Pavement Marking Degradation Modeling and Analysis

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Abstract

The objective of this research was to determine the performance characteristics of thermoplastic pavement markings in NC and to create viable degradation models. Additionally, an evaluation of paint pavement marking materials was conducted and models were created for them as well. The resulting models provide pavement marking managers with valuable tools that will allow them to focus limited resources where they are most needed and avoid replacing materials with effective life still remaining in them.

Consideration was given to the analysis of the relationships between pavement marking retroreflectivity values and variables such as time, traffic volume, and marking color. Unique to this research is the inclusion of lateral location as a key variable affecting the performance of pavement markings. Another key contribution to pavement marking management from this research was the development and use of level of service increments for describing the status of a given marking at some point in time.

Using the tools reported herein an expected service life for thermoplastic and paint pavement markings in NC can be estimated. A key finding of the research is that the markings have a far greater life expectancy than originally expected. Combining our predictive tool with level of service increments provides a holistic infrastructure management approach to pavement markings.

Keywords: Pavement Markings, Retroreflectivity, Pavement Management, Thermoplastics, Service Life

Subject Headings: Pavement Management, Pavement Markings, Traffic Control Devices, Service Life, and Regression Models

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INTRODUCTION

In 1993 the United States Congress directed the Secretary of Transportation to revise the Manual on Uniform Traffic Control Devices (MUTCD) to include a minimum standard of retroreflectivity for pavement markings [United States Congress 1993]. Although no official standards have been published yet, candidate minimum values for road pavement markings have been established [Turner 1998] and the FHWA is expected to publish pavement marking retroreflectivity standards in the near future.

With 78,000 miles of state maintained roads the North Carolina Department of Transportation (NCDOT) is charged with managing over 312,000 lane miles of pavement markings [Howard 2006]. Pavement markings cost NC approximately $14.5 million dollars a year in contractor-performed work [Howard 2006] and much more when one also considers in-house work. The proposed Federal standards are of concern to NC and other states.

The purpose of this paper is to present the results of an analysis of pavement marking deterioration and the predictive models that were established to determine it. These models can provide NC and other states with new information about pavement marking performance that will focus limited resources where they are most needed and help them avoid replacing materials with effective life still remaining, thus helping them address any new Federal standards in an efficient way.

OBJECTIVE AND SCOPE

The objective of this study was to determine the performance characteristics of thermoplastic pavement markings using data from the NCDOT and to create viable life cycle predicative models for those markings. Although the focus of this research was on thermoplastics an evaluation of paint pavement marking materials was also conducted and models were created for the performance of both thermoplastics and paints. Specifically, this paper:

- Evaluated variables that affect pavement marking service life.
- Created a pavement marking degradation model for thermoplastics and paints.
- Established performance-based level of service increments using the proposed minimum standards and the degradation rates established from the degradation model.
- Predicted the life of pavement markings, based on their deterioration rate and on FHWA/NCDOT minimum levels.

BACKGROUND

Understanding retroreflectivity performance over time is important to establishing an optimum pavement marking strategy. This section provides a basic description of pavement marking materials and retroreflectivity measurement, and highlights five previous studies that addressed pavement marking service life.

Marking Materials

According to the American Association of State Highway and Transportation Officials (AASHTO), markings control traffic to encourage safe and expeditious operations [AASHTO 2004]. For highways and streets AASHTO classifies markings into three general types, which are pavement markings, object markings, and delineators [AASHTO 2004]. This research focuses on pavement markings, which AASHTO further defines as center stripes, lane lines, no-passing lines, and edge striping [AASHTO 2004]. In all cases pavement markings refer to long-lines and should not be confused with object markings or delineators. In this paper the type of pavement marking is defined by its lateral location on the roadway. Specifically, this paper refers to edge lines or “middle lines,” where middle lines represent both centerlines and lane (skip) lines.

Pavement markings are sometimes defined by type. Migletz and Graham [2002] listed 16 types of line marking materials available on the market as of 2002. The majority of the materials are defined as durable pavement markings, which simply means that they are expected to last longer than one year. Waterborne and solvent-based paints are typically considered to be nondurable pavement markings. These are expected to have a short service life of one year or less.

The NCDOT primarily uses four pavement marking materials which are paint, thermoplastics, epoxy, and polyurea. Paints make up nearly 60 percent of the pavement marking inventory for the NCDOT while thermoplastics represent another 23 percent [Howard 2006]. In 2003 the NCDOT decided to use polyurea instead of epoxy for concrete applications. Epoxy is still used in some limited applications but is in the process of being phased out of the inventory [Howard 2006].

Retroreflectivity

Pavement marking retroreflectivity is a term used to describe the amount of light returned back to a driver from a vehicle’s headlights as it is reflected from the pavement marking. The light provides drivers with critical information about the road and enables the driver to navigate safely at night. National Highway Cooperative Research Program (NCHRP) Project 17-28 concluded that there is no correlation between safety and the level of pavement markings retroreflectivity (Bahar, et al., 2006). Specifically the NCHRP 17-28 study indicated that what is important is the presence of markings but not necessarily whether the marking are “new marking bright” or “old marking bright”. The authors state that one hypothesis is that drivers compensate for the different levels by slowing down as the markings decrease in retroreflectivity (Bahar, et al., 2006). The authors also state that the best estimate of the joint effect of retroreflectivity and driver adaption is approximately zero for non-intersection road segments during non-daylight conditions (Bahar, et al., 2006). However, the NCHRP Project 17-28 study confirms that the presence of markings has an affect on safety. Ultimately, retroreflectivity is what makes pavement markings visible at night and the visibility of markings directly relates to driver safety [Al-Masaeid and Sinha 1994].

American Society for Testing Materials (ASTM) standard E1710-05 specifies that pavement marking retroreflectivity should be calculated by measuring the amount of light returned from a pavement marking when a handheld device directs light at the pavement marking. The entrance angle should be 88.76 degrees, which is measured from the reference axis which is a perpendicular line from the pavement surface. Additionally, the returned amount of light is measured at an observation angle of 1.05 degrees. The observation angle is based on a headlight mounting point at 0.65 meters directly over the stripe, and an eye height of 1.2 meters directly over the stripe which is the angle measured from the difference of the vehicle's headlight back to the drivers view from a point 30 meters in front of the vehicle [ASTMa, 2005].

