

The studies conducted by Sasidharan et al. (2009), Sitzabee et al. (2009), and others have centered primarily on paint and thermoplastic pavement markings which resulted in good models being constructed for those materials. But in order to have a more complete asset management plan for pavement markings, degradation models need to be constructed for all types of pavement marking materials used in a given region.

Pavement Marking Minimum Standards

In order to use these degradation models, there must first be a standard with which to compare pavement marking performance. The commonly accepted characteristic in question is the retroreflectivity value of the marking. As of 2009, the Federal Highway Administration (FHWA) has declared minimum standards for the various types highway sign retroreflectivity (Federal Highway Administration 2009). However, the FHWA has yet to implement a minimum standard for pavement marking retroreflectivity. In the summer of 2010, these minimum standards were submitted and, barring significant intervention, will soon be made into law (Federal Highway Administration 2010). Table 1 presents these standards.

Table 1-2: Proposed Minimum Standards

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

After the initial literature review, it appears the most commonly accepted minimum R_L value is in the range of 100 to 150 mcd/m^2/lux (Sitzabee, Hummer, and Rasdorf 2009; Hummer, Rasdorf, and Zhang 2009; Fitch 2007; Lee, Maleck, and Taylor 1999). Even though numbers around 100 mcd/m^2/lux are commonly used throughout the nation, there is no scientific evidence that this number is correct. It seems to have been arbitrarily used by one or two DOTs initially and then copied by other states as a benchmark value. (This number does not come into play when building degradation models, but it does impact life-cycle costs as seen in the Sasidharan et al. (2009) data.) Ultimately impacting asset management strategies, it is important to have a minimum R_L value such that retroreflectivity is still high enough to be of use to drivers and 100 seems to be a benchmark number until someone proves otherwise. Therefore, this research will use 100 mcd/m^2/lux as the minimum standard for life-cycle planning.

Model Variables

To construct an effective degradation model, the correct variables, based on the region of interest, must be included in the model. The model for thermoplastics presented by Sitzabee et al. (2009) suggests that the model include time, initial R_L value, AADT, lateral location of line, and marking color as the independent variables. While this model yields good results compared to similar models for thermoplastic, it does not take into account variables that create significant impact in other regions. For example, the Vermont study suggests a degradation of over 100 mcd/m^2/lux, directly linked to snow plowing, during the first winter a marking is placed (Fitch 2007). The Sitzabee et al. (2009) data suggests snow plowing may have an effect, but the NCDOT data did not provide a statistically significant impact. In regions similar to Vermont with significant annual snowfall, the effects of snow removal on R_L values is profound, but in southern regions such as Louisiana, there is no impact caused by snow removal.

A further discrepancy between models is found in a Michigan study which shows no correlation between AADT and retroreflectivity decay (Lee, Maleck and Taylor 1999). It should also be noted this study's models had very low R^2 values. This lack of AADT impact is probably due to the overwhelming effects of snow removal operations done in that state. While the study did not specifically include the effects of snow removal on R_L degradation, the authors did take note of the annual snowfall in each region within their study and discovered the areas with significantly higher snowfall did in fact have a much greater loss of retroreflectivity than areas which had significantly less snowfall.

Each study considered in this literature review speaks to the unique variables in their respective regions of study. These variations in main effects show that each DOT needs to consider, not exact models created in previous research, but the variables that will be significant in their specific region. A model should be objectively considered to determine if that model is appropriate for a specific region of interest.

Each model reviewed in the literature will be considered applicable primarily within its region. However, there are variables common to all models, regardless of region, that can be included in any model. Variables such as initial R_L, lateral line location (Sitzabee, Hummer and Rasdorf 2009) and in most cases AADT can be included in any model, for any region. Since the data were collected in North Carolina, the following variables were explored:

- AADT
- Initial R_L value
- Lateral line location
- Brand of materials used (polyurea, reflective beads)
- Impacts of snow removal
- Time

The material in question, polyurea, is impacted by these variables just as paint and thermoplastics are. However, polyurea cannot be modeled using paint or thermoplastic models because polyurea's physical properties differ from paint and thermoplastic. Unlike paint and thermoplastic, polyurea is designated as a long-life pavement marking (NCDOT 2006) with a higher resilience to degradation. For this reason, polyurea is used primarily in high traffic areas, bridge decks, and areas with high snowplow usage. What is unknown is exactly how much longer of a lifespan polyurea has. With the life-cycle unknown and a considerably higher initial cost, a degradation model is absolutely critical to effectively managing this asset.

Why Polyurea

Migletz and Graham (2002) list the 16 most common materials used across the United States and Sitzabee et al. (2009) highlighted the four most common materials used in North Carolina as waterborne paint, thermoplastics, epoxy, and polyurea. Currently, pavement markings in North Carolina consist of 60% paint and 35% thermoplastic. Polyurea currently comprises less than one percent of pavement markings in North Carolina; nevertheless, research into its attributes is still warranted.

While polyurea is only used in specific applications, all of which experience high volumes of traffic, NCDOT has implemented a policy to replace epoxy with polyurea. This policy will significantly increase its usage. This is significant for two reasons. First, the high volume of vehicle passes over a marking causes that marking to wear at an accelerated pace. Second, when re-striping is required in these areas, significant traffic delays are caused by closing lanes for the re-striping operations. Additional concerns are raised due to construction crews being exposed to high volumes of traffic. With the implementation of NCDOT’s policy, these concerns become even more significant. Development of a performance model describing polyurea creates a tool which pavement marking managers can use to better plan when and where polyurea pavement markings should be used. This understanding potentially can save money as well as reduce worker exposure to high volume traffic.

