Pavement Marking Specifications Compliance and Modeling of Retroreflectivity Performance

by

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Abstract

This study provided an analysis of a database containing 7,840 observations of 40 highway pavement marking projects constructed in Alabama in 2007 to determine the extent to which marking properties complied with ALDOT specifications. A statistical analysis was also performed on these observations to determine mean, standard deviation, and coefficient of variation by color and type of markings for marking properties. Results showed that retroreflectivity had significant variation.

This research also developed models of retroreflectivity performance over time for thermoplastic markings, which was executed for 15 projects that had measurements of retroreflectivity for the same locations in 2007, 2008, 2009, and 2010. A linear model considering age, initial retroreflectivity, and AADT as independent variables was the one which best represented data, with R^2 values of 0.398 for white markings and 0.479 for yellow markings.

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Chapter One

Introduction

Highway systems are comprised of a number of elements, each with own role. Pavement markings are elements which can convey regulations, guidance, warnings, and may also be used as supplements to other traffic control devices. As pavement markings guide road users, providing them information to understand what happens in the roadway, they can improve safety by reducing the risk of accidents.

There are many different materials and colors used for pavement markings (e.g. primarily white and yellow in the U.S.). Many factors can influence the performance of pavement markings over time, and consequently, their useful life. Higher traffic volumes, for example, may cause more rapid marking degradation, a centerline marking might have greater wear than an edge line, and higher percent of trucks may cause greater deterioration. Also, geographic location and climate can influence pavement marking durability.

Pavement markings need to be visible, during the day as well as at night, to support the driver's understanding of the roadway, supplementing other traffic control devices or used alone to convey regulations, guidance, or warnings. A sufficient level of visibility, or serviceability, can be determined through measurement of a number of properties. Minimum thickness requirements support visibility of the marking and also avoid premature maintenance. Chromaticity quantifies the color of the marking, and it needs to meet color specifications to distinguish a yellow marking from a white marking very clearly. For each chromaticity, there is a unique optimal color having its maximum luminance, which represents the amount of light emitted from a particular area. Retroreflectivity measures the incident light from a vehicle's headlights reflected back toward the general area of the light source, particularly the eye of the driver of the vehicle; this property is critical to nighttime visibility.

The rate of degradation of pavement marking retroreflectivity can be influenced by many factors, such as type of material, geographic location and climate, traffic volume, and percent of heavy vehicles. Determination of service life is essential to maintenance of markings, and it is closely related to retroreflectivity. This topic is becoming increasingly important, which can be attested to by the significant development of research on establishing minimum retroreflectivity levels, including a proposed amendment to the *Manual on Uniform Traffic Control Devices* (MUTCD) that would create a national standard (FHWA, 2010).

1.1. Background

Over the past decade, much advancement has been made with respect to quality and durability of pavement marking materials. When quantifying the performance of pavement markings, properties such as retroreflectivity, thickness, luminance, and chromaticity are typically measured. Agencies responsible for construction and maintenance of highways typically develop criteria for pavement markings to determine whether a new installation is acceptable.

The *Standard Specifications for Highway Construction*, produced by the Alabama Department of Transportation (ALDOT), is the document which provides the requirements for all projects performed in the State of Alabama (ALDOT, 2008). The edition applicable to the data analyzed in this study was published in 2006 and, since then, several changes on traffic stripe, markings, and legends specifications have been made and included in a series of five Special Provisions during 2007. The most recent publication is the draft of the 2012 edition of the *Standard Specifications for Highway Construction*, but only the 2007 Special Provisions apply to projects studied in this research.

There has not been a detailed study related to these changes in ALDOT specifications and the quality of pavement marking projects in Alabama have not recently been evaluated. As a result, there are some unanswered questions, such as the effects of ALDOT specification changes, the cost-effectiveness of materials used by the ALDOT for pavement markings, and durability of retroreflectivity.

A database containing observations of pavement marking properties on 40 projects in Alabama in 2007 was obtained from ALDOT. Additionally, data from 2008 to 2010 for 15 of these projects were available for analysis. The 2007 database includes properties such as thickness, retroreflectivity, luminance, and chromaticity; the 2008, 2009, and 2010 data has only retroreflectivity measurements. This thesis utilized this information to answer the important questions mentioned above related to pavement markings in Alabama.

1.2. Objectives

To guide the analysis of data applied to this study, and also understand how pavement markings in Alabama have performed, the main objectives of this research project are:

1. Document recent changes in ALDOT specifications (2007 Special Provisions);
2. Mine the database to:
    a. Determine the extent to which observations from the 40 projects from 2007 meet specifications;

b. Execute a statistical analysis of the observations from the 40 projects from 2007 (mean, standard deviation, and coefficient of variation by color and type, for each property measured);
c. Perform a benefit/cost analysis of pavement markings used in Alabama;
d. Model change in retroreflectivity over time, utilizing data from 2007 to 2010;
e. Develop a framework for future research, stating limitations of this study and how the results of this research can be extended in long-term studies.

1.3. Scope

A general analysis of 7,840 observations from all 40 projects in the 2007 database was performed. Properties of the markings of the projects in Alabama were compared to specifications to examine the percentage of observations that met ALDOT requirements. A statistical analysis, including mean, variance, standard deviation, and coefficient of variation is also provided for properties such as chromaticity, thickness, luminance, and retroreflectivity. This study also examined the feasibility of establishing a methodology to determine benefits based on retroreflectivity. Cost data were obtained from the ALDOT Tabulation of Bids database. Retroreflectivity modeling is also presented. Mathematical models were developed associating available variables, within the limitations of the database. This thesis can also serve as a starting point for more detailed studies in the future. Finally, the data included in these analyses were collected by ALDOT, and these data represent only a small portion of all ALDOT-sponsored projects that were constructed in 2007.

1.4. Outline

Chapter Two includes a detailed literature review which consists of a summary of pavement markings characterization, including materials, colors, and measurable properties related to them, such as thickness, retroreflectivity, luminance, and chromaticity. This chapter also includes an overview of pavement marking retroreflectivity models in the literature. In this chapter, a summary of pavement marking materials specifications and requirements in Alabama is presented, according to the 2006 Edition of the ALDOT *Standard Specifications for Highway Construction* and subsequent Special Provisions. Methods regarding economic evaluation, including benefit/cost estimation examples, and details about pavement markings service life and related retroreflectivity thresholds conclude the literature review.

Chapter Three contains the methods used to achieve the objectives of this research project. It provides an overview of changes in ALDOT specifications during 2007, as well as the approach to performing data mining and analysis of the 2007 database. Chapter Three also provides a framework for the retroreflectivity modeling performed in this thesis. This process includes the preparation of data for modeling and application of existing models in the literature to the current dataset. The feasibility of a benefit/cost analysis, given the available data, is also provided in this chapter. Finally, the development of several new models of retroreflectivity over time is explained in Chapter Three.

Chapter Four includes the results related to the application of the methodology explained in Chapter Three. Chapter Five presents the conclusions of this research and gives recommendations for subsequent studies, considering limitations of the existing dataset and approaches to overcome them.

Chapter Two

Literature Review

Pavement markings have an essential role in the highway system (Fu and Wilmot, 2008). In some cases, markings are used to supplement other traffic control devices such as signs and signals. In other instances, markings are used alone to effectively convey regulations, guidance, or warnings in ways not obtainable by the use of other devices (FHWA, 2009). The risk of accidents in roadways is reduced due to pavement markings, as they provide the driver's understanding of the roadway and his or her ability to stay on course (Montebello et al., 2000).

Characteristics of pavement markings can vary among the different materials and colors available, these variables include luminance, retroreflectivity, and cost for each type of pavement marking. An important issue with pavement markings is durability; the development of mathematical models that can predict the service life of pavement markings is a common approach to quantifying durability. These models typically refer to retroreflectivity as the main variable of analysis and typical independent variables are initial retroreflectivity, age of marking, and traffic. A highway agency typically develops requirements that have to be met. In Alabama, acceptable values for pavement marking parameters are presented in ALDOT's "*Standard Specifications for Highway Construction*" (ALDOT, 2008). Economic evaluation is also an important analysis for the project.

This chapter describes general characteristics of pavement markings, indicating the most commonly used types. It also provides an overview of existing models to predict life service of pavement markings. Finally, it presents a summary of different methods of economic evaluation analyses.

2.1. Characterization of Pavement Markings

There are a wide variety of characteristics, costs, and benefits among the different pavement marking materials which can make it a challenging task deciding which factors should be considered when selecting the type of pavement marking material for a particular road. There are several manufacturers of pavement marking materials competing for business and they distribute information on their products and on the competition's products, making comparisons based on this information difficult to understand and somewhat unreliable. (Montebello et al., 2000).

There are numerous types of materials used for pavement markings in the field today, including paint, epoxy, tape, and thermoplastic (Thomas et al., 2001). Each material has its own set of unique characteristics related to durability, retroreflectivity, installation cost, and life-cycle cost. Marking types are also wide-ranging and they include pavement and curb markings, delineators, colored pavements, channelizing devices, and islands (FHWA, 2009). Most used materials for pavement and curb markings placement are paints or thermoplastics (FHWA, 2009).

The materials used for markings should provide the specified color throughout their useful life. The *Manual on Uniform Traffic Control Devices* (MUTCD) determines that markings shall be yellow, white, red, blue, or purple. Black, in conjunction with one of the aforementioned colors, is also a usable color (FHWA, 2009). Pavement markings include longitudinal lines, transverse lines, words, and symbols. Longitudinal markings include centerlines, lane lines, and edge lines on paved streets and highways (Fu and Wilmot, 2008). The general functions of longitudinal lines are: a double line indicates maximum or special restrictions, a solid line discourages or prohibits crossing (depending on the specific application), a broken line indicates a permissive condition, and a dotted line provides guidance or warning of a downstream change in lane function (FHWA, 2009).

White and yellow are the two most commonly used colors for pavement markings (Fu and Wilmot, 2008). White markings, when used for longitudinal lines, delineate the separation of traffic flows in the same direction or the right-hand edge of the roadway. Yellow markings, when used for longitudinal lines, delineate the separation of traffic traveling in opposite directions, the left-hand edge of the roadways of divided highways and one-way streets or ramps, or the separation of two-way left-turn lanes and reversible lanes from other lanes (FHWA, 2009).

Marking systems should offer the best possible performance at the lowest possible cost. Regarding performance, the purpose of the markings is to facilitate safe and efficient traffic flow on highways (Cuelho et al., 2003). Configurations and visibility requirements of pavement markings are generally well-defined by publications such as the *Manual on Uniform Traffic Control Devices* (MUTCD) (Cuelho et al., 2003). Each standard marking shall be used only to transmit the meaning prescribed for that marking in the MUTCD (FHWA, 2009). All necessary markings should be in place before any new highway, private road open to public travel, paved detour, or temporary route is opened to public travel (FHWA, 2009).

Service life is one of the first factors to be considered when choosing a pavement marking material. Many factors can influence the service life of a pavement marking material including weather conditions, winter maintenance activities, installation conditions and quality, retroreflective optics used, binder type, binder thickness, binder color, traffic volume, and the minimum selected retroreflectivity level. Among these, the major factors that are known to have significant impacts on marking service life are traffic volume and minimum required pavement marking retroreflectivity level (Songchitruksa et al., 2011).

2.2. Retroreflectivity Threshold

The determination of when a pavement marking material is no longer serviceable is rather complex. Given a quantified terminal condition of a pavement marking material, it is not a simple task to forecast the remaining service life. The performance of a pavement marking material has been judged based primarily on its retroreflectivity. Retroreflectivity has been used extensively in past studies as an important factor in analyzing the performance and cost-effectiveness of a pavement marking material (Zhang et al., 2006). Retroreflectivity can be defined as the portion of incident light from a vehicle's headlights reflected back toward the eye of the driver of the vehicle. Retroreflectivity is provided in pavement marking materials by glass or ceramic beads that are partially embedded in the surface of the material (Thomas et al., 2001). Figure 1 shows how retroreflection occurs.

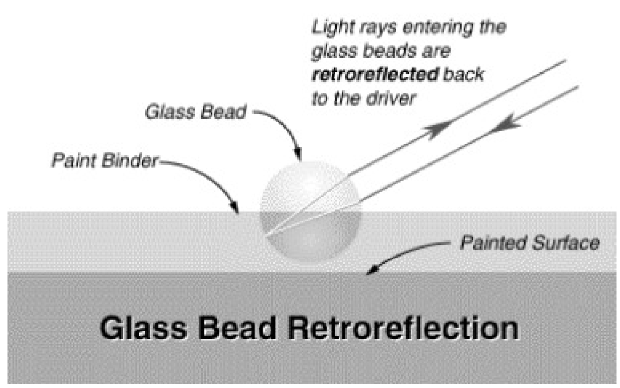

Figure 1 – Glass Bead Retroreflection

SOURCE: Thomas et al., 2001

Pavement markings are typically retroreflective. This retroreflective property of the pavement markings is essential for nighttime visibility. Retroreflectivity is typically measured in units of millicandelas per square meter per lux (mcd/m^2/lux) using retroreflectometers. The candela is the International System (SI) unit for luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540×10^{12} hertz and that has a radiant intensity in that direction of $^1/_{683}$ watt per steradian. A common candle emits light with roughly 1 candela luminous intensity. The SI unit for illumination is defined as lux, and it represents the illumination produced by a luminous flux of 1 lumen distributed uniformly over an area of 1 square meter, or the illumination produced at a surface all points of which are at a distance of one meter from a uniform point source of one candela (NIST, 1979). According to the MUTCD, markings that have to be visible at night shall be retroreflective except for the cases when ambient illumination assures that the markings are adequately visible (FHWA, 2009).