The FHWA has not yet determined minimum retroreflectivity levels. Research recommendations have established three options as shown in Table 1 [Turner, 1998]. Essentially, the column headings have yet to be finalized. Prior to publication as a standard, the three options will likely need to be reduced to a single definition of roadway classifications and speeds.

The proposed standards are set up as a matrix that accounts for three major variables, which are speed, presence of raised retroreflective pavement markings (RRPMs), and color. The matrix separates roadways with and without RRPMs, and also provides separate standards for white and yellow markings. For example, white pavement markings on a road with a speed limit of 70 mph and without RRPMs would require a value of 150 $mcd/m^2/lx$, as shown by the shaded portion of Table 1.

Previous Studies

Five major studies were reviewed that provide insight into pavement marking retroreflectivity performance. These five studies are by Andrady; Lee, et al.; Migletz, et al.; Abboud and Bowman; and Sarasua, et al. Each of the five studies evaluated pavement marking retroreflectivity performance over time and explored the performance characteristics of pavement markings so that predictive models, service life estimates, or degradation curves could be established. Thus, they are closely related to the work reported here. The researchers recognize that there are many ongoing studies regarding pavement marking retroreflectivity, most of which are focused on the relationship between safety and retroreflectivity. These five studies were the ones in the literature with a primary focus on pavement marking performance and modeling.

Andrady

Sponsored by the NCHRP, Andrady [1997] developed one of the first degradation models for pavement marking retroreflectivity. The focus of Andrady's study was to determine the environmental impact of volatile organic compounds and to identify alternative pavement marking materials. Part of Andrady's study was to evaluate the performance characteristics of pavement markings in terms of retroreflectivity. Andrady created the logarithmic model shown below for thermoplastics:

$$T_{100} = 10^{(R_0 - 100)/b} \qquad (1)$$

Where:

T_{100} = Time in months for the retroreflectivity to reach 100 $mcd/m^2/lx$

R_0 = Estimate of the initial retroreflectivity value

b = Gradient of the semi-logarithmic plot of retroreflectivity

The end of service life for this model was defined by reaching a retroreflectivity value of 100 $mcd/m^2/lx$. No goodness of fit measures have been published for this model.

Lee, et al.

In the mid-90's Michigan State University (MSU) evaluated the performance of several pavement-marking materials [Lee, et al., 1999] for the Michigan DOT. Their study sought to provide insight and guidance on how to implement cost effective procedures for pavement marking management. Focusing on four major marking materials (paints, thermoplastics, thermosets, and tapes) the study used 50 sample sites throughout Michigan to determine degradation rates for the various materials and a minimum threshold value of 100 $mcd/m^2/lux$ to indicate satisfactory marking performance.

The measuring device used was the Mirolux 12, which is a 15-meter geometry device. The study reported that there was a great deal of variability in the measurements provided by this device and that any future studies should consider better data collection equipment and methods.

Large variances in service life were reported. Data collection limitations minimized the amount of data that could be compared over time. Although the degradation rates were deemed to be linear, the R^2 values seemed low ($R^2 = 0.14$), providing little confidence that a linear degradation model was the best fit to the data. Of significant note was the finding that snowfall (snow plowing) was highly correlated to retroreflectivity degradation. Alternatively, Annual Average Daily Traffic (AADT), speed limit, and percent commercial traffic showed no correlation with degradation of retroreflectivity and were eliminated from the model.

The basic conclusions of the study indicated that water-borne pavement markings are the most cost effective type. This conclusion was based on reasonable performance compared to the low cost. Other materials performed better but the cost involved did not justify the improved service life. The model for thermoplastics by Lee, et al. is shown below.

$$R_L = -0.3622*X + 254.82 \qquad R^2 = 0.14 \qquad (2)$$

Where:

R_L = Retroreflectivity of pavement marking ($mcd/m^2/lx$)
X = Age of the pavement marking in days

The end of service life for this model was defined by reaching a retroreflectivity value of 100 $mcd/m^2/lx$.

Migletz, et. al.

The study used regression analysis to evaluate various materials and establish a predictive degradation curve of material performance over time. Marking material type, road surface type, and marking material color were the independent variables evaluated. Conducted by the Transportation Research Board (TRB) using a Laserlux mobile retroreflectometer (model number not specified), this study took place from 1994 to 1998 [Migletz, et al., 2001]. Its purpose was to evaluate the life of durable pavement markings. Included in the study, as a benchmark, was some limited evaluation of waterborne paints. The researchers collected data on 362 longitudinal (edge, center, and lane) pavement-marking lines from 85 sites across 19 states.

Results from the regression analysis indicated there was a great deal of variation in the performance of identical materials at different sites. The variation was attributed to differences in roadway type, region of the country, marking specifications, quality control, and winter maintenance. Analysis indicated that yellow lines performed better than white but this was attributed to the use of a lower threshold rather than to superior durability.

A follow up study [Migletz, et al. 2001] established a service life matrix that provides degradation rates for each color of each material type sorted by cumulative traffic passages and elapsed months. Cumulative traffic passages are the cumulative sum of the AADT over time. The matrix provides average service lives, standard deviations, and service life ranges in months. The findings for the two most common pavement marking materials are:

- Average life of waterborne white paint markings is 10.4 months
- Average life of thermoplastics is 26.2 months (white) and 27.5 months (yellow)

Abboud and Bowman

This study explored the application cost, service life, and user cost related to crashes for pavement marking retroreflectivity for the Alabama DOT. Abboud and Bowman [2002] developed an exponential regression model to depict the relationship between pavement marking retroreflectivity and vehicle exposure (VE). VE is a function of time and AADT. Also unique to this model is the absence of marking color and surface material, both of which have been established as dependent variables for pavement marking degradation in the other four studies cited here. The degradation model presented for paint was:

$$R_L = -19.457 * \ln(VE) + 26.27 \qquad R^2 = 0.31 \qquad (3)$$

The model for white thermoplastic edge lines was:

$$R_L = -70.806 * \ln(VE) + 150.55 \qquad R^2 = 0.58 \qquad (4)$$

Where:

R_L = Pavement marking retroreflectivity ($mcd/m^2/lx$)
ln = Natural logarithm
VE = Vehicle exposure = AADT * PM_age * 0.0304
AADT = Annual average daily traffic
PM_age = Age in months

Sarasua et. al. (2003)

The South Carolina Department of Transportation (SCDOT) supported a research project at Clemson University and The Citadel to evaluate the effective life cycle of pavement marking retroreflectivity over time [Sarasua, et. al. 2003]. The primary research objective was to develop predictive models that could estimate the rate of pavement marking degradation. The models could then be applied in an overall pavement markings management plan.