Additionally, polyurea is considered a low profile marking material when compared to thermoplastic. NCDOT specifies polyurea to be 20 mils thick while thermoplastics are specified to be 90-120 mils thick when placed (NCDOT 2006). Because of its thinner profile, polyurea is used in areas with high snowplow exposure as well as areas with limited access, such as bridge decks. Its thin profile allows snow plows to pass with minimal damage to the marking and all other traffic to pass with minimal impact (Sasidharan et al. 2009). Furthermore, polyurea’s long life and durability make it an ideal candidate for application on high impact assets such as airfields.

Chapter 3: Methodology

Data Collection

The retroreflectivity data for this study were collected over a 5 year period using a modified Laserlux mobile retroreflectometer (model LLR5) mounted on a Chevrolet Suburban. A mobile retroreflectometer lends itself to collecting large volumes of data because it can be used at highway speeds. This allows the technician to remain safely inside the vehicle and collect large amounts of data in a short period of time. For a data collection effort of this magnitude, a handheld retroreflectometer simply would be too time consuming to be effective.

The LLR5 uses the standard 30-m geometry as required by ASTM E 1710-97. The R_L readings were averaged for every tenth of a mile for a specified pavement marking. The units were recorded in mcd/m^2/lux and averaged via an onboard computer, thereby eliminating data entry error caused by human entry.

Vehicle-mounted retroreflectometers are safe and accurate, but they are not without error. To minimize this error, a rigorous calibration process was adhered to for the duration of the data collection. Prior to every trip, the unit was calibrated against a known test bed of pavement markings at the NCDOT maintenance facility. This test bed R_L value was established with a handheld LTL2000 retroreflectometer. Each time, the LLR5 was calibrated against the test bed and adjustments were made to account for suspension changes, tire pressure, and ambient light. Additionally, the LTL2000 was taken into the field on each trip and used to verify the calibration of the mobile unit each time any condition changed in the field.

The resulting data set contained hundreds of thousands of data points describing things from R_L values to the name of the technician that took the readings. Consequently, the data set had to undergo an extensive data mining operation in order to be useful in this research. This mining operation consisted of identifying only that data which directly related to polyurea pavement markings. The remaining data was removed from the data set. After mining was completed, 1,174 data points remained for analysis.

Performance Modeling Techniques

JMP® statistical software was used to build the degradation model. JMP® is a software package used primarily by practicing statisticians and is well regarded within the field. The primary model is a simple regression model of the form

(1)

where

Response Variable (R_L value)

Regression coefficients

X_k = Predicting variable

ε = Random error

The majority of models in the reviewed literature use linear regression with good results. The reason for this model's commonality is the ease of model construction and ease of model explanation to audiences with varying educational backgrounds. In order to use this modeling method, the assumptions that the residuals of the dependent variable are independent, normally distributed, and that residual variances are equally distributed about the mean must be satisfied. To satisfy these assumptions, the Shapiro-Wilk test and the Breusch-Pagan test was used. The Shapiro-Wilk test for normality was accomplished within the JMP® software and the Breuch-Pagan test for constant variance was accomplished with a Microsoft Excel® macro.

A second method that was considered was a Linear Mixed Effects Model (LMEM). Hummer et al. (2009) suggested that a LMEM was more appropriate for pavement marking degradation and would yield better results than a simple regression model. While their research achieved better R^2 values than simple regression models, this method required significant computing power as well as more complex statistical methods. Consequently, asset managers will have greater difficulty understanding how to actually use and explain this type of model. Therefore, this method of modeling was not pursued based on evidence in the literature that the increase in the goodness of the results was not worth the extra effort and complexity involved to construct and use the model.

Having researched these two modeling methods, it is clear the linear regression model is the most effective technique for modeling retroreflectivity degradation. With a previously achieved R^2 value of 0.6, the information generated by these models can immediately be used by pavement marking managers (but further research still need to be accomplished in order to explain further unknowns). Regression models' simplicity also makes them easy for managers to understand and implement, thereby creating more effective managers.

Model Validation

Once the regression model is complete, validation of the model was completed using the Mean Absolute Percentage Error (MAPE) method. This validation method compares the predicted values generated by the model to real-world data contained in the data set. This is accomplished by randomly withholding 20% of the data before model construction. The equation used for the MAPE process is

$$- \qquad \overline{} \qquad (2)$$

where

A_t = actual value

E_t = estimated value

Chapter 4: Analysis

Proposed Model

The proposed variables to be included were AADT, initial R_L value, lateral line location, time, brand of materials, and impact of snow removal. Previous models reported in the literature found the variables of AADT, initial R_L value, lateral line location and time were found to be significant; impact of snow removal was suggested for future research. Based on these findings and the selection of variables contained in the data set, it was determined that a stepwise insertion of variables into the model was unnecessary. Therefore, these variables along with bead type, for a total of seven variables, were directly inserted into the model and tested for significance (alpha of 0.05).

When modeled linearly, the assumption of constant variance was violated. Further investigation of the data resulted in the discovery of two populations based on bead type; standard reflective and highly reflective. This key finding is the cause of the non-constant variance and will be discussed in detail later in this chapter. No other issues were found with the database. Table 4-1 gives the definition of each proposed variable and is followed by a detailed description of the significance of each variable.