In 2006, The National Cooperative Highway Research Program sponsored a study focused on non-intersection, non-daylight crashes in California during 1992-1994 and 1997-2002 and related them to the retroreflectivity of the longitudinal pavement markings on the road at the time of the crashes. Over 118,000 crashes were considered in the study, which covered over 5,000 miles of state maintained freeways and highways in California. A main finding of the NCHRP study is that the amount of retroreflectivity is not important to driver safety as long as the marking is present and visible to drivers (Bahar et al., 2006). Therefore, there is a need to specify a minimum retroreflectivity value to determine if a marking is "visible".

Many researchers adopt FHWA candidate criteria for minimum pavement marking retroreflectivity in their studies (FHWA, 2000). These recommended guidelines are impacted by three factors: speed, roadway type, and the presence/absence of raised retroreflective pavement markers (RRPM) or lighting (Migletz and Graham, 2002). For freeways, minimum guideline retroreflectivity values of 150 mcd/m^2/lux and 100 mcd/m^2/lux are recommended for white and yellow pavement markings, respectively, when there is no RRPM or lighting; while 70 mcd/m^2/lux is used for both white and yellow pavement markings when there is RRPM or lighting (FHWA, 2000). Table 1 shows these values.

Table 1 – Threshold dry retroreflectivity values suggested by FHWA to define end of pavement marking service life

Material	Roadway type/speed classification		
	Non-freeway ≤ 40 mph	Non-freeway ≥ 45 mph	Freeway ≥ 55 mph
White	85	100	150
White with lighting or RRPM	30	35	70
Yellow	55	65	100
Yellow with lighting or RRPM	30	35	70

SOURCE: FHWA, 2000

When installed, the retroreflectivity of yellow markings is typically about 35% lower than that of white markings. As white and yellow markings are usually replaced at the same time, there is a lower minimum value for yellow markings, as shown in Table 1 (Fu and Wilmot, 2008). In 2010, the Federal Highway Administration (FHWA) had drafted a revision to the 2009 Edition of the *Manual on Uniform Traffic Control Devices* (MUTCD) to specify minimum retroreflectivity values for the pavement marking standard (FHWA, 2010). The FHWA is currently reviewing the docket comments received and the proposed revisions regarding maintaining minimum retroreflectivity of longitudinal pavement markings are tentatively designated as Revision 1 to the 2009 edition of the MUTCD. The proposed revision establishes that public agencies or officials having jurisdiction shall use a method designed to maintain retroreflectivity of white and yellow longitudinal pavement markings, at or above the minimum levels in Table 2. (FHWA, 2010).

Table 2 – Minimum Maintained Retroreflectivity Levels for Longitudinal Pavement Markings

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

SOURCE: Based on FHWA, 2010

Parker and Meja (2003) studied the relationship between retroreflectivity levels and user perception, depending on user's age. In addition to retroreflectivity, subjective ratings from a survey conducted with the participation of the New Jersey driving public along a 32-mi circuit were measured. Multiple regression techniques were used to correlate the average scores reported by the study participants for each specific roadway section with the corresponding measured retroreflectivity. The threshold value of acceptable versus unacceptable retroreflectivity, for both yellow and white markings, was between 80 and 130 mcd/m^2/lux for New Jersey drivers younger than 55 and between 120 and 165 mcd/m^2/lux for drivers over 55.

Smadi et al.'s (2008) analysis of safety effectiveness related to marking retroreflectivity showed that low retroreflectivity, less than 200 mcd/m^2/lux, is correlated to a higher crash probability. Values higher than 200 mcd/m^2/lux did not show significant increase in crash probability (Smadi et al., 2008). Figure 2 and Figure 3 show the behavior of crash probability for retroreflectivity lower than 200 mcd/m^2/lux for freeways.

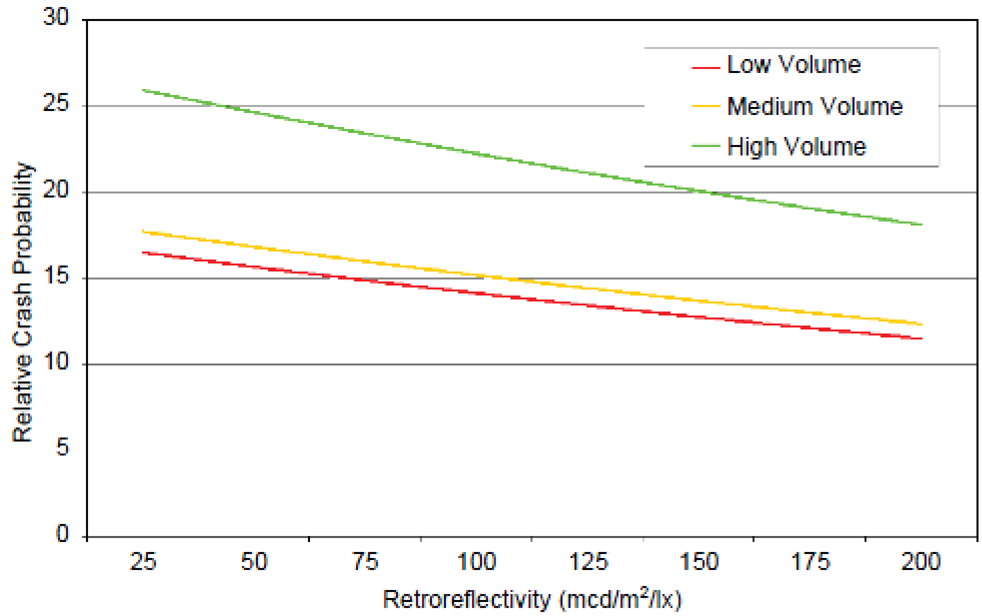

Figure 2 – Relative crash probability versus low retroreflectivity on freeways: white edge lines

SOURCE: Smadi et al., 2008

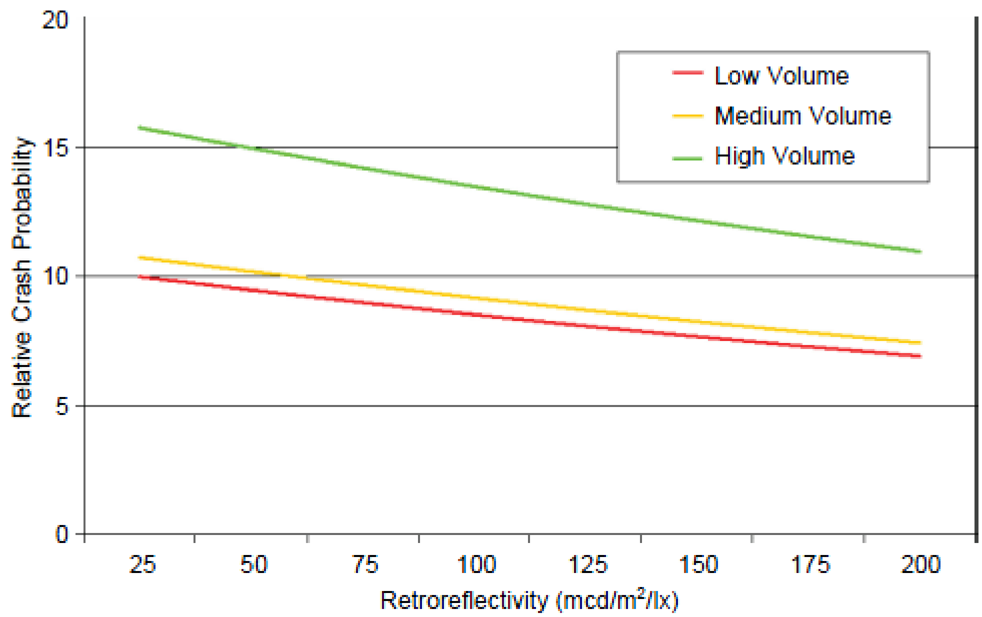

Figure 3 – Relative crash probability versus low retroreflectivity on freeways: yellow edge lines

SOURCE: Smadi et al., 2008

In 2008, Debaillon et al. (2008) used a computer model called the Target Visibility Predictor (TarVIP) to study pavement marking retroreflectivity needs. Key factors affecting pavement marking visibility included pavement marking configuration, pavement surface type, vehicle speed, vehicle type, and presence of raised retroreflective pavement markers. The recommended values of minimum retroreflectivity can be observed in Table 3.

Table 3 – Recommended minimum retroreflectivity values (mcd/m^2/lux)

Roadway Marking Configuration	Without RRPMs			With RRPMs
	≤ 50 mph	55 - 65 mph	≥ 70 mph	
Fully marked roadways (with centerline, lane lines, and edge lines, as needed)	40	60	90	40
Roadways with centerlines only	90	250	575	50

SOURCE: Debaillon et al., 2008

2.3. Pavement Marking Retroreflectivity Modeling

In the mid-1990s Michigan State University (MSU) evaluated the performance of several pavement marking materials for the Michigan DOT (Lee et al., 1999). Lee et al. (1999) developed the following linear regression model for both white and yellow thermoplastic markings. In order to establish if a model is good to represent the behavior of actual data, goodness-of-fit measures can be considered. One of these measures is the coefficient of determination, R^2, which represents the fraction of total variation in the dependent variable that is explained by the independent variables, and its value ranges from 0 to 1, with 1 indicating that the regression line perfectly fits actual data. The R^2 value for Lee et al (1999) model is 0.14:

$$Y = -0.3622X + 254.82 \quad \text{(Eq. 2.1)}$$

where

Y = retroreflectivity of pavement markings ($mcd/m^2/lux$);

X = age of marking in days.

In 2002, Abboud and Bowman (2002 [2]) determined pavement marking retroreflectivity using field retroreflectivity readings for 520 mi of longitudinal pavement markings in 9 Alabama counties. The minimum retroreflectivity threshold was determined to be 150 $mcd/m^2/lux$. Logarithmic regression analysis was used to establish the following relationship between pavement marking retroreflectivity and prolonged traffic exposure, for white thermoplastic markings:

$$R_L = -70.806 \ln(VE) + 639.66 \quad \text{(Eq. 2.2)}$$

where

R_L=pavement marking retroreflectivity ($mcd/m^2/lux$);

ln = natural logarithm;

VE = vehicle exposure.

Vehicle exposure is the total number of vehicles that have traversed a point on a highway up to the time frame of interest and represents the prolonged effect of traffic over time, combining the effects of marking age and traffic volume on the deterioration rate, and it is a function of time and traffic volume per lane and was expressed by Abboud and Bowman as:

$$VE = ADT_{Ln} * PMage * 30.4 * 10^{-3} \quad \text{(Eq. 2.3)}$$

where:

ADT_{Ln} = average daily traffic per lane (thousands of vehicles/day/lane);

$PMage$ = age in months (using a month-to-day conversion factor of 30.4).

Abboud and Bowman (2002 [1]) developed another exponential regression model to depict the relationship between pavement-marking retroreflectivity and vehicle exposure (VE). The value of R^2 for this method, related to white thermoplastic markings is 0.58:

$$R_L = -70.806 \ln(VE) + 150.55 \quad \text{(Eq. 2.4)}$$

Thamizharasan et al. (2003) identified patterns of retroreflectivity change over time in South Carolina, as it can be observed in Figures 4 and 5. Figure 4 shows the first pattern, where retroreflectivity increases for a short period of time, usually before 300 days after pavement marking application, then gradually decreases thereafter, for newly placed markings. The initial increase in retroreflectivity is because of more glass beads becoming exposed after some amount of wear.

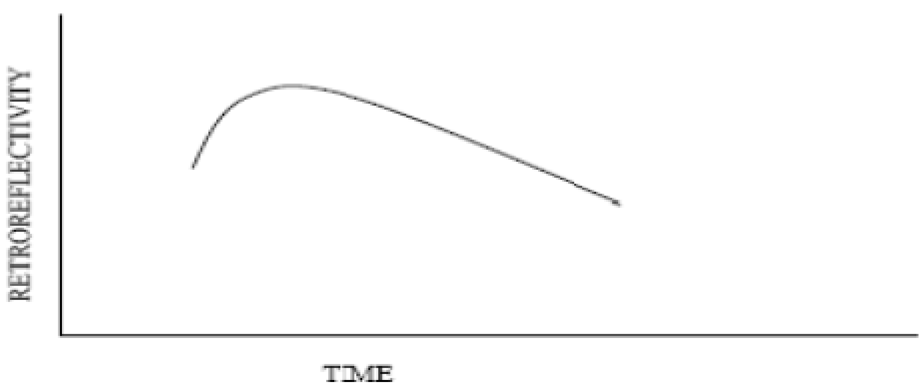

Figure 4 – Pattern representative of newly placed pavement markings

SOURCE: Thamizharasan et al., 2003

The second pattern, which can be observed in Figure 5, is where retroreflectivity decreases gradually with time. This is for the well-established markings that have passed the initial increase period, defined by Thamizharasan et al. as 300 days.