The project work focused on interstate highways and evaluated pavement marking retroreflectivity performance during a 28-month period. Data were collected 6 times at over 150 sites throughout SC's interstate system. An average R_L value was established from a series of 11 measurements taken with an LTL-2000 at each data collection site for each collection interval. Other retroreflectivity measurement instruments were used during the research but only the data from the LTL-2000 was used in the analysis. Furthermore, the data were collected using 30-meter geometry, which is the required geometry identified in ASTM E 1710-97.

In this study retroreflectivity performance was based on four major independent variables: surface type, marking material, marking color, and maintenance activities. Each variable was analyzed using regression analysis and was compared to the dependent variables. The dependent variables were the differences in retroreflectivity values and the percent differences in retroreflectivity values. Several other variables were considered but only these four were determined statistically to be viable independent variables that affected the performance of pavement markings over time. Traffic volume was one variable that was initially thought to impact performance but was later eliminated. Traffic volume was inversely correlated to the dependent variables and was thought to be adequately accounted for by the variable "time".

Sarasua, et al. developed two types of models for each combination of marking material, surface material, and color. One model was non-linear and represented the initial "break-in" period while the second model was linear and represented the degradation of the pavement marking retroreflectivity after the break-in period. The models were developed for thermoplastics and epoxy. The thermoplastics on asphalt models are shown below.

Model for white thermoplastics:	Diff = -0.06*(Days) – 6.80	$R^2 = 0.47$	(5)
	% Diff = -0.03*(Days) – 3.29	$R^2 = 0.39$	(6)
Model for yellow thermoplastics:	Diff = -0.03*(Days) – 3.63	$R^2 = 0.21$	(7)
	% Diff = -0.02*(Days) – 2.35	$R^2 = 0.24$	(8)

Where:

Diff = Difference in retroreflectivity over time
% Diff = Percentage of difference in retroreflectivity over time
Days = Time in days

The end of service life for this model was defined by reaching a retroreflectivity value of 100 mcd/m^2/lx.

Summary of Literature

This literature review presented the existing knowledge base in the field of pavement marking retroreflectivity performance modeling. Table 2 shows a summary of the five studies reviewed. There are large differences in the degradation models between the different research efforts. Three of the five studies concluded that pavement markings degrade linearly while two concluded that they follow a logarithmic decay model.

Another finding is that none of the previous efforts examined the impact of lateral line location on the overall performance of a given pavement marking. Logically, the performance of a line should depend on its lateral placement, since some lines like lane lines are typically hit by vehicles more often than other lines like edge lines.

METHODOLOGY

This section presents the methodology used for data collection and analysis in this study. The data used for this study were collected by an independent contractor who was originally hired by the NCDOT to measure retroreflectivity for specified NC roads for the purpose of quality assurance for new markings. Since the researchers did not have control over the data collection methodology there were some limitations on the analysis associated with using the existing data. Fortunately, some of the data were useful for this purpose. For most of the results reported herein the available data set was reduced to roads that used thermoplastic pavement markings. Furthermore, for the initial analysis, only those roads that had been under observation for a full five years were used. Limited data were available for analyzing paint based pavement markings.

Least squares analysis was employed as the modeling method. A range of possible variables was evaluated for inclusion in the model, but only those variables with a significant impact on the degradation of pavement markings were kept in the model.

Data

The retroreflectivity data for this study were collected via a modified Laserlux mobile retroreflectometer (model LLR5) mounted on a Chevy Suburban. According to Lundkvist and Isacsson [2007] vehicle-mounted retroreflectometers are preferred because they allow a technician to safely collect a large amount of data at highway speeds. The alternative to the mobile collection device is a handheld unit, like the LTL-2000 that was used in other studies. NCDOT's decision to use the mobile device enabled the safe and efficient collection of a large amount of data.

The data were collected using the standard 30-meter geometry required by ASTM. The R_L readings are averaged for every tenth of a mile and recorded in the onboard computer. The R_L value has units of mcd/m^2/lx and is an average of all the valid scans recorded for a tenth-mile road segment. The data collected for thermoplastics included 56 segments that represent approximately 450 miles of roadway. The data collected for paints included 37 segments that represent approximately 300 miles of roadway.

Vehicle-mounted devices are subject to errors from variations in the vehicle suspension and in the roadway surface. Current standards are not published for mobile collection devices; however, the calibration process used throughout data collection minimized these errors. Prior to a data collection trip the Laserlux unit was calibrated with a known test bed of pavement markings at the fleet's maintenance facility. The test bed was comprised of pavement markings with known retroreflectivity values that were established using the LTL-2000 hand held device. The LTL-2000 calibration process met the ASTM standards required for pavement markings retroreflectivity. Using the known test bed, established with the LTL-2000 handheld device, enabled the technician to calibrate the mobile device. The calibration process accounted for errors due to changes in vehicle load, tire pressure, and ambient light. In the field a handheld LTL-2000 was used to make sure that the Laserlux mobile device stayed calibrated to handheld standards. Calibration was performed in the field on each collection segment and during collection when conditions changed.

Minimum Standard

Establishing a minimum standard for pavement marking retroreflectivity is a key step in determining its service life. This study used a classification system based on the level of service (LOS) concept to identify the current condition of pavement markings as well as to determine the expected lengths of their service lives. The LOS increments and NC minimum standards are derived from existing pavement marking specifications for retroreflectivity [Sitzabee, 2006]. The LOS is separated into durable (thermoplastics) and nondurable (paints) since each have a different application within the state of NC based on the roadway's AADT.

Table 3 shows the LOS increments used in this research. The left columns show the increment values for thermoplastic markings and the right columns show the increment values for paint markings. All values are in mcd/m^2/lx. The red LOS, shaded in Table 3, indicates the minimum standard for retroreflectivity that was used in this study and is the basis for defining the end of service life condition.