Table 4-1: Variable Definitions

Variable	Definition
AADT	Average Annual Daily Traffic: This is the best guess of how many vehicle passes will be on a section of road; based on traffic surveys
Initial R_L Value	Initial retroreflectivity value calculated within 30 days of marking installation
Lateral Line Location	Position of marking on road; edge line vs center line
Time	Number of months since marking installation
Brand of Materials	Brand of paint/beads used for a particular marking
Impact of Snow Removal	Number of passes of a snowplow a marking experiences
Bead Type	High Reflectivity vs Standard Reflectivity

AADT

The AADT contained in this data set ranged from less than10,000 to greater than 100,000 and was entered into the model as a continuous variable. This variable was found to be statistically insignificant, base on an alpha of 0.05. However, previous models showing this variable to be significant prompted an investigation of the distribution of this variable in order to identify possible dummy variables (DV). As a result of this investigation, it was decided that a dummy variable describing the AADT range of 20,000-60,000 could be significant. When this dummy variable was entered into the model, it was found to be significant. However, the coefficient for this variable was positive rather than negative. This suggested AADT increased the R_L of the marking rather than decrease it. This finding defies logic and all previous research. Therefore, it was removed from the final model.

Initial R_L Value

The assumption behind inclusion of Initial R_L is the higher the Initial R_L, the longer the R_L value will remain above an acceptable minimum. This variable exists in the data set as continuous and when modeled as such was found to be statistically significant. This finding is consistent with the literature.

Lateral Line Location

Describing the marking's position on the road, this variable was modeled as a dummy variable (center vs edge). This variable was found to be significant in both models and serves as confirmation of the findings of Sitzabee et al. (2009) that lateral line location impacts degradation of pavement markings. This finding is consistent with the literature.

Time

Time should be a significant factor in the degradation of anything and degradation of pavement markings is no exception. Time also represents a host of other variables not contained in the data set. These "unseen" variables could represent UV radiation, sandblasting effects from high winds, hail damage, or any number of other things. Time is represented in the data set as ordinal, but for the same reasons as mentioned before, it was modeled as a continuous variable and found to be significant.

Brand of Materials

For this data set, all materials analyzed were of the same brand so this variable was not included.

Impact of Snow Removal

Previous research strongly suggests snow removal greatly impacts degradation of pavement markings. The Michigan study (Lee, Maleck, and Taylor 1999) suggested that markings which experience frequent snow removal have a higher degradation rate than those which do not. Some of the markings in the Lee et al. (1999) study had to be re-striped annually as a result.

For this data set, snow removal was modeled in several ways (ordinal, continuous, and with dummy variables) and each time it was found to be insignificant. However, this variable should not be excluded from future research for two reasons. First, the data set used in this research contained few data points for snow removal data. Additionally, the annual snowfall in the region of North Carolina in which the data were collected could have been small enough to be insignificant.

Bead Type

For this research, two types of beads were recorded, standard beads and highly reflective elements (HRE). The difference being beads are spherical and elements are sphere-like with jagged irregularities in the surface. When modeled as a dummy variable, Bead Type was found to be insignificant. However, when each bead type was modeled separately, the significance of the bead type was revealed. The standard reflective bead model resulted in a statistically sound model with no issues. However, the highly reflective elements did not. When modeled linearly, the highly reflective elements display significant non-constant variance creating a model that could not be used with acceptable levels of certainty. Further probing into the highly reflective model yielded a polynomial model which passed the statistical tests for a valid model. This model is further discussed in Highly Reflective Elements Model section of this chapter.

Initial Model

As a result of the analysis, four variables were eliminated: AADT, brand of materials, impact of snow removal, and bead type DV. The remaining three proposed variables were found to be significant and are displayed in Table 4-2.

Table 4-2: Variable Significance

Variable	Significance
Line Position DV	<.0001
Initial R_L Reading	<.0001
Time	<.0001

Because of the dual populations, three models were generated and contain the same variables. The first model contains both bead types. The other two models separate the data based on bead type.

Combined Model

The five year data set contained thousands of entries; much of which did not relate to this research. After extensive data mining, the sample size was reduced to 1,174 entries related to polyurea. The reduced data set was then used to build one linear regression model describing polyurea degradation. The resulting model had an adjusted R^2 of 0.62. However, when tested for normality using the Shapiro-Wilk test, the model failed. Next, the distribution of the residuals was examined with a normal distribution curve fitted to the data to visually check for normality. Figure 4-1 depicts this graph.