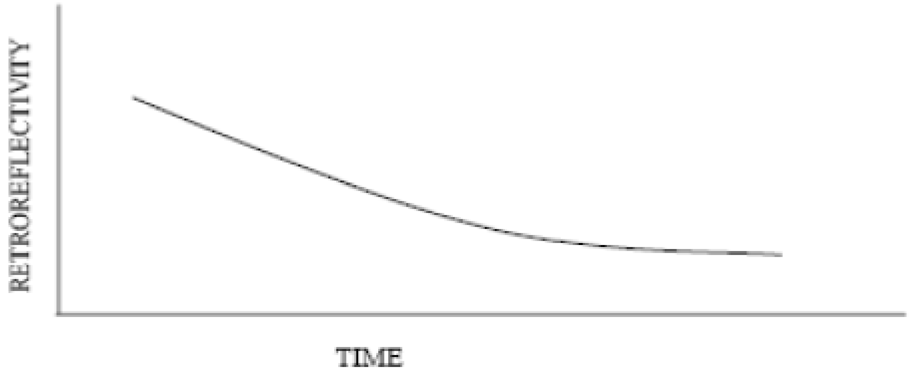

Figure 5 – Pattern for established sites – markings older than about 300 days

SOURCE: Thamizharasan et al., 2003

Thamizharasan et al. (2003) developed two models to predict marking retroreflectivity, including a non-linear model for the time the retroreflectivity increases when markings are newly applied and a linear model for the time retroreflectivity decreases to a minimum value. The models were stratified by marking color (white or yellow), surface type (AC or PCC), and marking material (thermoplastic or epoxy). Traffic volume was not found to be significant in the analysis.

The non-linear model, for white thermoplastic materials, has a R^2 value of 0.22:

$$Difference\ in\ Retroreflectivity = -0.0005 * Days^2 + 0.18 * Days + 1.10 \quad \text{(Eq. 2.5)}$$

where:

$Days$ = age of pavement marking (days).

For yellow thermoplastic materials, the R^2 value is 0.20:

$$Difference\ in\ Retroreflectivity = -0.0001 * Days^2 + 0.04 * Days + 1.23 \quad \text{(Eq. 2.6)}$$

The linear model, for white thermoplastic materials, has R^2 value of 0.47:

$$Difference\ in\ Retroreflectivity = -0.06 * Days - 6.80 \quad \text{(Eq. 2.7)}$$

For yellow thermoplastic materials, R^2 value is 0.21:

$$Difference\ in\ Retroreflectivity = -0.03 * Days - 3.63 \quad \text{(Eq. 2.8)}$$

The National Transportation Product Evaluation Program (NTPEP) has collected retroreflectivity data from various sites located in different regions of California. The variables contained within the NTPEP data set include age of marking, color, material type, traffic volume, pavement surface, climate region, and snow removal (Bahar et al., 2006). The polynomial model developed to predict the retroreflectivity was:

$$R = \frac{1}{\beta_0 + \beta_1 * Age + \beta_2 * Age^2} \quad \text{(Eq. 2.9)}$$

where:

R = retroreflectivity of pavement marking (mcd/m^2/lux);

$\beta_0, \beta_1, \beta_2$ = model parameters to be estimated;

Age = age of pavement marking (months).

For white thermoplastic markings in a hot humid climate and no usual snow removal, the values found in the NTPEP study were β_0 = 2.42 x 10^{-3}, β_1 = 1.32 x 10^{-4}, and β_2 = -1.18 x 10^{-6}. For yellow markings in the same conditions, β_0 = 4.89 x 10^{-3}, β_1 = 1.85 x 10^{-4}, and β_2 = -8.00 x 10^{-8} (Bahar et al., 2006).

A general linear model was developed by Sitzabee et al. (2009) in North Carolina for thermoplastics on asphalt based on the variables that were validated by the effects test (time, initial retroreflective value, AADT, color, and lateral location). The thermoplastic model produced an R^2 value of 0.60 which is greater than those found in previous studies reviewed in the literature:

$$R_L = 190 + 0.39 \times R_{L_{initial}} - 2.09 \times time - 0.0011 \times AADT + 20.7 \times X_1 - 20.7 \times X_2 + 19 \times X_3 - 19 \times X_4 \quad \text{(Eq. 2.10)}$$

where:

R_L = retroreflectivity in mcd/m^2/lux;

$R_{L\ \mathrm{initial}}$ = initial retroreflectivity in mcd/m^2/lux;

time = time since installation in months;

AADT = annual average daily traffic in vehicles per day;

X1=1 if edge line, 0 otherwise;

X2=1 if middle line, 0 otherwise;

X3=1 if white line, 0 otherwise;

X4=1 if yellow line, 0 otherwise.

In 2009, Clarke and Yan (2009) performed a retroreflectivity investigation in 85 sites with 90-mil thermoplastic longitudinal markings located in 14 counties across the state of Tennessee. Three models were developed by color, a linear, a logarithmic, and a quadratic. The models for white 90-mil thermoplastic had R^2 values of 0.015 (linear), 0.008 (logarithmic), and 0.017 (quadratic) and are expressed by Equations 2.11, 2.12, and 2.13, respectively:

$$Y = 298.004 - 0.053t \quad \text{(Eq. 2.11)}$$

$$Y = 331.366 - 9.510\ln(t) \quad \text{(Eq. 2.12)}$$

$$Y = 287.019 + 0.022t - 0.000092t^2 \quad \text{(Eq. 2.13)}$$

where

Y = retroreflectivity (mcd/m2/lux);

t = age of marking (days).

Yellow 90-mil thermoplastic models, which had R^2 values of 0.003 (linear), 0.007 (logarithmic), and 0.017 (quadratic) are represented by Equations 2.14, 2.15, and 2.16, respectively.

$$Y = 150.233 + 0.016t \quad \text{(Eq. 2.14)}$$

$$Y = 120.845 + 6.181\ln(t) \quad \text{(Eq. 2.15)}$$

$$Y = 133.718 + 0.124t - 0.000t^2 \quad \text{(Eq. 2.16)}$$

Traffic volume, typically expressed as AADT (Annual Average Daily Traffic), is a continuous parameter that measures the volume of traffic on the roadway in vehicles per day. Traffic volumes vary from day to day and over the course of a year, and are another source of variation that contributes to the complexity of the analysis (Songchitruksa et al., 2011). Thamizharasan et al. (2003) argued that AADT was not significant and was accounted for as a function of time. However, some reports indicate that AADT has a significant impact on pavement marking degradation apart from time (Sitzabee et al., 2009).

Different sources are considered to analyze retroreflectivity behavior over time. Karwa and Donnell (2011) used Artificial Neural Networks (ANN) to model the degradation pattern of pavement marking retroreflectivity (PMR) in North Carolina as a function of several input variables, including the initial PMR, age of the markings, and traffic flow characteristics. It was found that the degradation of thermoplastic pavement markings occurs generally at a nonlinear rate, and the rate of decay appears to differ among different pavement marking types. It was also found that there may be a different degradation process according to the geographic location of the markings as well as by the color of the marking. The initial PMR also appears to be an important service life predictor. The variability in traffic volume, however, does not appear to have a strong association with retroreflectivity degradation for most of the pavement marking types (Karwa and Donnell, 2011).

2.4. Pavement Marking Materials Specifications and Requirements

On contracts for the Alabama Department of Transportation (ALDOT), requirements for all projects are based on the Alabama *Standard Specifications for Highway Construction* (ALDOT, 2008). The 2007 Special Provisions, an interim update to the 2006 Edition of ALDOT's *Standard Specifications for Highway Construction*, will be the reference for this thesis as the projects on which data were collected are governed by the 2006 Edition and its subsequent Special Provisions. These specifications define classes of traffic stripe. The required type of material is designated by "Class" in accordance with Table 4 (ALDOT, 2007).

Table 4 – Class of Traffic Stripe

Class of Traffic Stripe	
Class	**Material**
1	Paint
1H	High Build Paint
2	Standard Thermoplastic Material
2T	Thin Film Spray Applied Thermoplastic Material
3	Tape
W	Warranted Traffic Marking Material

SOURCE: ALDOT, 2007

Thermoplastics are generally composed of four ingredients: binder, glass beads, titanium dioxide and calcium carbonate. The binder is used to hold the mixture together as a rigid mass, the glass beads are used to provide reflectivity, the titanium dioxide is used for reflectivity enhancement, and calcium carbonate or sand is used as an inert filler material. Typical thermoplastic markings are 15 to 33 percent binder, 14 to 33 percent glass beads, 8 to 12 percent titanium dioxide and 48 to 50 percent filler (Cuelho et al., 2003).

Thermoplastic is a blend of solid ingredients that becomes liquid when heated and returns to a solid state on cooling. Thermoplastics are classified into two types: hydrocarbon-based plastics derived from petroleum, and alkyd, which is a naturally occurring resin (Migletz and Graham, 2002). Alkyd-based binders are more widely used because they are resistant to chemical decomposition from motor oil and other hydrocarbon contaminants. Thermoplastics can be applied to the roadway surface by spraying or extrusion. Extruded thermoplastics are thicker than sprayed thermoplastics (Fu and Wilmot, 2008).

According to Lindly and Marci, (2006), thermoplastic markings are all-weather pavement markings. These markings should be visible at night during a rainfall of up to 0.25 inch per hour. Thermoplastic has been used successfully in warmer climates for a number of years.

Class 2 thermoplastic is the marking type for which data will be analyzed in this research. Class 2 thermoplastic may be applied to asphalt and concrete surfaces, and according to ALDOT specifications, they have to be placed to produce a minimum uniform thickness of 0.100 inch for all stripes. Thickness less than 95% of this required value may be deemed unacceptable. The retroreflectivity is required to be a minimum of 450 mcd/m^2/lux for white stripe and 350 mcd/m^2/lux for yellow stripe. The Contractor may be compelled to replace stripe that is 90% or less of this retroreflectivity requirement (ALDOT, 2007).

Class 2T thermoplastic markings are also analyzed in this study. Class 2T thermoplastic may be applied to asphalt and concrete surfaces, and ALDOT specifications require that they need to be placed to produce a minimum uniform thickness of 0.040 inch. Thickness less than 95% of this required value is not acceptable. The retroreflectivity has to be a minimum of 300 mcd/m^2/lux for white stripe and 250 mcd/m^2/lux for yellow stripe. The Contractor is required to replace stripe that is 90% or less of this retroreflectivity requirement (ALDOT, 2007).

ALDOT specifications require initial daytime chromaticity for yellow materials to fall within the box created by the coordinates presented in Table 5 (ALDOT, 2007).

Table 5 – Initial Daytime Chromaticity for yellow materials

Initial Daytime Chromaticity Coordinates (Corner Points)				
	1	**2**	**3**	**4**
X	0.530	0.510	0.455	0.472
Y	0.456	0.485	0.444	0.400

SOURCE: ALDOT, 2007

The initial daytime chromaticity for white materials must fall within the box created by the coordinates showed on Table 6 (ALDOT, 2007).

Table 6 – Initial Daytime Chromaticity for yellow materials

Initial Daytime Chromaticity Coordinates (Corner Points)				
	1	**2**	**3**	**4**
X	0.355	0.305	0.285	0.335
Y	0.355	0.305	0.325	0.375

SOURCE: ALDOT, 2007

According to ALDOT specifications, luminance factor requirements for white markings are daylight luminance factor at 45 degrees / 0 degrees - 50% minimum, and daylight luminance factor at 45 degrees / 0 degrees – 35% minimum for yellow markings.

2.5. Economic Evaluation of Thermoplastic Materials

Another critical factor to consider when choosing the best material for pavement markings is the associated cost. But it is not only the initial cost that should be analyzed, as a material with a higher initial cost could also have a longer lifetime, possibly resulting in a more cost-effective material (Thomas et al., 2001).

The total cost of pavement markings includes not only the cost of the material, but also the cost of the crew and the application equipment, as well as manufacturer guarantees over a specified time, in which case manufacturers replace deteriorating materials free of charge if their product does not achieve certain guidelines (Thomas et al., 2001). Basic costs of the materials and the equipment, and time required for their installation, fundamentally determine marking system costs, but secondary issues also can have a noticeable impact. The volume of markings to be installed and whether or not markings are installed by private firms or public agencies are some secondary issues that can influence the cost of pavement markings. Usually, the greater volume of markings to be installed, the lower the unit cost of their installation. The reasons for the differential in costs between private and public agency installation are uncertain, although they may be related, in part, to volume of work (Cuelho et al., 2003).

Even if there are many factors to be considered when choosing the type of pavement marking material to be used, the decision is often dictated by the initial cost. There are limited guidelines leading to a more cost-effective selection and this approach to pavement marking can result in lack of durability, poor retroreflectivity, increased long-term costs and increased exposure to traffic for staff (Montebello et al., 2000).

Service life is an important parameter in selecting a marking system and it is mainly determined from the level of retroreflectivity provided by the pavement marking. Other conditions that may end the service life of a marking include detachment from the pavement, extensive loss of pigment, and obliteration by pavement maintenance activities. Some of the major factors that affect the performance and service life of a particular type of pavement marking include type of road surface, volume of traffic, orientation with respect to traffic, and schedule of pavement maintenance activities (Cuelho et al., 2003).

Thermoplastic materials have been used in the United States since the 1950s, and they are one of the most widely used pavement marking materials (Jiang, 2008). Thermoplastic markings provide excellent performance when applied properly, being the most durable of the commonly used pavement marking systems. The life of thermoplastic markings varies widely because of its dependence on installation procedures, volume of traffic, atmospheric conditions when placed, and snowplow activity. The range of life expectancy is typically from four to seven years (KDOT, 2002). This relatively long service life can sometimes exceed the interval between pavement maintenance activities (Cuelho et al., 2003).

There are some issues to be considered when applying thermoplastic to pavement markings, in addition to service life. One of the advantages of using thermoplastic is that the material can be re-applied over older thermoplastic markings, thereby refurbishing the older marking as well as saving on the costs of removing old pavement markings. However, thermoplastic color and appearance are disadvantages. Thermoplastic is grayish, making it less visible by day and it has a tendency to crack. (Jiang, 2008).