Modeling the Data

The researchers used Jump software to develop a degradation model for the data. Both continuous and categorical data were considered in fitting the model to the data. The analysis for thermoplastics on asphalt included 56 road segments all of which had a full five years of available retroreflectivity data that were collected at the following increments: 0, 6, 12, 24, 36, 48, and 60 months. The data set included pavement marking retroreflectivity values, time, initial retroreflectivity, AADT, geographical region within NC, line width, line thickness, and snowplow activity. Values for these variables, including their ranges, are given in the "Variables" section below.

A stepwise selection process was used in developing the model. Each candidate variable was inserted into the model one by one and checked. Only those variables that reached a level of significance greater than 95 percent were left in the model. Once the variables were defined the candidate model was developed and evaluated based on R^2.

A linear regression model makes two major assumptions. The first major assumption is that the responses are independent and normally distributed. A Q-Q plot is a method used to check that this assumption is true. A Q-Q plot is a graph of the residuals plotted against a set of percentiles of the standard normal distribution. Under the assumption of normality, the Q-Q plot should approximate a straight line.

The second major assumption is that the population variances are equal. A plot of the residuals against the predicted values is used to confirm this assumption. The residual plot of the predicted values is a graphical representation of the offset of each value. The desired outcome is an even distribution of residuals around the mean value. A consistent pattern that shows equal offsets is expected if the variances are equal. However, the equal variance assumption is often violated because the variances typically increase or decrease with the expected response, showing a cone shape in the plot of the residuals.

RESULTS

A detailed evaluation of the variables that affect the degradation of pavement markings was conducted. This section presents the results of these studies for both thermoplastics on asphalt and for paints. Based on the models the researchers found that pavement marking R_L degraded linearly for the first five years of its life cycle. To obtain the service life the linear degradation was extrapolated to the point where the curve reached the defined end state. The assumption is that the material would not subsequently change the nature of the degradation pattern and would remain linear for the remainder of the life cycle. This was considered a conservative assumption consistent with the literature. Recall that three of the five studies presented earlier were linear and two were logarithmic. If the degradation was in fact logarithmic beyond the range of this database, this would result in an even longer service life.

Variables

During stepwise selection the F-statistic was used to check the effect of each candidate variable on the model. A forward stepwise selection was performed where the model starts with one independent variable and the effect was checked using the F-statistic. During each step forward the researchers added and checked a new independent variable. If the variable passed the effects test it was retained in the model. If it failed the variable was removed from the model. The researchers repeated this process until all the variables had been checked.

Retroreflectivity (R_L) was chosen as the dependent variable. The results of the effects test for the consolidated model are summarized in Table 4, which shows that time, the initial R_L value, AADT, line type, and color each significantly affected the model.

The researchers believe that the snowplow, region, line width, and line thickness variables could have an impact on pavement marking performance to some extent and checked each of those. However, each of the variables was not considered statistically significant. The lack of statistical significance for these variables is attributed to limitations in the data and not necessarily because of a lack of impact on degradation. Further explanation of each variable in the model is presented below.

For the effects test the null hypothesis (H_0) stated that the impact of the variable on the degradation of pavement marking retroreflectivity was insignificant. The alternative hypothesis (H_a) stated that the impact of the variable on the performance of pavement marking retroreflectivity was statistically significant. A probability of F-value less than $\alpha = 0.05$ indicates that H_0 should be rejected in favor of H_a and the variable should be kept in the model because there is statistical evidence that the variable impacts the performance of pavement marking retroreflectivity. As a final step in evaluating the variables the correlation of all the combinations of variables was checked and none were above $|0.5|$.

The independent variables included in the model for thermoplastics were:

1. Time – is a continuous parameter and is the most significant variable affecting degradation of pavement marking retroreflectivity. All pavement-marking studies reviewed included time as the most significant variable affecting retroreflectivity degradation. Time is measured in

months from marking installation. The points of time that were modeled were 0, 6, 12, 24, and 60 months.

2. Initial R_L value – is a continuous variable measured in mcd/m^2/lx. This variable is the initial value of retroreflectance and is measured within the first 30 days of application of the marking. Tables 5 and 6 illustrate the values of initial R_L used in this study for both thermoplastics and paint. The mean, standard deviation and range of R_L values are given.

3. AADT – Annual average daily traffic is a continuous parameter that measures the volume of traffic on the roadway in vehicles per day. Sarasua, et al. [2003] argued that AADT was not significant and was accounted for as a function of time. However, we included AADT as a candidate variable because of the previous report by Abboud and Bowman [2002] which indicated that AADT had a significant impact on pavement marking degradation apart from time.

   The reader should note that AADT is not used as a variable in the paint model. This is because the paint AADT ranged from 200 - 50,000, a variance which caused it to fall out of the model. The paint data was also limited to contractor performed painting that was installed in non-typical applications of AADT > 4,000. Thus, it was not deemed to be generally representative.

   For thermoplastics we acquired actual AADT values from the NCDOT for the year 2006. The AADT range was 2,500 – 50,000. The mean and standard deviation were 21,102 and 17,300, respectively.

4. Line Type – also called lateral location – is a categorical parameter that is defined by the transverse position of the pavement marking on the roadway. This variable was included because of the intuitive perception of different vehicle wear attributed to the location of the line on the roadway. This parameter has two positions: edge lines or middle lines. For the purpose of this study centerlines and skip lines were combined into a single category called middle lines. This was done since both types are in a wheel path.

5. Color – is a categorical parameter that defines the color of the pavement marking material. In this study color is either white or yellow.

The AADT and initial R_L variables warrant more discussion. First, an estimate of AADT is usually available for most roads. The AADT values used in this model were 2006 and were used with the understanding that the changes from year to year are minor. Future studies would enhance the model by tracking the actual AADT per year along with the R_L value recorded. Even though this is a limitation in the current model and contributes to some unknown error the effect on the overall model should be small since the coefficient for this variable was small. Additionally, the AADT values are not updated by the NCDOT every year for every road, and even when available by year often have large errors. Still, when using the model to predict future R_L values a forecasted AADT value could be used to increase the quality of the predicted life cycle of the pavement marking.

The initial R_L variable can be handled two ways in the model. NCDOT required that the initial R_L values meet a minimum specification value. Analysts can then use the model along with the initial specification values for R_L in predicting the pavement marking lifecycle. This would be useful in a large majority of the cases where the initial values are not known. However, use of actual initial R_L values would give analysts a better prediction of the lifecycle and is highly recommended in future studies.