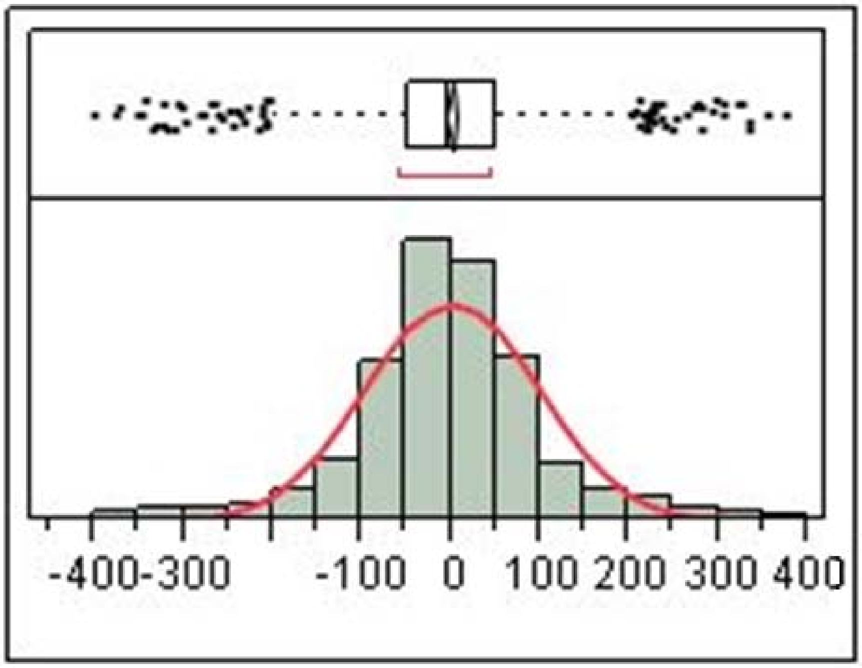

Figure 4-2: Combined Model Residual Distribution

The appearance of normality in this graph prompted further investigation that resulted in accepting this distribution as normal. It was determined that failure of the Shapiro-Wilk test was due to the size of the sample. A database of this magnitude approached population size, mathematically speaking. Because of this, the algorithm used by the software thinks this sample is actually a population. By treating the data like a population, any deviation from normality will cause the algorithm to reject the sample as normal. Because this data is field data it contains errors and deviations from normality. As a result, the Shapiro-Wilk test cannot be used to verify normality. By plotting a histogram of the residuals, it is clearly seen this distribution is normal.

Next, the assumption of constant variance was tested, which the model also failed. The failure of the Breusch-Pagan test for constant variance was due to the failure of the Shapiro-Wilk test for similar reasons. Visual inspection was also required to validate the failure. Figure 4-2 shows the residual plot used for this validation.

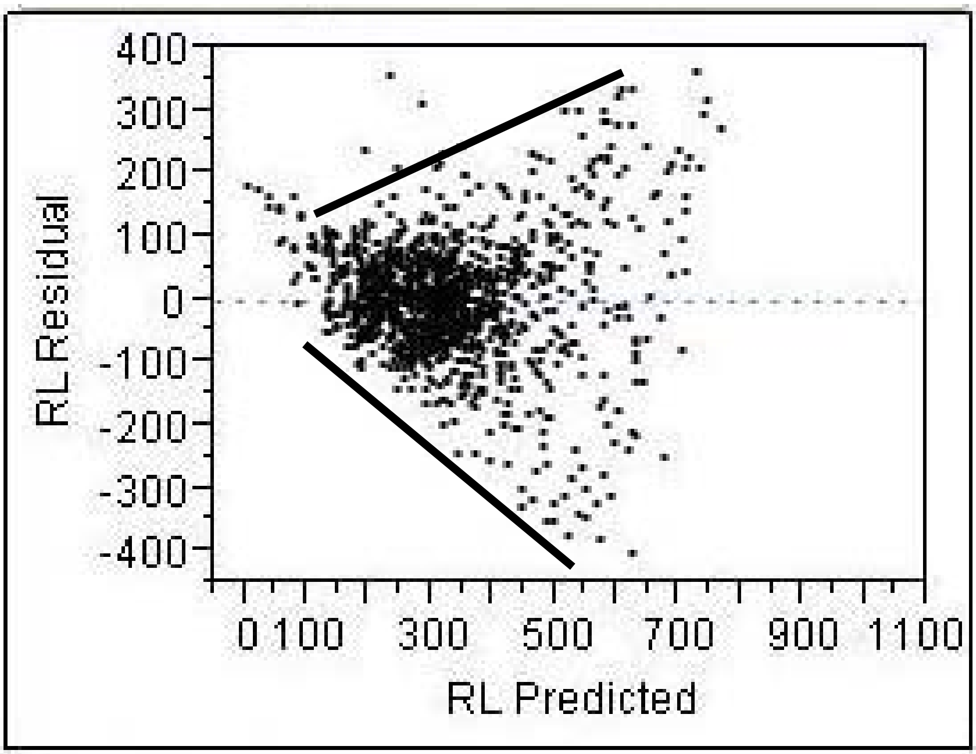

Figure 4-3: Combined Model Residual Plot

For a model to display constant variance, the residuals must be evenly distributed about the mean of the residuals. The fanlike shape of the residuals violates this requirement and confirms this model fails the second assumption required of a regression model. As a result, very little confidence can be placed in the predictions generated by this model.

While this model produced a good coefficient of determination and displayed a normal distribution, an examination of its confidence interval shows this model's lack of practical usefulness. Due to the failure of the constant variance assumption, MAPE cannot be used to validate this model. Chebychev’s rule must be used in its place to calculate the confidence interval. This rule makes no assumptions of the underlying distribution; therefore, failure of normality or constant variance tests are of no consequence.

Chebychev’s rule is based upon the raw deviations between actual and predicted values and the standard deviation of those differences. The raw deviation calculation is of the form

(3)

where

A_t = actual value

E_t = estimated value

Once the raw deviation was calculated for all 1,174 observations, the arithmetic mean and standard deviation were used to calculate the confidence interval. For a 75% confidence interval, the resulting equation is of the form

(4)

where

= arithmetic mean

s = standard deviation

For a 89% confidence interval the resulting equation is of the form

(5)

For the purpose of this paper, a 75% confidence interval is presented.

With the raw deviations calculated for all 1,174 observations, the mean and standard deviation was found to be -0.06 and 0.40, respectively. These numbers result in a 75% confidence interval of (-0.86, 0.74). This is interpreted as 75% of the estimates produced by this model will absolutely be incorrect by -86% to +74%. While this is a very large interval, these numbers are the absolute worst case scenario. However, the interval's large size shows the model's lack of practical applicability.