Thermoplastics are expensive in comparison to conventional paints, with installed costs ranging between $0.19 and $0.26 per linear foot based on a four-inch wide longitudinal strip (KDOT, 2002). Thermoplastics, on the other hand, are the most durable of the commonly used pavement marking systems, which can result in a more cost-effective use of thermoplastics in the long-term (KDOT, 2002). In Alabama, the averages of contract bid prices are $0.26 per linear foot for Class 2T thermoplastic materials and $0.65 per linear foot for Class 2 thermoplastic materials (ALDOT, 2010[1]).

The objective of a pavement marking economic evaluation is to identify the most economical pavement marking materials. Some methods have been employed. For example, Kansas DOT (KDOT, 2002) developed a sophisticated methodology to determine the most economical type of pavement marking to be used under different conditions. Materials are selected based on the remaining pavement service life, traffic volume level, and a Brightness Benefit Factor (BBF). In the Kansas DOT document, there is one table for each remaining service life, between 1 and 7 years; columns of these tables represent AADT levels (<5,000, 5,000-50,000, and >50,000 veh/day) and rows represent BBF for each type of material; the material with the highest BBF represents the best combination of durability, retroreflectivity, and cost for the considered remaining service life and ADT. The BBF is a benefit/cost ratio representing the combined effects of a material's retroreflectivity, durability, and installed cost. The BBF is defined as:

$$BBF = \frac{R_a T_s}{S} \qquad \text{(Eq. 2.17)}$$

where:

R_a = average useful retroreflectivity over the anticipated service life of the project in $mcd/m^2/lux$;

T_s = pavement marking service life in years;

S = average cost per unit length in dollars per meter.

In the calculation of BBF, additional retroreflectivity over the minimum required level is considered a benefit to the user. As a result, the higher the retroreflectivity obtained during the material lifetime, the higher the BBF (KDOT, 2002).

Cottrell and Hanson (2001) used cost-effectiveness analysis to select marking materials for Virginia DOT (VDOT). They found that there is not much benefit in using a marking with a retroreflectivity value greater than 600 $mcd/m^2/lux$ compared to one with a value of 300 $mcd/m^2/lux$. As a result, their study did not use retroreflectivity as a benefit, only service life. Figure 6 illustrates the two methods. The horizontal axis is time measured by month; the vertical axis is retroreflectivity; R_{min} is the minimum retroreflectivity threshold (Fu and Wilmot, 2008).

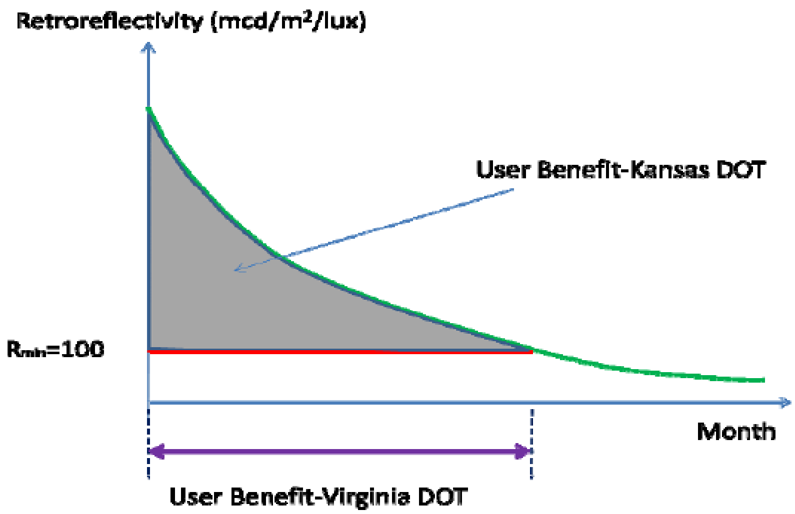

Figure 6 – Measuring user benefit: Kansas and Virginia

SOURCE: Fu and Wilmot, 2008

Lindly and Wijesundera (2003) used life cycle cost analysis (LCCA) to compare different marking materials for Alabama DOT. LCCA assumes the alternatives yield the same level of service, provided the retroreflectivity of the pavement markings meets the minimum value requirement. LCCA requires identification of pavement marking service life and total cost and then calculates the net present worth (NPW) or the equivalent uniform annual cost (EUAC). The material with the lowest NPW or EUAC is selected.

Loetterle et al.'s study of public perception of pavement marking retroreflectivity leads to an intuitively appealing way to measure user benefit. Based on their data, user benefit can be considered to increase approximately in a linear fashion when retroreflectivity is under 200 mcd/m^2/lux, while above 200 mcd/m^2/lux, there is little additional benefit. Thus, provided the retroreflectivity is at least 200 mcd/m^2/lux, full benefit of the pavement marking is received (Loetterle et al., 2001).

On the other hand, below a certain minimum threshold value of retroreflectivity, pavement markings are considered to be unacceptable and have no value to the driving public. This minimum value indicates the end of service life of the pavement marking. Calling these two values R_{max} and R_{min}, respectively, then Figure 7 demonstrates an alternative measurement of benefit.

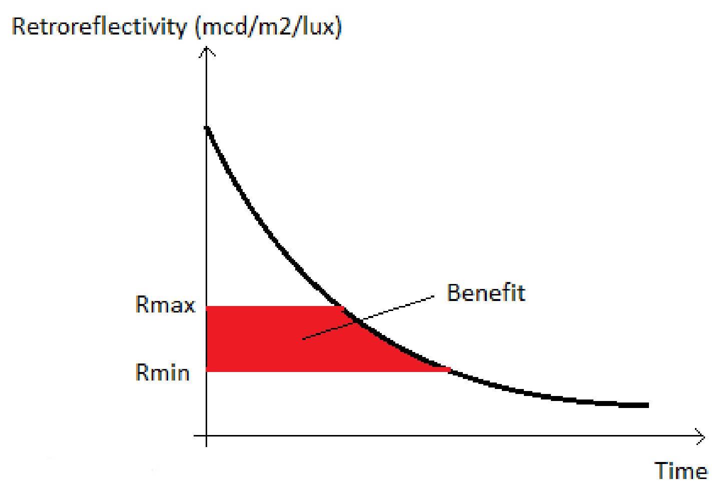

Figure 7 – Alternative measurement of benefit

Fu and Wilmot (2008) shows that the suggested user benefit is measured by the area between R_{min} and R_{max}. Benefit is measured in units of month*vehicle*mcd/m^2/lux. The benefit/cost ratio can be simply calculated by:

$$\frac{benefit}{cost} = \frac{benefit * AADT}{total\ cost} \qquad \text{(Eq. 2.18)}$$

2.6. Service Life of Thermoplastic Pavement Markings

Migletz and Graham (2002) established a retroreflectivity of 150 $mcd/m^2/lux$ as a threshold to predict the service life of white thermoplastic pavement markings on freeways. The obtained mean estimated service life was 22.6 months, in a range of 7.4 to 49.7 months. The mean service life of yellow markings on freeways in the Migletz and Graham (2002) study was 24.7 months, in a range of 11.0 to 41.6 months. The minimum retroreflectivity threshold for yellow thermoplastic was considered as 100 $mcd/m^2/lux$. Minimum retroreflectivity thresholds were based on the FHWA suggested values (FWHA, 2000).

Abboud and Bowman (2002 [1]) considered in their study the useful lifetime of white edge lines. For low ADT (<2500 veh/day), the service life for white edge thermoplastic markings was found to be 53 months; for intermediate ADT (2500 to 5000 veh/day), useful lifetime dropped to 18 months; for high ADT (>5000 veh/day), the service life was 10.5 months. According to the FHWA (2000), the threshold for minimum acceptable retroreflectivity was considered equal to 150 $mcd/m^2/lux$ and the midpoint of each ADT range was used as representative (Abboud and Bowman, 2002 [1]).

Thamizharasan et al. (2003) developed a model to predict retroreflectivity and established the threshold of 100 $mcd/m^2/lux$, for both yellow and white markings, as the minimum acceptable retroreflectivity; this threshold was chosen based on an NCHRP study (Andrady, 1997). Average service life for white thermoplastic marking on asphalt pavement was found to be 65 months, for retroreflectivity variation in a range from 30 to 690 $mcd/m^2/lux$, with an average of 203 $mcd/m^2/lux$. For yellow thermoplastic marking on asphalt pavement, the average useful lifetime was 103 months, for retroreflectivity variation in a range from 26 to 429 $mcd/m^2/lux$, with an average of 135 $mcd/m^2/lux$.

Sitzabee et al. (2009) used an AADT of 10,000 veh/day to estimate the service lives of thermoplastic markings. For white edge lines, average service life was 102 months; for white broken lines, average useful lifetime was 84 months; for yellow edge lines, average service life was 85 months; and for yellow broken lines, average useful lifetime was 65 months. For white markings, the minimum retroreflectivity value was 150 mcd/m^2/lux; for yellow markings, the considered threshold was 100 mcd/m^2/lux, based on most common research recommendations. Initial retroreflectivity was 375 mcd/m^2/lux for white markings and 250 mcd/m^2/lux for yellow markings.

Clarke and Yan (2009) performed a study which investigated changes in retroreflectivity over time for 90-mil thermoplastic markings of 85 sites in 14 counties of Tennessee. The average service life of the 90-mil thermoplastic white markings is 1,100 days (36 months) while that of the yellow markings is 900 days (30 months).

Karwa and Donnell (2011) predicted service life of pavement markings using Artificial Neural Networks. Service life was estimated for white and yellow line types, considering centerlines and edgelines separately. Two different threshold values for minimum retroreflectivity were considered: 150 and 200 mcd/m^2/lux. Also, three different ADT levels were considered, along with two different percent truck and two different initial PMR levels. White edgeline markings generally had longer predicted service lives than all other pavement marking types. The shortest mean predicted service life was most often computed for the yellow centerline markings. There was also considerable variability in the predicted service life across the engineering divisions, which shows the importance of geographic location when developing models to predict service life. In addition, increasing the ADT from 5,000 to 25,000 reduced the mean predicted service life by 7 months or less. The impact of different vehicle types was also analyzed, and it was found that roadways with higher truck traffic volumes decrease pavement markings service life due to abrasion between the tires and the markings (Karwa and Donnel, 2011).

2.7. Summary of findings

Pavement markings have an essential role in the highway system. It is a complex decision, balancing many competing objectives, to decide which factors should be considered when selecting the type of pavement marking material for a particular road. This is essentially an agency's policy decision, which can be supported by research. There is a wide variety of characteristics, costs, and benefits of the different pavement marking materials.

There are numerous types of materials used for pavement markings in the field today, including paint, epoxy, tape, and thermoplastic. Thermoplastic is the most widely used.

AADT was sometimes not significant for service life analysis. However, most reports indicate that AADT has a significant impact on pavement marking degradation apart from time.

The performance of a pavement marking material has been judged based primarily on its retroreflectivity. There are many models to predict marking retroreflectivity. The best prediction found in the literature is a general linear model that was developed by Sitzabee et al. (2009), with R^2 equal to 0.60 for thermoplastics. Table 7 shows a summary of all models cited in Section 2.3 of this thesis.

Table 7 – Summary of models to predict retroreflectivity

Study	Location	Type of Marking	Independent Variables	R^2
Lee et al. (1999)	Michigan	White and Yellow Thermoplastic	Age of marking	0.14
Abboud and Bowman (2002 [1])	Alabama	White Thermoplastic	ADT per lane Age of marking	0.58
Abboud and Bowman (2002 [2])	Alabama	White Thermoplastic	ADT per lane Age of marking	N/A
Thamizharazan et al. (2003) Non-Linear	South Carolina	White Thermoplastic in Asphalt	Age of marking Initial Retroreflectivity	0.22
Thamizharazan et al. (2003) Non-Linear	South Carolina	Yellow Thermoplastic in Asphalt	Age of marking Initial Retroreflectivity	0.2
Thamizharazan et al. (2003) Linear	South Carolina	White Thermoplastic in Asphalt	Age of marking Initial Retroreflectivity	0.47
Thamizharazan et al. (2003) Linear	South Carolina	Yellow Thermoplastic in Asphalt	Age of marking Initial Retroreflectivity	0.21
Bahar et al. (2006)	California	White Thermoplastic, Hot Humid, No snow removal	Age of marking	N/A
Bahar et al. (2006)	California	Yellow Thermoplastic, Hot Humid, No snow removal	Age of marking	N/A
Sitzabee et al. (2009)	North Carolina	White and Yellow Thermoplastic	Initial Retroreflectivity Age of marking AADT Marking location (edge, middle) Marking color (white, yellow)	0.6
Clarke and Yan (2009) Linear	Tennessee	White 90-mil Thermoplastic	Age of Marking	0.015
Clarke and Yan (2009) Linear	Tennessee	Yellow 90-mil Thermoplastic	Age of marking	0.008
Clarke and Yan (2009) Logarithmic	Tennessee	White 90-mil Thermoplastic	Age of Marking	0.017
Clarke and Yan (2009) Logarithmic	Tennessee	Yellow 90-mil Thermoplastic	Age of marking	0.003
Clarke and Yan (2009) Quadratic	Tennessee	White 90-mil Thermoplastic	Age of Marking	0.007
Clarke and Yan (2009) Quadratic	Tennessee	Yellow 90-mil Thermoplastic	Age of marking	0.017

Economic evaluation is also important when deciding which material will be used for pavement markings. Basic costs of the materials and the equipment and service life are the most characteristics analyzed to perform a cost-effective evaluation. The objective of a pavement marking economic evaluation is to identify the most economical pavement marking materials. Some methods have been employed.