Models

This section shows the results for the models developed for thermoplastics and paints. The thermoplastic model is presented first followed by the paint model. In each case a summary is presented of the candidate model. Next, an explanation is presented of the statistical checks used to validate the linear regression assumptions. Finally the models are summarized and an estimated service life is presented for both thermoplastic and paint pavement markings.

<u>Thermoplastics</u>

There were a total of 336 observations recorded for all thermoplastics on asphalt. All of the thermoplastics applications followed NCDOT specifications and were contractor-installed using a ribbon-extrude technique. In most cases the thermoplastic material uses a standard bead size with a refractive index of 1.50 or greater. The specification calls for seven pounds of beads for every 100 square feet of thermoplastic. In some cases large beads were used but NCDOT discourages their use.

A general linear model was developed for thermoplastics on asphalt based on the variables that were validated by the effects test (time, initial R_L value, AADT, color, and lateral location). However, the reader is cautioned not to extrapolate the model beyond the bounds of the data. The thermoplastic model produced an R^2 equal to 0.60 which was considered to be good compared to previous studies reviewed in the literature. Table 7 shows a summary of the parameter estimates for the model and gives the standard error, t-ratio, and Probability > |t| values. The model was:

$$R_L = 190 + 0.39 * R_{L\ Initial} - 2.09 * time - 0.0011 * AADT + 20.7 * X_1 - 20.7 * X_2 + 19 * X_3 - 19 * X_4 \quad (11)$$

Where:

R_L = Retroreflectivity in mcd/m^2/lx
$R_{L\ Initial}$ = Initial retroreflectivity in mcd/m^2/lx
time = time since installation in months
AADT = Annual average daily traffic in vehicles per day
X_1 = 1 if edge line, 0 otherwise
X_2 = 1 if middle line, 0 otherwise
X_3 = 1 if white line, 0 otherwise
X_4 = 1 if yellow line, 0 otherwise

Figure 1 shows a residual plot for the model's predicted values. The desired effect is to have an even distribution of the residuals around the mean value which is represented by the horizontal line at zero. The plot shows a fairly distributed set of residuals about the mean indicating that the variances are consistent across the population of predicted R_L values.

Figure 2 shows the q-q plot of the model's residuals. The plot clearly shows a straight-line pattern. A straight-line pattern is a visual cue that the distribution is normal. A Shapiro-Wilk goodness of fit test is a statistical check that can determine if the distribution can be assumed to be normal. In a Shapiro-Wilk test the null hypothesis states that the population is normal and that any value below 0.05 would support rejecting the null hypothesis. In this case the probability of $P < W$ equaled 0.2142, providing statistical evidence to keep the null hypothesis and assume that the distribution is normal. This is an important step in validating a regression model since the model relies heavily on the assumption of normality.

Paints

Before this project, the NCDOT believed that paint markings had a limited service life of approximately one year. This belief was based in large part on the Migletz, et. al. [1999] study which found a mean life of a paint marking to be approximately 10 months. The intent of the NCDOT in collecting paint data was therefore entirely for quality assurance, the data were not intended for analysis, and only a limited number of data points were collected for paints. However, because paints make up nearly 60 percent of the pavement markings on the roadways in NC, an evaluation of the available paint data was performed during this research.

There were 37 road segments that had a full year of available data. The data were collected for paint at the initial, six-month and one-year points. The data collected included R_L values, initial R_L, time, road surface, material, color, and lateral location. The data collected for paints were for roads that were marked by contractors and therefore had to meet the minimum specification required by the NCDOT. All of the paints follow a specification using the same paint material manufactured by the NC prison system. The paint specifications call for a standard size bead with a refractive index of 1.50, and beads are applied at a rate of six pounds per gallon of paint. It is important to note that the model developed in this study was from contractor-installed paints but the majority of paint operations in NC are performed in-house.

The paint model is a general linear model for all paints on both asphalt and concrete. An effects test, using the F-statistic, was performed. The test revealed that the only important variables for this sample were initial R_L and time. Lateral location, color, surface material, AADT, snowplow, thickness, and width were all ruled out by the effects test using the F-statistic. The pavement marking retroreflectivity degradation model for paint is:

$$R_L = 55.2 + 0.77 * R_{L\ Initial} - 4.17 * time \tag{12}$$

Where: R_L = Retroreflectivity in mcd/m^2/lx
$R_{L\ Initial}$ = Initial retroreflectivity in mcd/m^2/lx
time = Time after installation in months

Table 8 shows the summary of the parameter estimates and gives the standard error, t-ratio and Probability > |t| values. The R^2 (0.75) and adjusted R^2 (0.75) values for the paint model were considered to be very good.

Figure 3 shows a residual plot of the model's predicted values. Unlike thermoplastics the distribution of residuals about the mean for paints is not as equal as desired and begins to show a fan-like pattern as shown by the two dashed lines in Figure 3. This would indicate that a transformation should be explored.

Figure 4 shows the Q-Q plot of the paint residuals. The plot shows a straight-line pattern, which supports the conclusion that the residuals are normally distributed. However, the pattern does deviate slightly at the ends indicating that another distribution may be appropriate. As such, the researchers also performed a Shapiro-Wilk test on the paint data. The test revealed that the $P < W$ value was equal to 0.0414. This value is below the desired value of 0.05 and would suggest rejecting the null hypothesis that the distribution is normal.

Because of the fan-like shape in Figure 3 and the null hypothesis being rejected by the Shapiro-Wilk test, the researchers performed a log transformation of the data and attempted to fit a new model. The Q-Q plot for the model using the log-transformed data looked similar to that of Figure 3, and the Shapiro-Wilk test for this new model resulted in a $P < W$ value equal to 0.0133. This gave evidence that a log transformation was not the right solution. Exponential and polynomial transformations were also tried with ineffective results. One possible cause of the questionable normality in the data is that this model combines the paint color and lateral location data into a single model.

As a result of the failing transformations, our best estimates for paint markings remain based on the linear model. The important finding with this model is that after two years the majority of paint markings were still above LOS F, suggesting that paints in NC typically have a service life of two years or more.

<u>Validation</u>

A good way to validate a model is to reserve data from the original collection and then compare those points to predictions from the developed model. This was considered early on in the research, but the limited amount of data in some areas would not allow for a random removal of the reserved data without negatively impacting the modeling effort. It was evident that additional data would need to be collected in order to validate the model.