This interval's large size is due to the extreme variance in the initial R_L values of the pavement markings caused by the presence of highly reflective elements. In order to improve the range of this interval, the α-Trim Mean method was used. This method removes overly influential data points from the set by trimming an equal percentage of data from each end of the distribution. For this interval, a 10% trim was used. Removing the lower and upper 10% of observations from the data set yielded an of -0.02 and an s of 0.18. The resulting 75% confidence interval was (-0.38, 0.36). While this interval produces a more palatable range, the 10% trim created problems of its own. Since 20% of the observations were removed, the model now has a 20% chance of producing an estimate that is completely wrong. Using Chebychev's Rule along with α-Trim Mean to calculate an 89% confidence interval only worsens the problems with this model. This serves as confirmation that a model based on multiple bead types will produce results that are un-usable by asset managers for practical purposes.

Standard Bead Model

Using the independent variables of time, initial R_L, and line position, a linear model was constructed to describe the degradation of polyurea pavement markings containing standard beads. The resulting model had an adjusted R^2 of 0.49 and is presented below.

$$R_L = 153.55 - 2.67 * Time + .43 * InitialR_L - 36.72 * LPDV \quad (6)$$

As expected from such a large data set, the model failed both the Shapiro-Wilk test for normality and the Breusch-Pagan test for constant variance due to the size of the sample. However, after visual inspection of the residual plot and histogram, it was determined the model satisfied both assumptions for a valid regression model. Figure 4-3 and Figure 4-4 show these graphs.

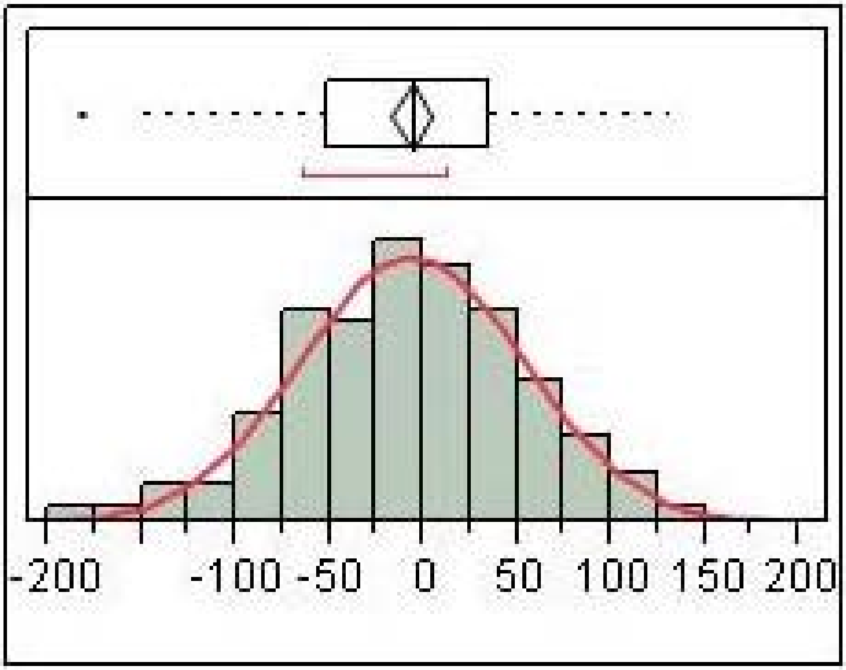

Figure 4-4: Standard Bead Model Histogram

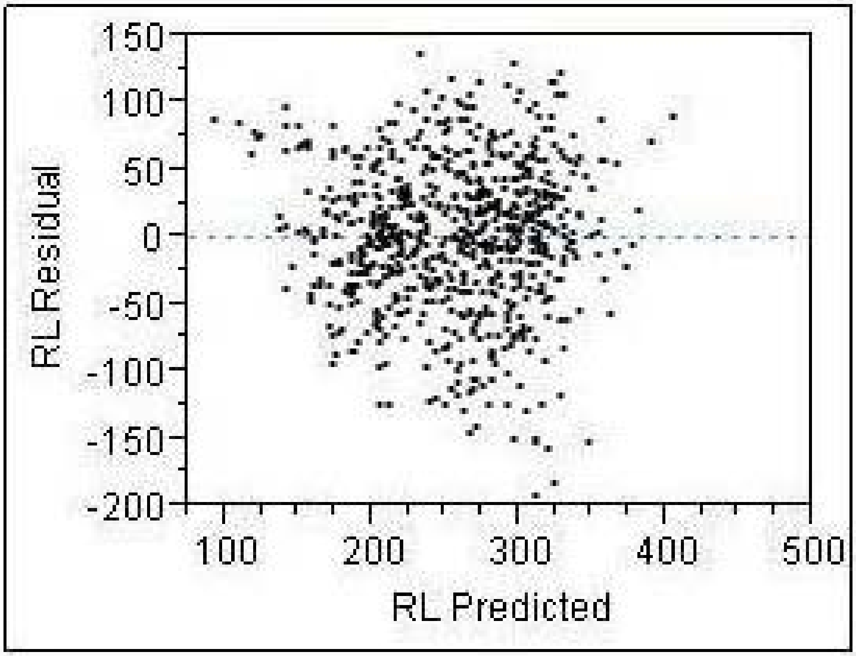

Figure 5-4: Standard Bead Model Residuals

Highly Reflective Elements (HRE) Model

The same methodology applied to the standard beads was applied to the highly reflective elements to construct a linear performance model. Initial results exhibited substantial evidence that a linear model was not the best fit for this segment of the data set. While the model passed the graphical test for normality, the residuals, shown in Figure 4-6, highlight a signifcant trend in the variance.