Prediction of service life, usually based on retroreflectivity levels, varies from one model to another. A summary of predicted service life for pavement markings analyzed in Section 2.6 can be observed in Table 8. Adopted retroreflectivity thresholds are also in Table 8.

Table 8 – Summary of Predicted Service Life

Study	Marking	Retroreflectivity ($mcd/m^2/lux$)		Service Life (months)		
		Threshold	Average Initial	Minimum	Maximum	Average
Migletz and Graham (2002)	White Thermoplastic	150	-	7.4	49.7	22.6
	Yellow Thermoplastic	100	-	11	41.6	24.7
Abboud and Bowman (2002)	White Edge Thermoplastic	150	-	10.5	53	-
Thamizharasan et al. (2003)	White Thermoplastic on Asphalt	100	203	-	-	65
	Yellow Thermoplastic on Asphalt	100	135	-	-	103
Sitzabee et al. (2009)	White Edge Thermoplastic	150	375	-	-	102
	White Middle Thermoplastic	150	375	-	-	84
	Yellow Edge Thermoplastic	100	250	-	-	85
	Yellow Middle Thermoplastic	100	250	-	-	65
Clarke and Yan (2009)	White 90-mil Thermoplastic	-	296.1	-	-	92
	Yellow 90-mil Thermoplastic	-	154.5	-	-	75
Karwa and Donnell (2011)	Yellow Edgelines	150, 200	300, 400	(values differ according to ADT and percent trucks)		
	Yellow Centerlines	150, 200	300, 400			
	White Edgelines	150, 200	300, 400			
	White Skip Lines	150, 200	300, 400			

Chapter Three

Methodology

Chapter Three provides details of the methods applied to this thesis with the purpose of achieving the objectives stated in Chapter One. These methods include the data mining and analysis of a database of pavement markings applied in 2007 highway projects for ALDOT. This process determined the extent to which observations from this database meet the ALDOT *Standard Specifications for Highway Construction* for thickness, retroreflectivity, luminance, and color of pavement markings. A statistical analysis was also executed to evaluate trends in mean, standard deviation, and coefficient of variation for each class and color of markings. Retroreflectivity modeling based on models found in the literature was developed in this research project. A methodology for development of new models related to preparation of data and model fitting, as well as considerations regarding benefit/cost analysis are also discussed in this chapter.

3.1. ALDOT specifications study

The database analyzed in this thesis was developed by ALDOT in 2007 and includes measurements of pavement markings observed at 7,840 locations from 40 projects in Alabama. In this year, five different General Application Special Provisions for Traffic Stripe, which constitute updates to ALDOT's *Standard Specifications for Highway Construction*, were approved. A documentation of the recent changes in these special provisions was prepared.

3.2. Data Mining and Analysis

The database studied in this thesis contains multiple pavement marking measurements from 40 projects in Alabama. The list including the number of these projects and their locations can be observed in Table 9.

Table 9 – List of the 40 Pavement Marking Projects in the 2007 ALDOT Database

Project Number	County
99-307-203-100-701	Covington County
99-307-346-010-701	Henry County
STPNU-3128(200)	Geneva County
STPNU-3140(200)	Geneva County
99-307-164-167-701	Geneva County
STPNU-2014(200)	Covington County
EB-0042(507)	Mobile County
EB-0074(513)	Cullman County
99-302-391-101-701	Lauderdale County
99-307-162-088-703	Coffee County
STPNU-4816(201)	Marshall County
99-304-154-009-701	Cleburne County
STPAA-0052(506)	Geneva County
99-305-632-069-703	Tuscaloosa County
STPSA-0021(515) & 99-306-434-021-701	Lowndes County
STPNU-CN07(203) (1Y) OLD McGEHEE	Montgomery County
STPNU-CN07(203) (1W) OLD McGEHEE	Montgomery County
STPNU-CN07(203) (2Y) MARLER	Montgomery County
STPNU-CNO7(203) (2W) MARLER	Montgomery County
99-308-663-089-706 & STPSA-0089(500)	Wilcox County
EB-0016(505)	Baldwin County
STPSA-0185(500) & 99-306-074-185-701	Butler County
STPAA-0079(506)	Blount County
STPNU-3423(201)	Henry County
99-302-473-013-704	Marion County

Table 9 (Continuation) – List of the 40 Pavement Marking Projects in the 2007 ALDOT Database

Project Number	County
EB-0004(509)	Jefferson County
STPSA-0001(529) & 99-301-285-001-705	Etowah County
99-303-595-003-709	Shelby County
NHF-STPSAF-0053(525) & 99-307-234-053-701	Dale County
NHF-0056(500) & BRF-0102(527)	Montgomery County
STPNU-1713(201)	Colbert County
99-302-473-171-706	Marion County
STPNU-2221(201)	Cullman County
99-305-632-069-702	Tuscaloosa County
EBF-0012-(522)	Houston County
EBF-0012-(522)B	Houston County
EB-0035(506)	DeKalb County
99-303-582-004-708	St. Clair County
STPSA-0079(505) & 99-301-484-079-708	Marshall County
STPSA-0079(505) & 99-301-484-079-708(2)	Marshall County

All projects in the 2007 database contain measurements of Class 2 (Standard Thermoplastic) or Class 2T (Thin Film Spray Applied Thermoplastic), and colors are white or yellow. After identifying changes in 2007 General Application Special Provisions, a data mining plan was developed. The original database obtained from ALDOT was a Microsoft Access file that was then imported into Microsoft Excel. All data were assembled into one table. A screen capture of Microsoft Excel, in Figure 8, shows an example of the available information for all 40 projects. Table 10 presents the meaning of each entry represented on Figure 8.

<table>
<tr><th>PROJECT_NO</th><th>CONTRACTOR</th><th>COUNTY</th><th>BEAD_MAN_1</th><th colspan="2">BEAD_MAN_4</th></tr>
<tr><td>EB-0016(505)</td><td>Ozark Striping</td><td>Baldwin County</td><td>Potters Industries (TX)</td><td colspan="2">Swarco-Reflex(TX)</td></tr>
<tr><th>THERMO_MAN</th><th>APP_METHOD</th><th>CLASS</th><th>LOT_ID</th><th colspan="2">PLACED_DATE</th></tr>
<tr><td>Dobco Thermoplastic</td><td>Extrusion</td><td>2</td><td>5</td><td colspan="2">02-Jul-07</td></tr>
<tr><th>TEST_DATE</th><th>RETRO_ID</th><th>COLOR_ID</th><th>STRIPE_TYPE</th><th colspan="2">STRIPE_COLOR</th></tr>
<tr><td>27-Jul-07</td><td>SG070986</td><td>SG070975</td><td>solid</td><td colspan="2">white</td></tr>
<tr><th>DIRECTION</th><th>INSPECTOR_1</th><th>INSPECTOR_2</th><th>PROJECT_MAN</th><th>LOT_ID</th><th>Station</th></tr>
<tr><td>West</td><td>Jones</td><td>Yarbrough</td><td>Jones</td><td>66</td><td>360+20</td></tr>
<tr><th>Thickness</th><th>Retro</th><th>Luminance</th><th>Color x</th><th>Color y</th><th>Color P/F</th></tr>
<tr><td>0.12</td><td>469.00</td><td>54.31</td><td>0.33</td><td>0.36</td><td>PASS</td></tr>
</table>

Figure 8 – Information from 2007 Database

Table 10 – Meaning of ALDOT Database Entries

Entry	Meaning
PROJECT_NO	Number used to identify the project
CONTRACTOR	Contractor of project
COUNTY	County where project is located
BEAD_MAN	Bead Manufacturer
THERMO_MAN	Thermoplastic Manufacturer
PROJECT_MAN	Project Manager
INSPECTOR	Inspector of the Project
APP_METHOD	Method used on the application of marking
CLASS	Class of marking
LOT_ID	Identification of marking in ALDOT records
PLACED_DATE	Date when marking was placed
TEST_DATE	Date when marking properties were measured
RETRO_ID	Identification of the equipment used to measure retroreflectivity
COLOR_ID	Identification of the equipment used to measure color
STRIPE_TYPE	Type of marking (solid or broken)
STRIPE_COLOR	Color of marking (white or yellow)
DIRECTION	Direction of traffic where marking was measured (e.g., "West" means "Westbound")
Station	Location of the marking
Thickness	Initial Thickness of the marking
Retro	Initial Retroreflectivity of the marking
Luminance	Initial Luminance of the marking
Color x	Coordinates of chromaticity measures
Color y	
Color P/F	Determination as to whether color passes or fails to meet specifications

Analyses were performed using data available from the 2007 ALDOT database. The evaluation of measurements of retroreflectivity, thickness, luminance, and chromaticity in regard to specifications was the first executed process, followed by a statistical analysis. Pavement marking measurements were compared with values given in the *Standard Specifications for Highway Construction Special Provisions* (ALDOT, 2007) to determine whether the values in the database complied with ALDOT requirements. As it was observed in Section 3.1, there were no changes in quantitative requirements from one special provision to another. Therefore, all Special Provisions presented the same required values shown on Table 11.

Table 11 – Minimum Required Values for Pavement Markings

Class	Color	Thickness (in)	Retroreflectivity (mcd/m^2/lux)	Luminance (%)
2	White	0.10	450	50
2	Yellow	0.10	350	35
2T	White	0.04	300	50
2T	Yellow	0.04	250	35

Although the values shown in Table 11 are the minimum required, the special provisions inform that a thickness greater than 95% of the minimum value is acceptable and a retroreflectivity greater than 90% of the minimum value meets requirements (ALDOT, 2007). Therefore, the values used to verify if the measured thickness, retroreflectivity, and luminance in Alabama were acceptable are shown in Table 12.

Table 12 – Acceptable Values for Pavement Markings

Class	Color	Thickness (in)	Retroreflectivity (mcd/m^2/lux)	Luminance (%)
2	White	0.095	405	50
2	Yellow	0.095	315	35
2T	White	0.038	270	50
2T	Yellow	0.038	225	35

The analysis of color was also performed according to the 2007 General Application Special Provisions (ALDOT, 2007). The initial daytime chromaticity for white and yellow materials must fall within the box created by the coordinates shown in Table 13 for the chromaticity to be in compliance with specifications.

Table 13 – Initial Daytime Chromaticity Coordinates (Corner Points)

White		Yellow	
x	y	x	y
0.335	0.375	0.472	0.400
0.355	0.355	0.530	0.456
0.305	0.305	0.510	0.485
0.285	0.325	0.455	0.444

SOURCE: ALDOT, 2007

The box created by the plot of the coordinates from Table 13, for white materials, can be observed in Figure 9 and the plot of the coordinates from Table 13, for yellow materials, is shown in Figure 10. If measured chromaticity values were located within constrained space in Figures 9 and 10, then color observations complied with specifications.

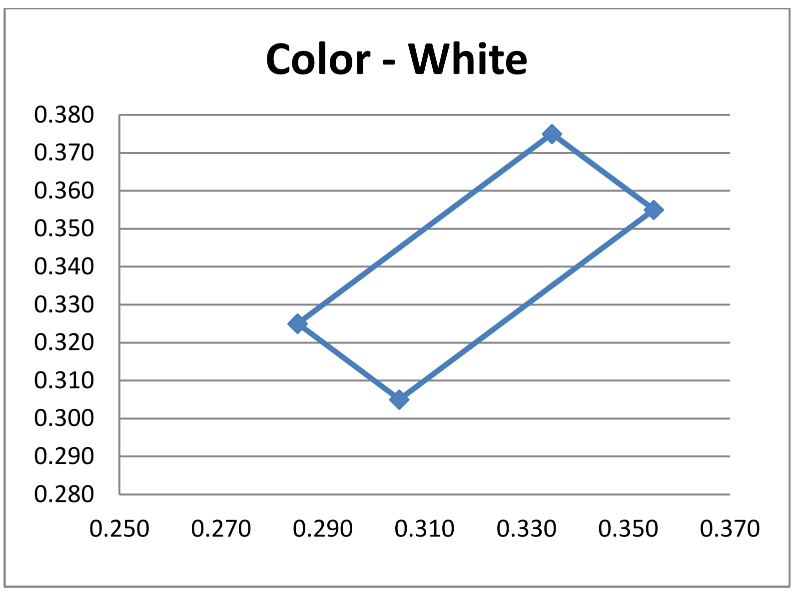

Figure 9 – Initial Daytime Chromaticity: White

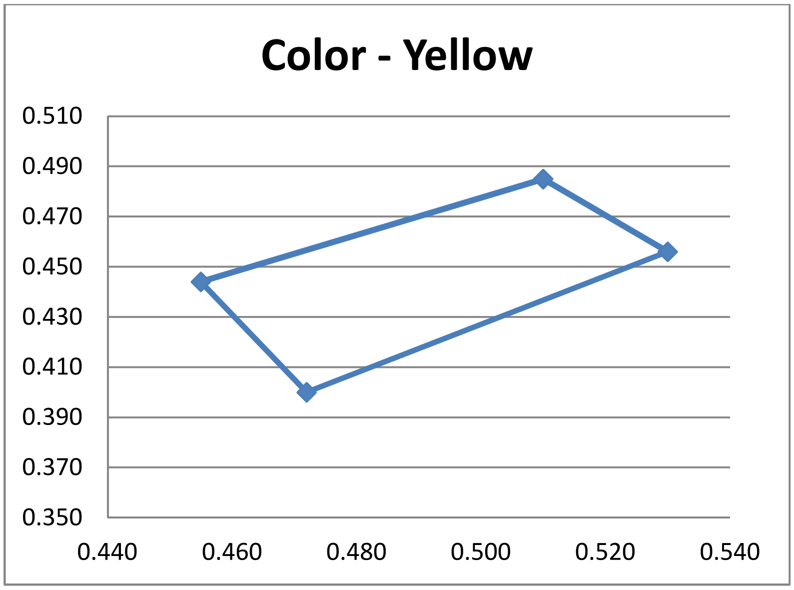

Figure 10 – Initial Daytime Chromaticity: Yellow

After analyzing all field measurements from the 40 projects in Alabama, some conclusions could be made. The percentage of projects that were according to specifications requirements can be observed in Chapter Four: Results. Finally, statistical measures were calculated, for each marking color and type. Mean, standard deviation and coefficient of variation were computed to demonstrate the variation of the measured observations of the 40 projects in Alabama. This analysis can provide the information on the central tendency for each marking property and the dispersion from the average. The detailed statistical analysis for each class and color of markings can be seen in Chapter Four: Results.