On September 18th and 20th of 2007 we collected additional data for the purpose of validating the thermoplastic and paint models previously established. A one-mile road segment was identified for both thermoplastics and paint. The thermoplastic segment had an eight year old white edge line and five year old yellow center and white skip lines. The paint segment had a two year old segment of white edge line and yellow centerline. A sample of 35 retroreflectivity readings was collected from each segment. The 35 readings were taken along the one mile section of road at random points selected by a random number generator.

Table 9 shows the estimates from the model and summaries of the validation data. Since the initial R_L values were not known for the road segments the average value for initial R_L from the database was used. The predicted estimate was very close to the mean of the field measurements for white thermoplastic and paint pavement markings. The model was within one unit of predicting the actual value for paint. In each case except yellow middle markings the predicted value was within one standard deviation of the mean of the field measurements.

In the fourth case in Table 9, the prediction for yellow middle markings was outside the 95 percent confidence interval ("Lower CI" and "Upper CI" in Table 9) and close to two standard deviations away from the mean of the measured values. However, it is important to note that during the collection of the yellow middle validation data the researcher observed a section of the markings that had clearly been overlaid with new material. It is possible that the time used to make the yellow middle model prediction was not accurate, or at least not accurate for a portion of the one-mile road segment. Validation of yellow middle values is a limitation of this study. Further validation in future studies is desired overall but specifically warranted for yellow middle markings.

Service Life

This paper presented pavement marking degradation models for thermoplastics and paints. The models yielded degradation rates of 2.09 $mcd/m^2/lx$ per month for thermoplastics and 4.17 $mcd/m^2/lx$ per month for paints. With these rates and the designation of minimum standards of retroreflectivity, service lives can be estimated as shown in Table 10.

Column one of the Table 10 shows the individual category, color, and material of the pavement marking. Columns two and three show the minimum required retroreflectivity value required by NCDOT for the marking to be useful and the initial specification value, respectively. Columns three and four show the resulting service life for pavement markings in months and years. Note that an AADT of 10,000 was used to estimate the generic service lives in Table 10. For more accurate service life of pavement markings on a given road segment, the actual initial R_L value recorded and the forecasted AADT could be used. It is important to remember, as noted above, that the service life predictions go beyond the range of data for the model but the values are considered viable for making management decisions.

CONCLUSIONS

In the literature review five studies were identified that have developed various pavement marking degradation models. Three of the five studies concluded that pavement markings degrade linearly while two studies suggest a logarithmic decay. This study confirmed that both thermoplastics on asphalt and paint pavement markings could be modeled as linear through 60 months for thermoplastics and through 12 months for paint.

An alternative logarithmic decay degradation model for paint was also developed and tested. However, the coefficient of determination dropped and the residual plots showed no improvement in the distribution of variances compared to the original linear model, so it was deemed unhelpful. Polynomial and exponential forms were checked and found to be unhelpful as well.

Specifically for markings in NC this study determined:

1. For an AADT of 10,000 vehicles per day, the expected service life for thermoplastics on asphalt ranges from 5.4 years to 8.75 years depending on the color and lateral location (see Table 10).
2. Paints have a service life slightly greater than two years (see Table 10).
3. Both thermoplastic and paint pavement markings were found to have a far greater life expectancy then originally expected.

4. Lateral location is a key independent variable in modeling thermoplastic pavement marking degradation.
5. AADT had a small but significant impact on the degradation of theormoplastic pavement markings.

The service life of paint pavement markings turns out to be a significant finding. In NC, paints are typically managed on an annual cycle because the assumption is that their service life is approximately one year. The predictive model for paints estimates a mean service life of more than two years. This has critical budget implications for pavement marking managers. It is important to note that the data used for developing the service life was from contractor-performed work. As such, in house marking operations would need to meet the same initial specifications required for contractors in order to achieve the same two year service life.

We have also verified that pavement markings located in the travel path (either center or skip) lines will degrade faster than pavement markings located at the edge of the pavement. This study confirms the findings about the impact of lateral line location on pavement marking degradation from earlier research [Craig, et al., 2007]. The discovery of the impact of lateral location as an independent variable affecting pavement marking degradation adds significantly to the existing pavement marking knowledge base and needs to be considered in both modeling and management of pavement markings.

Finally, there have been conflicting findings about the impact of AADT on pavement marking degradation. Sarasua, et al. [2003] found that AADT was not a significant factor whereas Abboud and Bowman [2002] found that AADT and time both contribute to the degradation of pavement markings. This study found that, for NC data, AADT and time both significantly impact the degradation of thermoplastic pavement markings.

FUTURE RESEARCH

It is highly recommended that additional studies of the degradation rates of other pavement marking materials, including polyurea and resin-based paints, be undertaken. Additionally, further study should be undertaken with respect to the effects of snow plowing on pavement markings. The NCDOT does not have to do a lot of snow plowing on its roads, and the data collected for this variable in this study were categorical, meaning that only a yes or a no was recorded if a road segment was plowed. A future research effort should collect continuous data on snow plowing, recording the number of times a year that a road segment is plowed and then exploring the impact that plowing has on pavement marking degradation.

Paints make up the overwhelming majority of pavement markings and warrant further study. This research was limited in the amount of paint data collected since the study used existing data from contractor-installed paint collected only at the initial, six-month, and one-year increments. The limited data contributed to the general form of the paint model. We recommend analysis of paint data from in-house installations, more segments, over longer time periods (0 to 24 months and beyond), and with more frequent collection. Tests for normality in the data suggest that the paint data in this study came from different populations. Future research should focus on exploring the development of individual models based on color and lateral location categories.

There is clear evidence to support the inclusion of color and lateral location as variables in the paint model. Future research should collect the appropriate data and explore this as well as the other variables that are suspected of impacting degradation but were not statistically significant in the models presented here.

DISCLAIMER

The views expressed in this article are those of the authors and do not reflect the official policy or position of the United States Air Force, Department of Defense, the U.S. Government, NCSU, or the NCDOT.