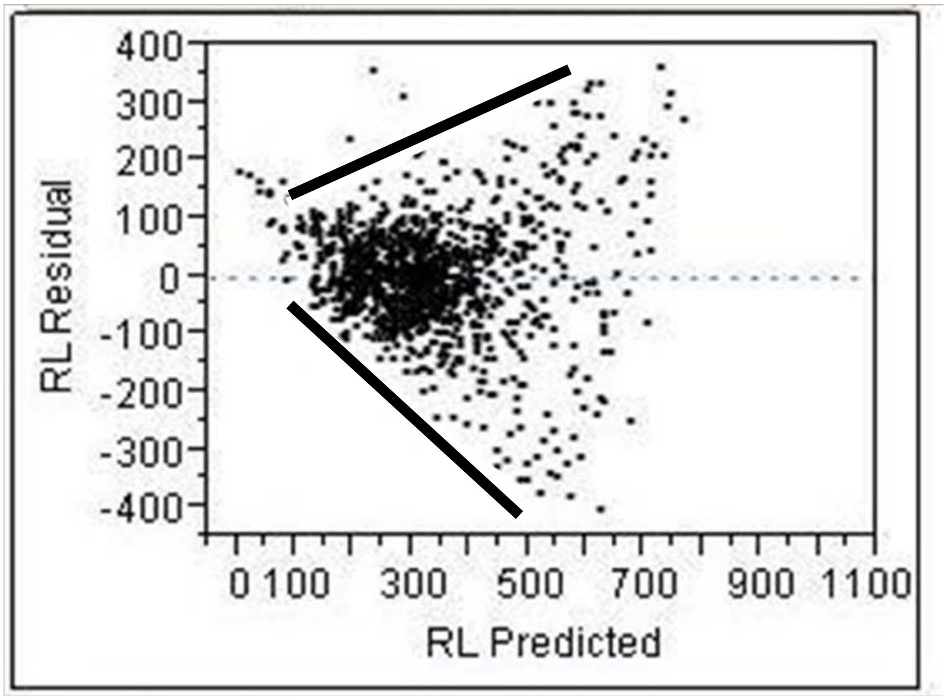

Figure 4-6: Initial HRE Model Residuals

The fanlike shape of the residuals clearly illustrates the sample does not satisfy the constant variance assumption. Thus, it is believed that the existence of the highly reflective elements data, in the initial model caused that model to fail the constant variance test, thereby rendering the model unusable. It is currently unknown as to why highly reflective elements cause non-constant variance.

Because of the non-constant variance issues created by the highly reflective elements population, it is misleading to describe pavement-marking degradation with one linear model. When modeled together, a higher adjusted coefficient of determination is produced to describe the data than when modeled separately (R^2 = 0.6 compared to R^2 = 0.49). However, due to the non-constant variance issues, the higher coefficient of determination does not mean the model is more predictive.

To further investigate this phenomenon, some basic analysis was completed using Excel spreadsheets. The average observed R_L for each time period recorded was plotted against time and fitted with a trendline. With an R^2 of 0.91, a polynomial trendline produced the best fit. This finding was then incorporated into the JMP® model resulting in a model with an adjusted R^2 of 0.56. This model is presented below.

$$R_L = 305.00 - 15.15 * \mathit{Time} + .13 * \mathit{Time}^2 + .50 * \mathit{InitialR}_L - 53.70 * \mathit{LPDV} \qquad (6)$$

The time variable was squared and added to the model as an additional variable producing a model that satisfied the assumptions for normality and constant variance. Figure 4-7 and Figure 4-8 shows these results.