3.3. Retroreflectivity Modeling

For all 40 projects in the initial ALDOT database, from 2007, only 15 have retroreflectivity data from 2008, 2009 and 2010. Table 14 and Figure 11 describe the location of these 15 projects. For these 15 projects, cost information was obtained from the Tabulation of Bids, from ALDOT (ALDOT, 2010 [1]).

Table 14 – Projects Included in the Retroreflectivity Modeling

Project ID	County	Division	Location	Map Key
EB-0016(505)	Baldwin County	9	SR-16 (US-90) from Robertsdale to Florida State line	9A
STPSA-0185(500)	Butler County	6	SR-185 from SR-263 in Greenville to the Lowndes county line	6A
EB-0074(513)	Cullman County	1	SR-74 (US-278) from east of CR-420 to I-65 in Cullman	1A
NHF-STPSAF-0053(525)	Dale County	7	SR-53 (US-231) from near CR-63 in Pinckard to near CR-18	7A
EB-0035(506)	DeKalb County	1	SR-35 from SR-7 (US-11) to MP 25.40 in Fort Payne	1B
STPSA-0001(529)	Etowah County	1	SR-1 (US-431) from west of I-59 in Attalla to 0.2 miles south of CR-137	1C
99-307-164-167-701	Geneva County	7	SR-167 from the Florida state line to near the south city limit of Hartford	7B
99-307-346-010-701	Henry County	7	SR-10 from SR-1 (US-431) to SR-95 in Abbeville	7C
99-302-391-101-701	Lauderdale County	2	SR-101 from the north end of Wheeler Dam to SR-2 (US-72) in Elgin	2A
STPSA-0021(515)	Lowndes County	6	SR-21 from the Wilcox county line to south of CR-45 near Mount Willing	6B
99-302-473-171-706	Marion County	2	SR-171 from the Fayette county line in Winfield to SR-118	2B
STPSA-0079(505)	Marshall County	1	SR-79 from SR-1 (US-431) through Columbus City to the Jackson county line	1D
99-303-595-003-709	Shelby County	3	SR-3 (US-31) from Seventh Avenue in Calera to I-65	3A
99-305-632-069-702	Tuscaloosa County	5	SR-69 from the north end of the Lake Tuscaloosa bridge to south of Windham Springs	5A
STPSA-0089(500)	Wilcox County	8	SR-89 from SR-21 west of Snow Hill to the Dallas county line	8A

Figure 11 – Location of the 15 Projects with Retroreflectivity Data from 2007 to 2010

SOURCE: Based on University of Alabama, 2011

All projects are located on State Routes, U.S. Routes, or Interstates, with 2 lanes (one in each direction) or four lanes (separated, two lanes on one side, two lanes on the other side). Figure 12 shows an example of a two-lane state route, a section of project STPSA-0185(500), in Butler County, on SR-185. More pictures showing details of these 4-year old pavement markings of project STPSA-0185(500) can be observed in Appendix A.

Figure 12 – Section of Project STPSA-0185(500), on SR-185

Retroreflectivity for 2007 data was measured at specific points, within stations. Retroreflectivity for 2008, 2009 and 2010 was measured in different locations, within mileposts. To build the retroreflectivity curves, it was necessary to correlate locations from the 2007 database and the 2008 to 2010 data. From ALDOT project records, the "Begin Project" location, in station, and the corresponding milepost were identified. Figure 13 shows an example for project NHF-STPSAF-0053(525). The project begins at Milepost 32.1, which is the same location as Station 251+67.

PROJECT NHF-STPSAF-0053(525)			
MP	FEET	FROM STA	TO STA
32	24639	246+39	299+18
33	29919	299+19	351+98
34	35199	351+99	404+78
35	40479	404+79	457+58
36	45759	457+59	510+38

MILES	FEET
1 mile	5280

INITIAL		
MP	FEET	STA
32.1	25167	251+67

Figure 13 – Example of Correspondence from Stations to Mileposts

For each milepost, there was a range of corresponding stations. The average retroreflectivity for this range of stations was calculated and set as the milepost retroreflectivity value for 2007. One retroreflectivity curve was built for each milepost, according to color and type of marking. Table 15 shows the total number of mileposts, across all projects, for each color and type; therefore, the number of retroreflectivity curves available for analysis. The complete list of mileposts by projects can be observed in Appendix B.

Table 15 – Total Number of Retroreflectivity Curves

TOTAL CURVES	Solid White	Broken White	Solid Yellow	Broken Yellow
	76	17	67	32

3.3.1. Preparation of Data for Modeling

The end of a pavement marking service life can be represented in a retroreflectivity curve as the time when the curve reaches a minimum retroreflectivity threshold. The adopted minimum values are 150 mcd/m^2/lux for white markings and 100 mcd/m^2/lux for yellow markings, as these were the most common values found in the literature.

The retroreflectivity curves that were built for each milepost, based on 4 years of data, do not reach these minimum retroreflectivity values; therefore, it is necessary to extrapolate curve points. Many existing models in the literature were applied to the available data to determine which one would be the best option to represent actual data. Among these models, those developed by Abboud and Bowman, and Sitzabee et al., required traffic information as input data. The Average Annual Daily Traffic (AADT) for the 15 project locations was obtained from the ALDOT website (ALDOT, 2010 [2]).

As there was not an exact correspondence between locations in the ALDOT traffic database and the location of the projects' measurements, some assumptions were made when determining AADT for each milepost. Three locations from the ALDOT traffic database, similar to locations of projects, were chosen, and the average AADT for these three locations was considered as the AADT for each milepost of the considered project.

To illustrate this process, Project 99-302-391-101-701, on SR-101, is shown as an example. It has retroreflectivity data at milepost 25.7, milepost 26.2, milepost 27.0, and milepost 28.0. The ALDOT traffic database contains traffic data at milepost 24.99, milepost 26.78, and milepost 28.24, as historical data, as shown in Table 16. The average of these three AADT historical data was calculated. From that, a linear regression analysis was applied in order to obtain an equation to estimate AADT as a function of time to relate AADT values to the times when retroreflectivity measurements were taken. All existing mileposts for this project (MP 25.7, MP 26.2, MP 27.0, and MP 28.0) will have the same AADT equation to calculate vehicles as a function of time.

Table 16 – ALDOT Historical Traffic Data

Traffic Counters 2010	
Counter ID	**AL-39-522**
Station	522
County	39
City	N/A
Route	101
Milepoint	24.99
AADT 2010	5990
AADT 2009	6580
AADT 2008	6380
AADT 2007	7050
AADT 2006	6980
AADT 2005	6890
AADT 2004	6930
AADT 2003	6540
AADT 2002	6370
K	11
D	55
TDHV	8
TADT	11
Heavy	50
Functional Class	6

Traffic Counters 2010	
Counter ID	**AL-39-521**
Station	521
County	39
City	N/A
Route	101
Milepoint	26.78
AADT 2010	7390
AADT 2009	7370
AADT 2008	7140
AADT 2007	7480
AADT 2006	7300
AADT 2005	7590
AADT 2004	7760
AADT 2003	7460
AADT 2002	7040
K	11
D	75
TDHV	7
TADT	9
Heavy	50
Functional Class	6

Traffic Counters 2010	
Counter ID	**AL-39-520**
Station	520
County	39
City	N/A
Route	101
Milepoint	28.24
AADT 2010	5640
AADT 2009	5360
AADT 2008	5150
AADT 2007	5400
AADT 2006	5270
AADT 2005	5540
AADT 2004	5300
AADT 2003	5100
AADT 2002	4860
K	11
D	55
TDHV	7
TADT	9
Heavy	50
Functional Class	7

SOURCE: ALDOT, 2010 [2]

This calculated AADT was used to estimate models in the literature. For Abboud and Bowman model, AADT per lane was considered; for Sitzabee et al. model, AADT for all lanes was used to calculate retroreflectivity.

3.3.2. Model Fitting

The determination of the best-fitting model from the literature when applied to ALDOT data was based on three performance measures: Area Under Curve Ratio, Average Model Error, and Average Percent Error.

The behavior of a curve can be represented by the area under it. The definite integral gives the area between the graph of the input and the x-axis. The technical definition of the definite integral is the limit of a sum of areas of rectangles, called a Riemann sum. There are four methods of Riemann summation: left sum, right sum, middle sum, and trapezoidal rule. The left Riemann sum approximates the function by its value at the left-end point; the right Riemann sum approximates the value at the right endpoint; the middle Riemann sum approximates the function at the midpoint of each interval; and the trapezoidal rule considers that the values of the function on an interval are approximated by the average of the values at the left and right endpoints (Thomas and Finney, 1996). Figure 14 shows how these four summation methods can be visualized.

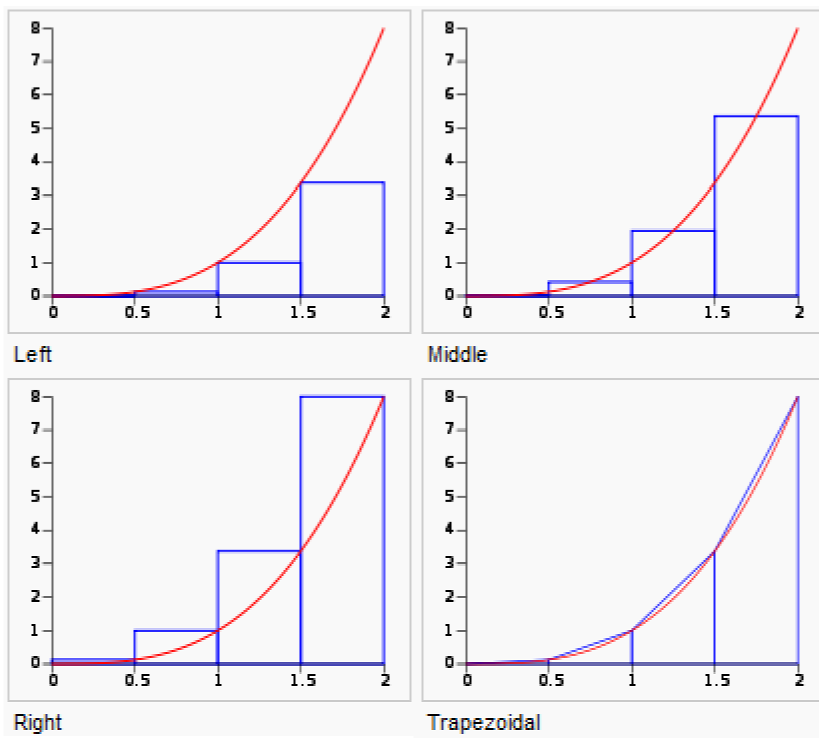

Figure 14 – Four Methods of Riemann Summation

SOURCE: Adapted from Thomas and Finney, 1996

The trapezoidal rule is applied to calculate the area under the curve resulted from actual data and the area under each curve representing a model in literature. Figure 15 illustrates the comparison between two curves considering this area.

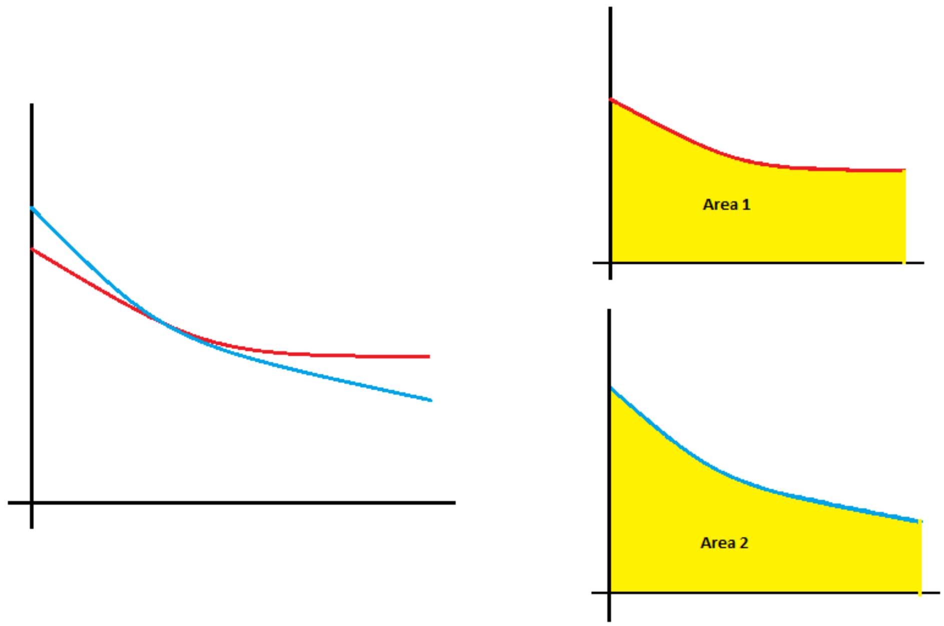

Figure 15 – Comparison Between Areas Under Curves

To have a numerical parameter of comparison between all models and a method to identify the "best-fitting" model, a ratio is calculated for each model, for each milepost, as shown in Equation 3.1.

$$Ratio = \frac{Area\ (Model)}{Area\ (Actual\ Data)} \qquad \text{(Eq. 3.1)}$$

The closer this ratio is to 1, the better fitting is the model.