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Tables

Table 1. Recommendations for Minimum Retroreflectivity Values [Turner 1998]

Option 1		Non-Freeway ≤ 45 mph	Non-Freeway ≥ 45 mph	Freeway ≥ 55 mph
Option 2		**≤ 40 mph**	**≥ 45 mph**	**≥ 60 mph and ≥ 10,000AADT**
Option 3		**≤ 40 mph**	**45 – 55 mph**	**≥ 60 mph**
With RRPM	**White**	30	35	70
	Yellow	30	35	70
Without RRPM	**White**	85	100	150
	Yellow	55	65	100

Note: Retroreflectivity values are $mcd/m^2/lux$ and measured with 30-m geometry
Adapted from an unpublished report.

Table 2. Summary of Modeling Studies

Research Sponsor	Year	Authors	Model Type	R^2	Marking Material
NCHRP	1997	Andrady	Logarithmic	Unavailable	Unavailable
MSU	1999	Lee, et al.	Linear	0.14	Thermo
TRB	2001	Migletz, et al.	Linear	Unavailable	Paint & thermo
Alabama DOT	2002	Abboud & Bowman	Logarithmic	0.31 - 0.58	Paint & thermo
SCDOT	2003	Sarasua, et. al.	Linear	0.21 - 0.47	Thermo
Thermo: thermoplastics					

Table 3. LOS Increments and NC Minimum Retroreflectivity Standards

LOS	Thermoplastics		Waterborne Paint	
	White	**Yellow**	**White**	**Yellow**
Blue (A)	≥ 275	≥ 210		
Green (B)	200-274	145-209	≥ 250	≥ 215
Yellow (C)	175-199	125-144	150-250	115-215
Amber (D)	150 - 174	100 - 124	100-149	65-114
Red (F)	≤ 149	≤ 99	≤ 99	≤ 65

Table 4. Effects Test for White Edge Using the F-Statistic

Variables	Sum of Squares	F Ratio	Prob > F
Time	535700	189	< 0.0001
Initial RL	129090	46	<0.0001
AADT	73461	26	<0.0001
Line Type	102641	36	<0.0001
Color	43318	15	0.0001

Table 5. RL Summary Statistics for Thermoplastics on Asphalt

Time (months)	Mean RL (mcd/m2/lx)	RL Standard Deviation (mcd/m2/lx)	RL Range of Values (mcd/m2/lx)
0	365	103	168 - 563
6	324	82	201 - 473
12	319	85	163 - 488
24	235	75	110 – 443
36	212	67	93 - 383
48	223	62	88 - 364
60	222	75	98 - 389

Table 6. RL Summary Statistics for Paint

Time (months)	Mean RL (mcd/m2/lx)	RL Standard Deviation (mcd/m2/lx)	RL Range of Values (mcd/m2/lx)
0	222	60	75-348
6	202	56	71-332
12	172	57	67-364

Table 7. Consolidated Model Parameter Estimates

Estimator	Estimate	Std. Error	t Ratio	Prob>|t|
Intercept	190.7	17.7	10.18	<0.0001
R_L Initial	0.385	0.057	6.75	<0.0001
Time	-2.090	0.152	-13.75	<0.0001
AADT	-0.00113	0.0002	-5.09	<0.0001
X_1	20.7	3.44	6.02	<0.0001
X_2	-20.7	3.44	6.02	<0.0001
X_3	19.0	4.85	3.91	0.0001
X_4	-19.0	4.85	3.91	0.0001

Table 8. White Middle Paint Parameter Estimates

Estimator	Estimate	Standard Error	t Ratio	Prob > |t|
Intercept	55	12.0	4.58	<0.0001
RL Initial	0.769	0.045	19.97	<0.0001
Time	-4.17	.606	-6.89	<0.0001

Table 9. Predictive Estimate Compared to Summary of Validation Data

Line Type	Time (Months)	AADT (vpd)	Initial RL ($mcd/m^2/lx$)	Estimated Value from Model ($mcd/m^2/lx$)	Validation Segment Mean ($mcd/m^2/lx$)	Validation Segment Lower CI ($mcd/m^2/lx$)	Validation Segment Upper CI ($mcd/m^2/lx$)	Validation Segment Standard Deviation ($mcd/m^2/lx$)
Thermoplastic								
White Edge	96	22000	423	169	156	144	169	37
Yellow Middle	60	22000	286	112	167	158	176	26
White Middle	60	22000	423	204	199	188	209	30
Paint	24	1300	225	128	127	111	143	67

Table 10. Summary of Thermoplastic Pavement Marking Service Life by Category

Category	**Minimum Standard ($mcd/m^2/lx$)**	**Initial Specification Value ($mcd/m^2/lx$)**	**Estimated Service life (Months)**	**Estimated Service Life (Years)**
White Edge Thermoplastics	150	375	102	8.5
White Middle Thermoplastics	150	375	84	7.0
Yellow Edge Thermoplastics	100	250	85	7.1
Yellow Middle Thermoplastics	100	250	65	5.4
White Paints	100	225	31	2.6
Yellow Paints	65	200	26	2.2