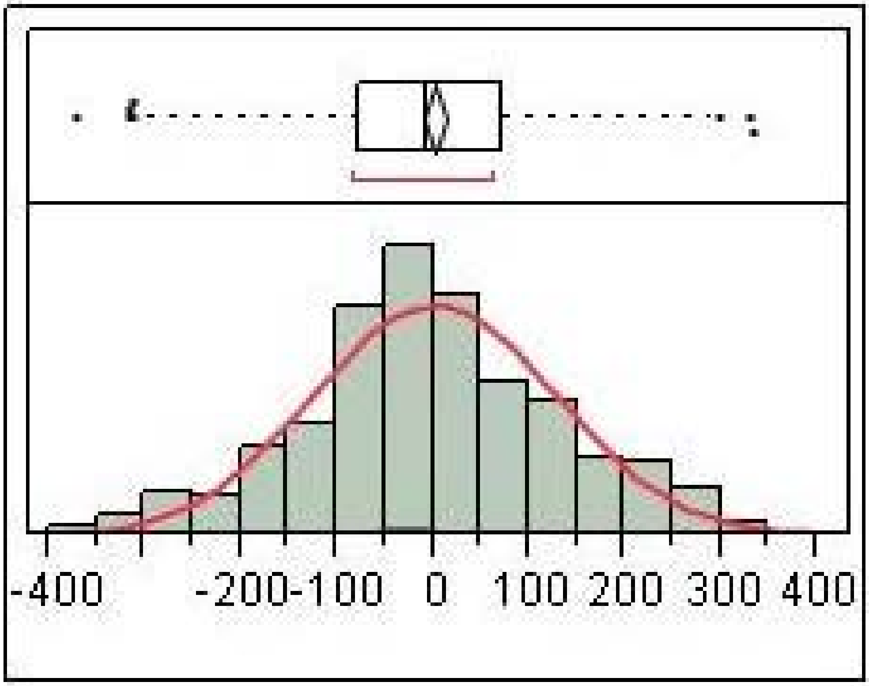

Figure 4-7: HRE Model Histogram

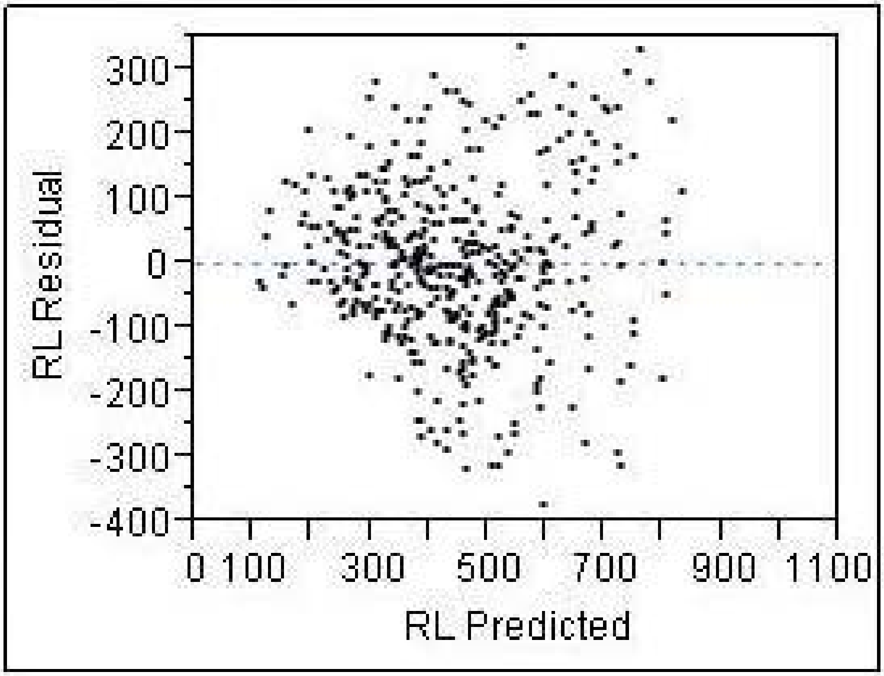

Figure 4-8: HRE Model Residuals

Additionally, each type of bead impacts the degradation model differently with the most notable impact being that highly reflective elements have a much higher initial R_L value than standard beads, but degrade at a faster rate. Figure 4-9 shows the degradation trend lines of polyurea pavement markings over time separated by bead type. The trend lines are based on 60 months of data. The sharper angle of the highly reflective elements trend line indicates a faster degradation than that of the standard bead trend line.

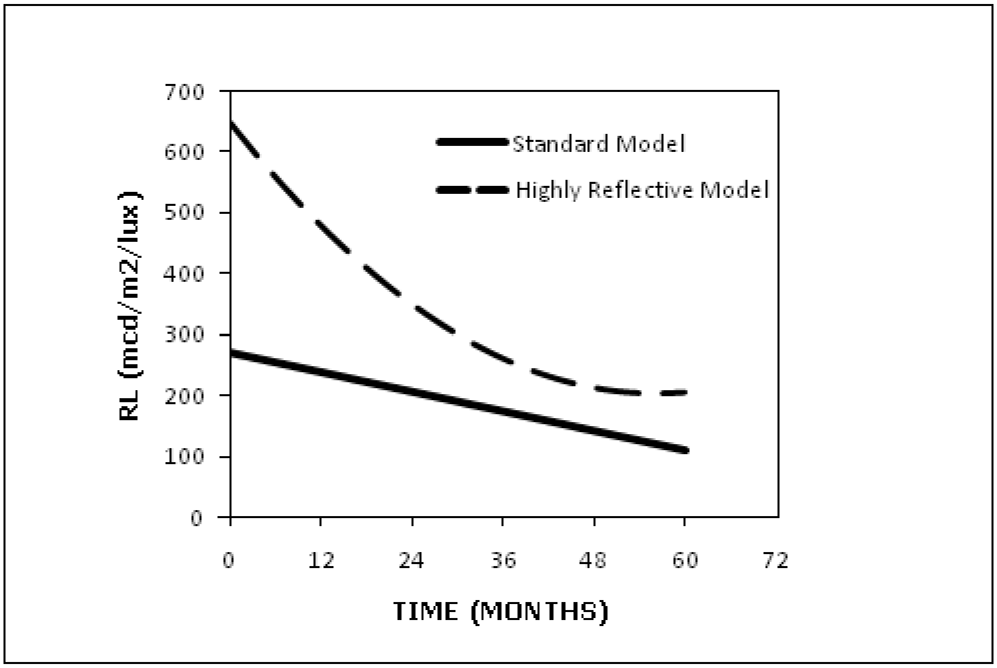

Figure 4-9: Bead Performance Over Time

Model Validation

To validate the models, the Mean Absolute Percentage Error (MAPE) method was used. As previously stated, the combined model cannot be validated due to the non-constant variance issues. For this section, only the two separate models are presented.

In order to have accurate data to validate against, 20% of the data set was randomly selected and withheld from the preliminary model. Once the MAPE process was complete, the withheld data were added to the final model for increased accuracy.

Using the MAPE equation presented in Chapter 3, the MAPE between the actual values in the withheld data set and the values estimated by the models using known parameters were calculated. The errors for the standard bead and highly reflective models were found to be ~16.5% and ~24%, respectively. With no other polyurea models found in the literature, it is still unclear how good these error numbers are, but they are the best estimate to date.

Chapter 5: Results

Using the models presented in Chapter 4, asset managers can somewhat predict the life-cycle of polyurea pavement markings. Since the adjusted R^2 for each model is significantly less than one, the predicted values generated by these models will absolutely contain error. Additionally, the presence of the exponential time variable in the highly reflective elements model does not allow for extrapolation of the model past 60 months. However, with error rates of approximately 16.5%-24%, each model offers advantages over using no model at all. The work done by Sitzabee et al. (2009) illustrates this point.