Another way to compare models is to calculate the average model error. This relationship is simply the difference between the model and actual data and it is given by Equation 3.2.

$$Average\ Model\ Error = Model - Actual\ Data \qquad \text{(Eq. 3.2)}$$

The last method used to evaluate the suitability of models found in the literature is average percent error. It is calculated by Equation 3.3.

$$Average\ Percent\ Error = \frac{Model - Actual\ Data}{Actual\ Data} * 100 \qquad \text{(Eq. 3.3)}$$

3.4. Benefit/Cost Calculation

Retroreflectivity curves developed for each milepost of the 15 projects in Alabama were extrapolated based on the best-fitting models from the literature, established according to the methodology described in Section 3.3.2. As shown in Chapter Two, there is a wide range of methods used to determine benefit/cost relationship of each available marking material. The method developed by Fu and Wilmot, considering the area between R_{min} and R_{max} as the benefit of the marking, was the most relevant to this study.

According to what was analyzed in Chapter Two, it is possible to set R_{max} = 200 mcd/m^2/lux, R_{min} = 150 mcd/m^2/lux for white markings, and R_{min} = 100 mcd/m^2/lux for yellow markings. Cost data were available from ALDOT Tabulation of Bids (ALDOT, 2010[1]). AADT was obtained from ALDOT Traffic Data (ALDOT, 2010 [2]). The benefit/cost ratio can be calculated by Equation 3.4.

$$\frac{benefit}{cost} = \frac{benefit * AADT}{total\ cost} \qquad \text{(Eq. 3.4)}$$

3.5. Modeling of Retroreflectivity Over Time

Using the data from the 15 projects with several years of observations, new models will be developed to represent the behavior of retroreflectivity over time in Alabama. First, locations are grouped by color and type: solid white, broken white, solid yellow, and broken yellow. The

Standard Specifications for Highway Construction Special Provisions (ALDOT, 2007), which were in effect at the time the projects included in this study were constructed, state that initial retroreflectivity shall be a minimum of 450 mcd/m^2/lux for white markings and 350 mcd/m^2/lux for yellow markings. Therefore, locations with initial retroreflectivity less than the required values are not considered in the modeling.

In the literature, separate models for solid and broken markings are not presented. Therefore, two groups of data will be considered in this study: white and yellow; within each color, measurements from solid and broken lines will be combined. It can also be inferred from the literature that most models consider only age as the independent variable, some consider the initial retroreflectivity, and a few consider traffic volume.

Regressions that consider only one independent variable are simple regressions; if 2 or more independent variables are included, they are defined as multiple regressions. For all developed models in this thesis, 2 or more independent variables are used; therefore, they are multiple regressions. When analyzing available data from ALDOT databases, two independent variables can be considered for the models: Initial Retroreflectivity and Age. AADT can be another independent variable as this data was obtained by the linear regression analysis based on ALDOT traffic data demonstrated in Section 3.3.1. Some research considers that AADT does not influence retroreflectivity degradation significantly; other studies affirm it is an important variable when estimating retroreflectivity over time. Therefore, this study will consider two approaches when predicting retroreflectivity models: the first one considers initial retroreflectivity and age of markings as independent variables, the second approach also considers AADT as an independent variable.

For the retroreflectivity modeling based on initial retroreflectivity and age of markings, four models will be evaluated according to the tendencies of data: linear, power, quadratic, and exponential. Models will be estimated using the software IBM Statistical Package for the Social Sciences (SPSS). The linear model general expression for two independent variables is represented by Equation 3.5.

$$y = m_1x_1 + m_2x_2 + b \quad \text{(Eq. 3.5)}$$

where:

y = Dependent Variable;

x_1, x_2 = Independent Variables;

m_1, m_2= Coefficients;

b = Constant.

The power model can be represented by Equation 3.6.

$$y = b * {m_1}^{x_1} * {m_2}^{x_2} \quad \text{(Eq. 3.6)}$$

The general expression for a quadratic model is observed in Equation 3.7.

$$y = m_1x + m_2x^2 + b \quad \text{(Eq. 3.7)}$$

The exponential model can be represented by Equation 3.8.

$$y = x_1e^{-bx_2} \quad \text{(Eq. 3.8)}$$

Considering initial retroreflectivity, age of markings, and traffic volume as independent variables to model retroreflectivity, a linear model will be developed based on the tendencies of data and existing model forms in the literature with these three variables. The model will also be estimated using the software IBM Statistical Package for the Social Sciences (SPSS) and its general expression is observed in Equation 3.9.

$$y = m_1x_1 + m_2x_2 + m_3x_3 + b \quad \text{(Eq. 3.9)}$$

Comparisons between all models, details related to each one and conclusions about the results obtained with all four regressions can be analyzed in Chapter Four: Results.

3.6. Summary of Chapter Three

This chapter presented the methods used to analyze the 2007 database, which included the determination whether observations met specifications and a statistical analysis to evaluate trends in mean, standard deviation, and coefficient of variation. Also provided herein are details related to the methodology applied to retroreflectivity modeling based on models found in the literature and preparation of data for development of new models. Model forms under consideration include linear, power, quadratic, and exponential when considering initial retroreflectivity and age of markings as independent variables to predict retroreflectivity; a linear model will be developed when AADT is also considered. The results obtained with the use of methods from this chapter will be presented in Chapter Four: Results.

Chapter Four

Results

This chapter presents the results for the procedures adopted in this thesis, described in Chapter Three. Chapter Four provides a summary illustrating the proportion of all 7840 observations among the 40 projects in Alabama that met ALDOT specifications, considering the properties of retroreflectivity, thickness, luminance, and chromaticity. Statistical calculations of mean, standard deviation, and coefficient of variation are also presented in this chapter.

The retroreflectivity modeling process provided several results. The development of retroreflectivity curves for each milepost of the 15 projects with data from 2007 to 2010 is described in this Chapter, as well as application and determination of best-fitting models from the literature. Considerations for the benefit/cost analysis are presented in this chapter. Finally, different proposed models of retroreflectivity over time are suggested to represent projects in Alabama.

4.1. ALDOT Data Mining and Analysis

After analyzing all measures from the 2007 database of 40 projects in Alabama, some conclusions can be made pertaining to compliance with specifications and statistical attributes. The first two columns of Table 17 indicate how many observations met specifications and how many did not; how many of the observation points did not have a property measured is also represented in the table. The final two columns show the percentage of observations which passed specifications and the percentage of total observations which was measured for the considered property of thickness, retroreflectivity, luminance, or chromaticity.

Table 17 – Material Property Compliance with Specifications

Property	Pass	Do not pass	Measured	Not measured	Total	% Passing	% Measured
Thickness	6025	1551	7576	264	7840	79.53	96.63
Retroreflectivity	5344	2356	7700	140	7840	69.40	98.21
Luminance	5831	1865	7696	144	7840	75.77	98.16
Color	7227	459	7686	154	7840	94.03	98.04

In addition, the 2007 ALDOT database provided data on whether chromaticity values met specifications. In this analysis a color check was also performed, and results of the present analysis and ALDOT analysis were compared. As can be observed in Table 18, some conclusions of the color measurements being in accordance with the Special Provisions were different, which means the ALDOT analysis found some color measurements passed the criteria and this data analysis did not, or vice-versa. In spite of these differences, 98.70% of the total compared showed equal conclusions.

Table 18 – Color Check Comparison

Different	Equal	Total	% Compared	%Equal
99	7536	7635	97.39	98.70

To describe the variation of the measured values from the 40 projects in Alabama in 2007, a statistical analysis was performed. Table 19 shows these measures for each analyzed group, by class and color of the material.

Table 19 – Statistical Calculations

Property	Class	Mean	Standard Deviation	Coefficient of Variation (%)	Number of Observations (n)
Thickness (in)	Class 2 - white	0.117	0.034	29.06	3971
	Class 2 - yellow	0.115	0.035	30.43	3031
	Class 2T - white	0.078	0.043	55.13	306
	Class 2T - yellow	0.065	0.033	50.77	268
Retroreflectivity (mcd/m^2/lux)	Class 2 - white	496	141.383	28.50	4000
	Class 2 - yellow	330	72.020	21.82	3126
	Class 2T - white	326	113.324	34.76	306
	Class 2T - yellow	202	87.783	43.46	268
Luminance (%)	Class 2 - white	55	10.189	18.53	3996
	Class 2 - yellow	37	5.241	14.16	3126
	Class 2T - white	65	5.437	8.36	306
	Class 2T - yellow	40	2.910	7.28	268

Table 19 shows that the most consistent property was luminance, with the lowest coefficients of variation. Thickness appears to be the less consistent one, as coefficient of variation can be as high as 55.13%. Retroreflectivity also has very dispersed observations, with a high coefficient of variation of 43.44% among the four color/class categories, and also very different means when contrasting all classes and types.

4.2. Retroreflectivity Modeling

4.2.1. Retroreflectivity Curve

Table 20 and Figure 16 show an example of the data and plot developed for all mileposts of the 15 projects that had data for four years. The total observations allowed for development of 76 curves for solid white markings, 17 for broken white, 67 for solid yellow and 32 for broken yellow markings.

Table 20 – Retroreflectivity Values of Project NHF-STPSAF-0053(525), for MP36

Curve 3: MP 36 Solid Yellow	
Date Tested (months)	**Retroreflectivity (mcd/m2/lux)**
0.00	249.90
8.40	291.00
22.77	224.00
34.67	220.50

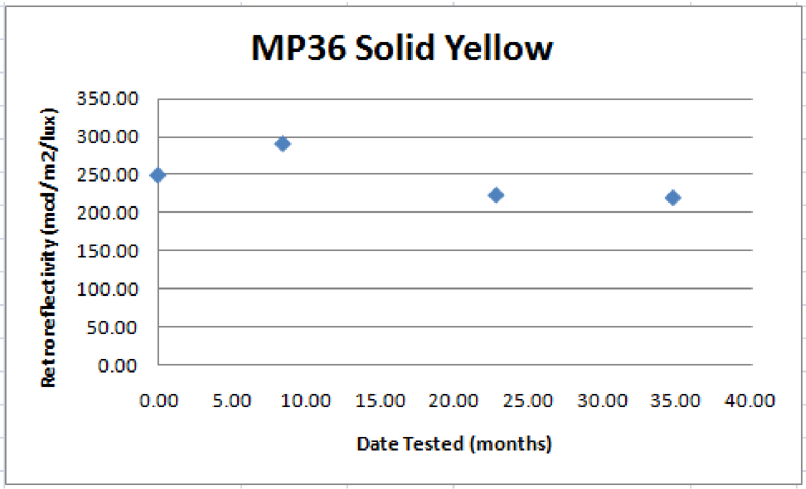

Figure 16 – Plot of Retroreflectivity Values of Project NHF-STPSAF-0053(525), for MP36

4.2.2. Model Fitting Analysis

The end of pavement marking service life can be determined when retroreflectivity reaches minimum values. The plots developed in Section 4.2.1 had retroreflectivity data for three years after markings' application, which did not represent the end of service lives. Retroreflectivity data had to be extrapolated until it could reach minimum threshold values, and to accomplish that, several models existing in the literature were tested to determine which one best represented actual data. For solid white and broken white pavement markings, 10 models were compared to actual data, Lee et al., Abboud and Bowman [1], Thamizharasan et al. linear, Sitzabee et al, Abboud and Bowman [2], Thamizharasan et al. non-linear, Bahar et al., Clarke and Yan linear, Clarke and Yan logarithmic, and Clarke and Yan quadratic. For solid yellow and broken yellow markings, the same models were tested, except for Abboud and Bowman models, which were developed specifically for white markings.

An example of application of the models found in the literature to the observed data, using data from Project STPSA-0185(500), Milepost 10, Solid White, can be observed in Figure 17.