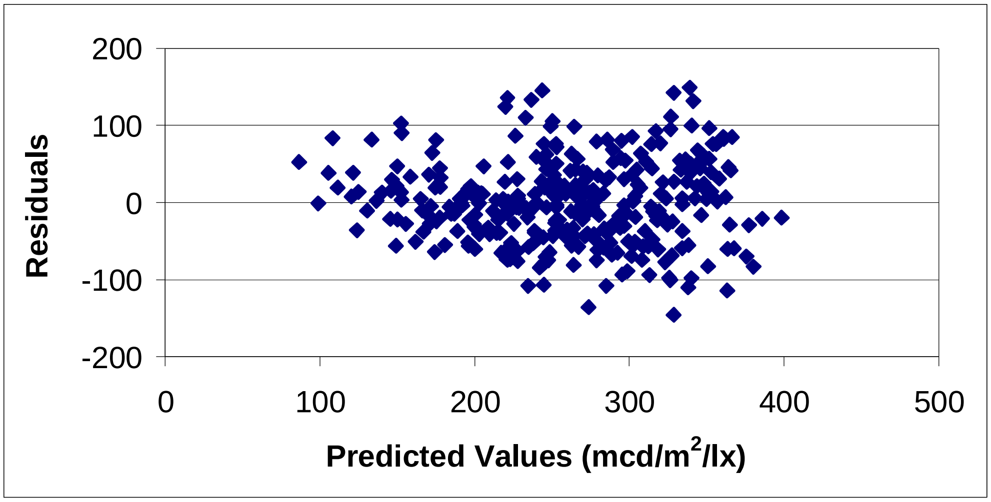

Figure 1. Thermoplastic Model Residual Plot of Predicted Values

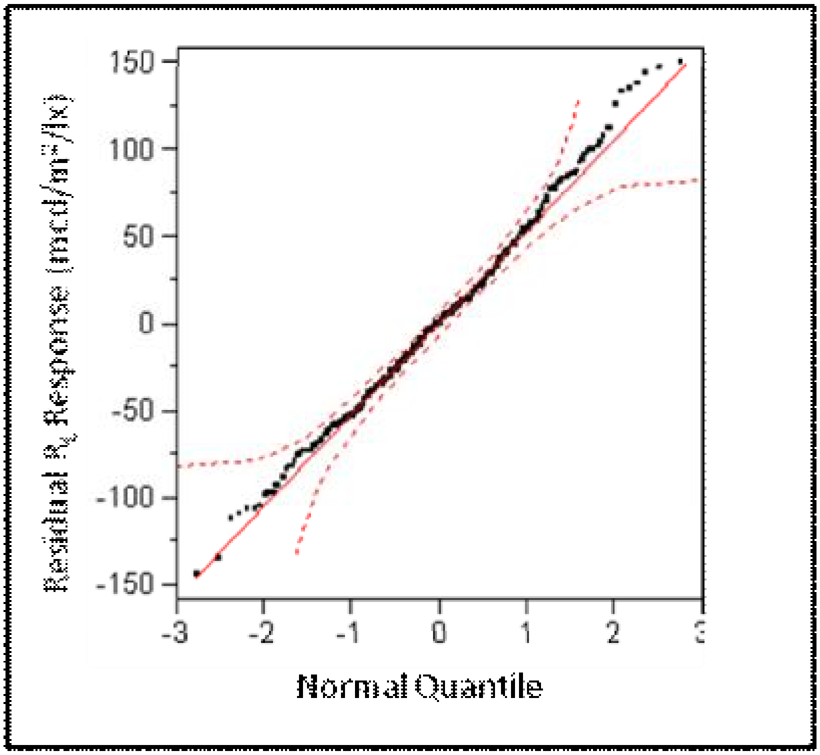

Figure 2. Thermoplastic Model Q-Q Plot

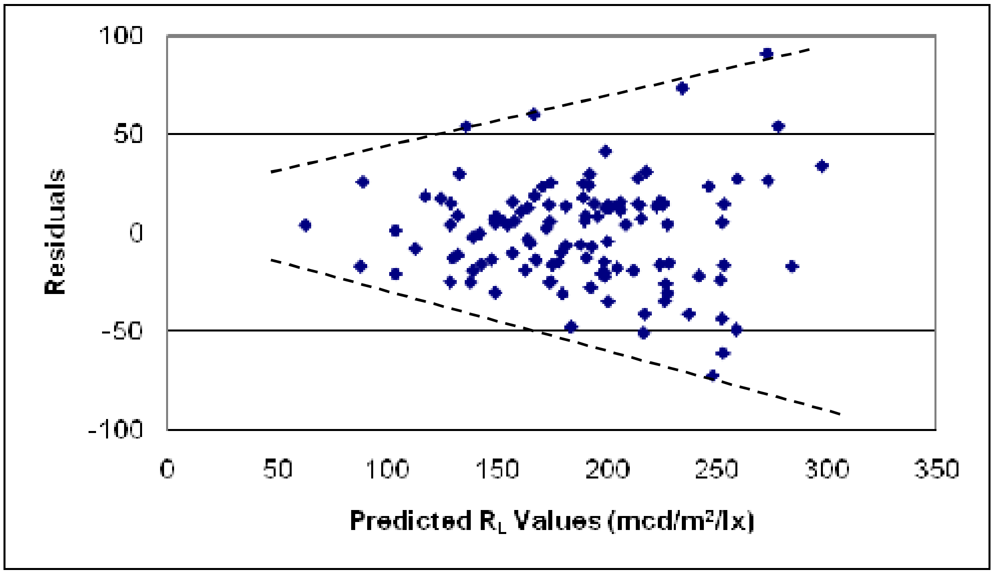

Figure 3. Residual Plot of the Predicted Values for Paints

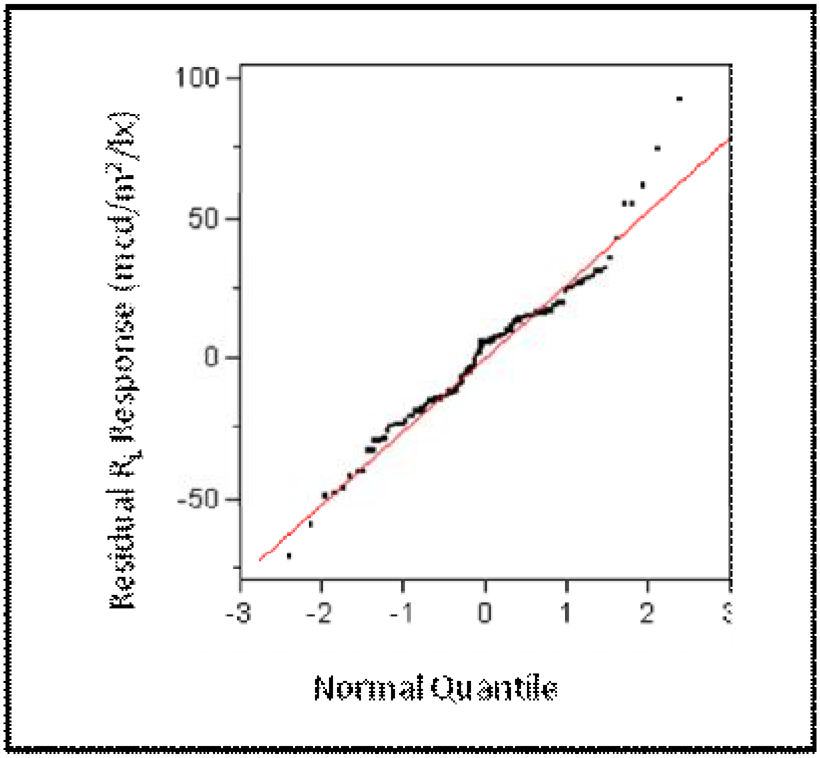

Figure 4. Q-Q Plot for Residuals of Paints