Until the authors were asked to do their research, NCDOT replaced painted pavement markings on an annual basis. The model generated by Sitzabee et al. (2009) (with an adjusted R^2 of 0.75) showed painted pavement markings in North Carolina have a life expectancy of more than 2 years. This understanding can now be used to better manage painted pavement markings and reduced the annual budget allocated for that resource. Using the models generated in the research, coupled with models created in previous research, asset managers now have the ability to make predictions to assist in optimizing pavement marking service lives.

Service Life

The standard bead model produced a degradation rate of 2.67 mcd/m^2/lux per month. Based on the data set, pavement markings with standard beads have an average initial R_L value of 364 mcd/m^2/lux. Using this number along with the proposed MUTCD minimum standards of 50 , 100, and 250 mcd/m^2/lux, and assuming linear behavior past

60 months, polyurea pavement markings have a service life of 82, 64, and 8 months respectively.

The service lives could not be calculated for the highly reflective elements model past 60 months due to the exponential time variable in the model. Because of the exponential variable, the resulting model is not linear. Therefore, extrapolation based on the model returns increasingly higher retroreflectivity values after the initial 60 months. More data are required for time periods past 60 months in order to accurately predict future retroreflectance. However, based on an average initial R_L of 780 mcd/m^2/lux, the 250 mcd/m^2/lux minimum standard was reached within the first 60 months and was found to be 39 months. At the 60 months point, polyurea pavement markings containing highly reflective elements exceeded the 50 and 100 mcd/m^2/lux standards with an R_L of 209 mcd/m^2/lux.

Using an asset management approach focused on optimization, and the above estimates, an asset manager can balance the pavement bead type with the expected paving cycle. For example, consider a 20-year paving cycle and a minimum R_L value of 100 mcd/m^2/lux; standard reflective beads reach the minimum around the 5-year point while highly reflective elements remain well above the minimum at the 5 year point. With asset managers typically re-striping a 20-year pavement at the 10-year point, the use of either bead type has advantages and disadvantages.

Managers need to consider several options. For example, do they restripe right at 10 years using standard beads and maximizing the full life-cycle or do they use highly reflective elements and restripe at 10-years potentially wasting several years of service life. Alternatively, they can restripe at the point of failure for the highly reflective elements and find another material that only has a life of the remaining 20 year cycle, which becomes a complicating step in the process. Ultimately, the manager needs to balance the use of beads with the paving cycle using sound economic analysis techniques. In this case, the use of standard beads applied four times in the life of the pavement seems to be the most economical and easiest choice. But what if another minimum standard is considered? Mangers have another consideration which is to take advantage of the higher values gained from highly reflective elements. However, there is no indication in the reviewed literature that higher R_L values actually provide any benefit, such as increased safety justifying the added expense (Bahar et al. 2004).

Comparison of Pavement Marking Materials

Using the models generated in this research, along with Sitzabee et al.'s (2009) paint and thermoplastic models, asset managers can take a specific set of conditions and compare pavement marking material's predicted life-cycles. Using the four models and considering a yellow centerline with an AADT of 50,000 as an example, Table 5-1 displays the results of each model.

Table 5-1: Life-Cycle Comparison of Materials

Marking Material	Time to Failure (Months)
Std Reflective Bead Model	63
HRE Model[1]	R_L=200 at 60 months
Thermoplastic	51
Paint	30

Asset managers can incorporate comparisons such as this in their management plans to better support their decision making process. For example, assume a particular road segment needed new markings but was due to be resurfaced in 20 months. Even though an AADT of 50,000 would normally require durable pavement markings, the asset manager could specify painted markings instead. By doing so, the retroreflectivity requirements for that road segment would be met while reducing the amount of dollars spent re-striping. Scenarios such as this show the importance of degradation models.

Conclusion

With no real model for polyurea presented in the reviewed literature, the results of this study are significant and can be considered the baseline for future research for this material. The five studies presented in this paper show that paint and thermoplastic pavement markings degrade in a linear fashion. The model presented in this paper for polyurea pavement markings containing standard beads is consistent with this finding while the highly reflective elements model is not.

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[1] The HRE Model cannot predict values past 60 months.

Future Research

The significant finding produced by this study is the impact of bead type on degradation. While highly reflective elements produce pavement markings with a much higher initial R_L values, the degradation rate is substantially greater than standard bead degradation. However, based on the models, at the 60 month mark pavement markings containing highly reflective elements produce almost twice the retroreflectance than those containing standard beads.

It is recommended that future research collect data specific to highly reflective elements. Advancements in understanding the performance characteristics of highly reflective elements have the potential to significantly impact the effectiveness of pavement marking performance models. Future studies should collect data pertaining to pavement markings with highly reflective elements, recording at a minimum the same variables used in this study. It is recommended that the collection effort continue until the markings begin to fail in order to improve upon the current model presented in this paper.

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14. ABSTRACT
Polyurea is a long life pavement marking material used for assets requiring long periods of uninterrupted accessibility. Knowing the performance characteristics of such markings is critical to asset management planning focused on maximizing marking material life-cycles. This paper presents the performance characteristics of polyurea pavement markings in North Carolina using linear regression models. The models generated by this research provide pavement marking managers with tools to better allocate limited manpower and resources in order to optimize budgets while meeting newly proposed pavement marking retroreflectivity levels of service as proposed by the Federal Highway Administration. This research constructed performance models for polyurea based on the independent variables of time, initial retroreflectivity, and lateral line location. Using the models generated by this research, the pavement marking manager can predict the level of service and remaining life of a given pavement marking. A key finding of this paper is that polyurea pavement marking degradation is significantly impacted by the type of glass bead inserted into the marking.

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