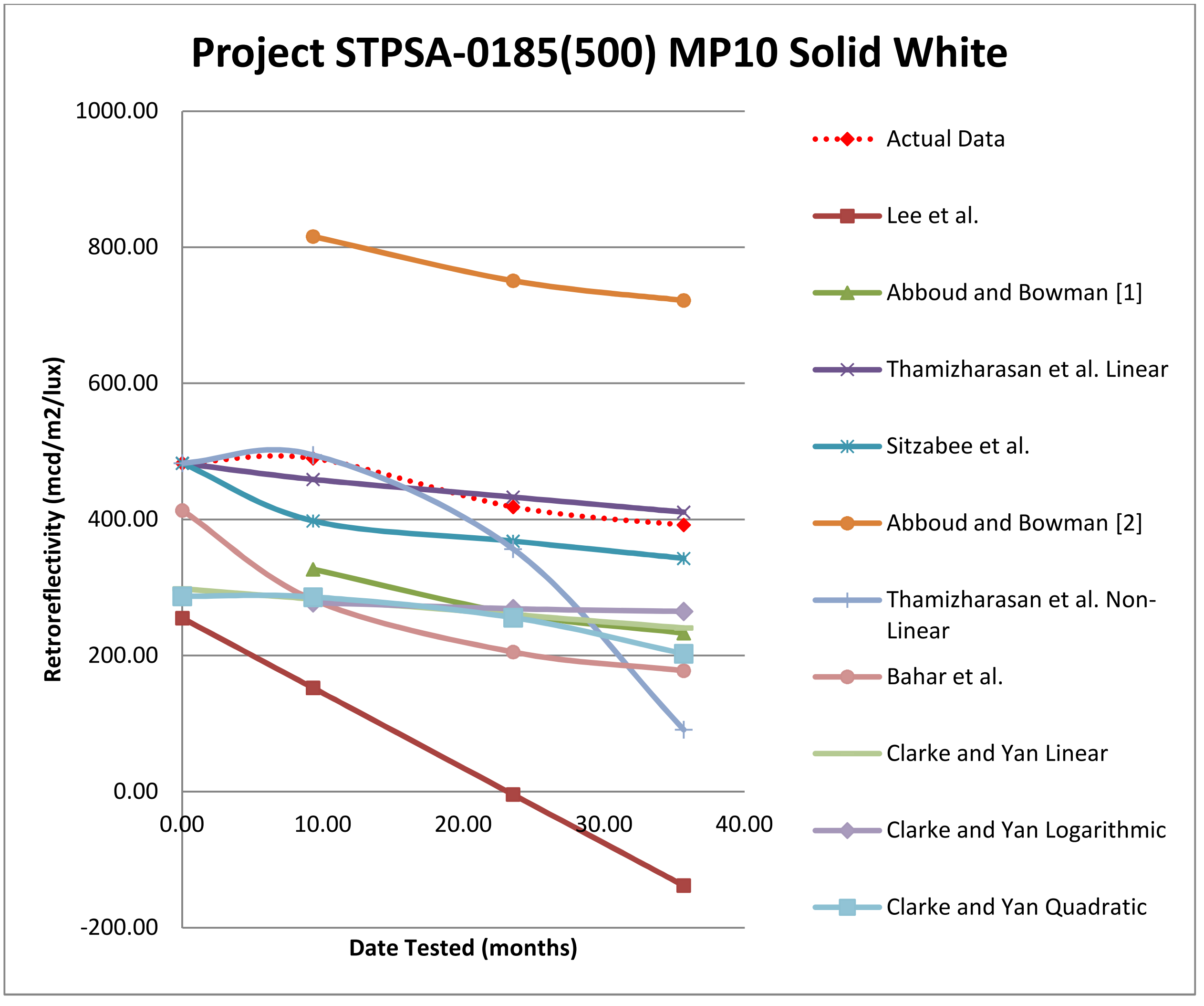

Figure 17 – Comparison between Models for Project STPSA-0185(500), MP10, Solid White

The comparison between models, using the methods area under curve ratio, average model error, and average percent error, as described in Section 3.3.2, was performed. The three best-performing models for each color and type can be observed in Table 21. Number of locations indicate the number of curves for each marking color and type (the number of existing mileposts with data).

Table 21 – Models in the Literature that Best Represented Actual Data

Marking Color and Type	Number of Locations	Best-Performing Models					
		Area Under Curve Ratio		Average Model Error		Average Percent Error (%)	
Solid White	**76**	Thamizharasan Linear	1.02	Thamizharasan Linear	10.54	Sitzabee	-7.48
		Sitzabee	0.86	Sitzabee	-55.84	Thamizharasan Linear	8.20
		Thamizharasan Non-Linear	0.85	Thamizharasan Non-Linear	-89.76	Thamizharasan Non-Linear	-20.27
Solid Yellow	**67**	Sitzabee	0.91	Thamizharasan Non-Linear	24.79	Sitzabee	-1.33
		Thamizharasan Linear	1.14	Thamizharasan Linear	29.84	Clarke Quadratic	-19.37
		Thamizharasan Non-Linear	1.14	Sitzabee	-30.44	Thamizharasan Non-Linear	22.49
Broken White	**17**	Sitzabee	0.97	Thamizharasan Non-Linear	-13.68	Thamizharasan Non-Linear	0.78
		Thamizharasan Non-Linear	1.09	Sitzabee	-19.76	Sitzabee	4.91
		Clarke Logarithmic	0.83	Thamizharasan Linear	76.96	Clarke Logarithmic	-11.45
Broken Yellow	**32**	Thamizharasan Non-Linear	1.06	Thamizharasan Non-Linear	7.92	Thamizharasan Non-Linear	8.61
		Thamizharasan Linear	1.06	Thamizharasan Linear	13.63	Sitzabee	-9.58
		Sitzabee	0.86	Sitzabee	-40.49	Thamizharasan Linear	11.55

4.3. Benefit/Cost Calculation

The determination of a benefit/cost ratio for each observation from the 15 projects with retroreflectivity data from 2007 to 2010 is described in this section. This analysis can identify which projects were best executed, by color and type, and make them models for future pavement marking construction in Alabama. The most adequate benefit/cost method to be applied in this study was the Fu and Wilmot method, and for that retroreflectivity extrapolation was required. From Table 21, it can be seen that Thamizharasan et al. Linear and Sitzabee et al. models were found to be the most appropriate to represent actual data. Therefore, an extrapolation of actual data, beyond the 4 years for which data are available, was performed, based on these two models. However, the service life, determined by when retroreflectivity reaches the minimum threshold value of 150 mcd/m^2/lux for white markings and 100 mcd/m^2/lux for yellow markings, is much higher than observed values for markings found in the literature. This fact can be illustrated by Figure 18, which shows estimated service life equal to 250 months; Figure 19, where estimated service life is 150 months; and Table 22, from where it can be observed that all service life values are greater than the maximum found in the literature (102 months for white markings).

Table 22 – Example of Benefit/Cost and Service Life calculations

SOLID WHITE					
Project	**MP**	**Benefit/Cost Thamizharasan et al. Model (month*vehicle*mcd/m^2/lux)**	**Benefit/Cost Sitzabeeet al. Model (month*vehicle*mcd/m^2/lux)**	**Service Life Thamizharasan et al. Model (months)**	**Service Life Sitzabee et al. Model (months)**
99-307-164-167-701	1	12379	7156	256	152
	2	10587	6555	221	140
	3	10946	6670	228	142
	4	9883	6311	207	135
	5	11381	6823	236	145
	6	9742	6273	204	135

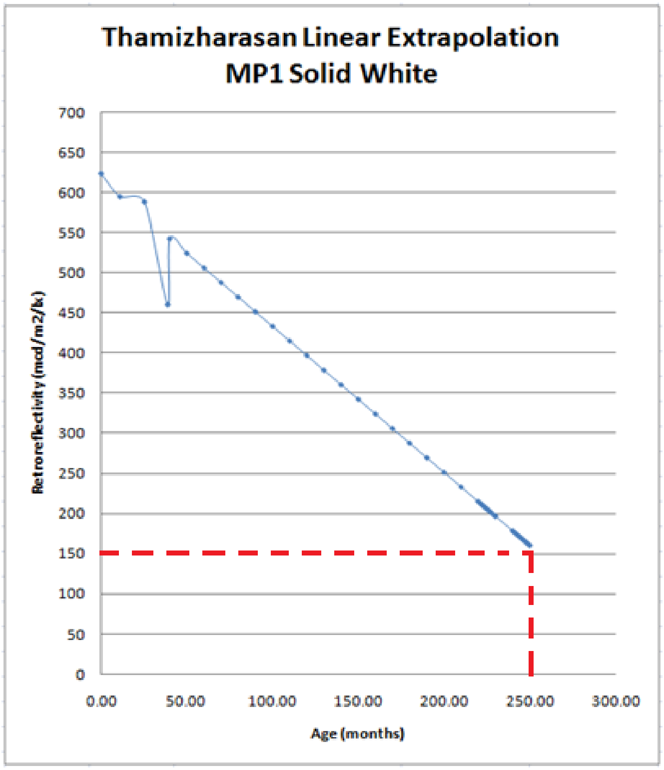

Figure 18 – Thamizharasan et al. Linear Extrapolation of Actual Data

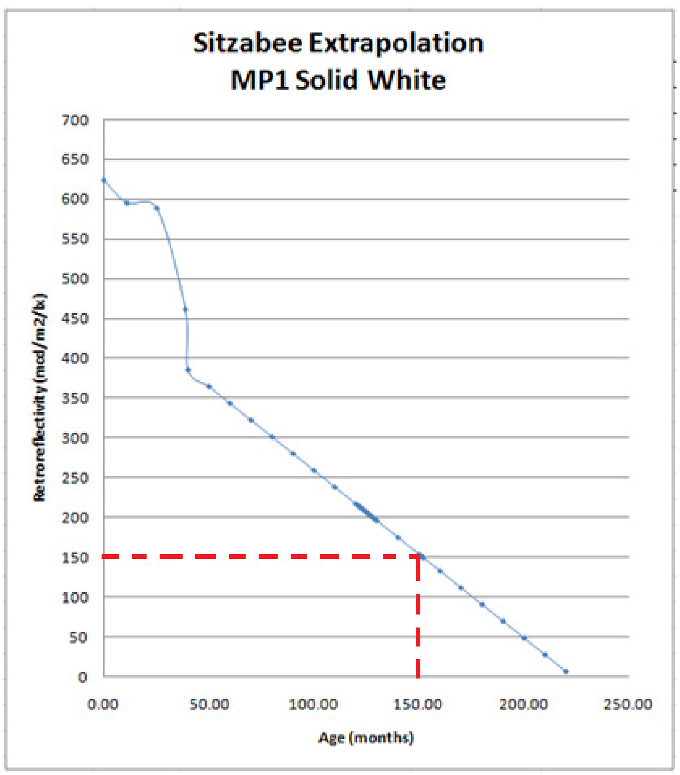

Figure 19 – Sitzabee et al. Extrapolation of Actual Data

Table 22 also shows that the Benefit/Cost values do not provide a useful idea of benefit related to cost; the meaning of the unit "month*vehicle*mcd/m^2/lux" is not tangible. In the literature, this method was valuable when comparing different materials, such as markings of Class 1 compared to markings of Class 2, and compared to markings of Class 2T, and determining the most cost-effective material among them. As the observations of the 15 projects in Alabama use only one type of material, thermoplastic Class 2, this benefit/cost analysis approach is not suitable in the case of the available data.

4.4. Modeling of Retroreflectivity Over Time

The models found in the literature, when applied to the Alabama data and extrapolated to acceptable minimum retroreflectivity values, do not result in reasonable service life projections. Therefore, new models were developed to try to represent better the behavior of retroreflectivity over time. First, locations were grouped by color and type: Solid White (76 locations), Broken White (17 locations), Solid Yellow (67 locations), and Broken Yellow (32 locations).

For model development, observations from all 15 projects were grouped only by color, one model for yellow and another for white markings; additionally, those below minimum initial retroreflectivity thresholds required by ALDOT were not considered. This approach to data organization for model development is consistent with those found in the literature. After applying this procedure, there are 63 observations for white markings and 42 for yellow markings.

In the literature, it is possible to observe that most models consider initial retroreflectivity and age of marking as the independent variables to estimate retroreflectivity; some models also consider traffic volume as an independent variable. For this reason, two different approaches were adopted in this study; first, four models were developed, by color, for data in Alabama: linear, power, quadratic, and exponential, as mentioned in Section 3.5. Table 23 shows all developed models for this approach and the corresponding R^2 for white markings in 63 locations and yellow markings in 42 locations. The dependent variable is retroreflectivity (R), measured in mcd/m^2/lux; the two independent variables are initial retroreflectivity (R_0), measured in mcd/m^2/lux, and age of marking (t), measured in months.

Table 23 – Developed Models considering initial retroreflectivity and age as independent variables

Color	Model	Equation	R^2
White	Linear	$R = 0.3242R_o - 4.745t + 384.4$	0.325
	Power	$R = 366.8 * 1.001^{Ro} * 0.9900^t$	0.335
	Quadratic	$R = R_o - 2.865t - 0.05300t^2 + 1.231$	0.181
	Exponential	$R = R_o * e^{-0.009747t}$	0.261
Yellow	Linear	$R = 0.1222R_0 - 4.778t + 338.3$	0.465
	Power	$R = 276.8 * 1.001^{Ro} * 0.9839^t$	0.480
	Quadratic	$R = R_o - 1.926t - 0.05119t^2 - 23.67$	0.320
	Exponential	$R = R_o * e^{-0.01682t}$	0.440

The second approach to the retroreflectivity estimate considered initial retroreflectivity, age of marking, and AADT as independent variables. Only linear models were developed, by color, which was consistent with the existing models in the literature. Table 24 shows the models for this approach and the corresponding R^2 for white markings in 63 locations and yellow markings in 42 locations.

Table 24 – Developed Models considering initial retroreflectivity, age, and AADT as independent variables

Color	Model	Equation	R^2
White	Linear	$R = 0.2296R_o - 4.967t - 0.004665AADT + 470.7$	0.398
Yellow	Linear	$R = 0.03928R_o - 4.932t - 0.002030AADT + 381.4$	0.479

4.4.1. Approach One: Initial Retroreflectivity and Age of Marking as Independent Variables

The linear model developed in this section was applied to estimate retroreflectivity over time for age and initial retroreflectivity values of actual data. The comparison for white markings between actual data points and linear model data points can be observed in Figure 20. It can be inferred from the figure that the range of data points representing the linear regression is not very similar to the range representing actual observations. The R^2 value for this relationship, as shown in Table 23, was 0.325. The data set could not be divided into more ranges because the number of locations in each would not be significant.

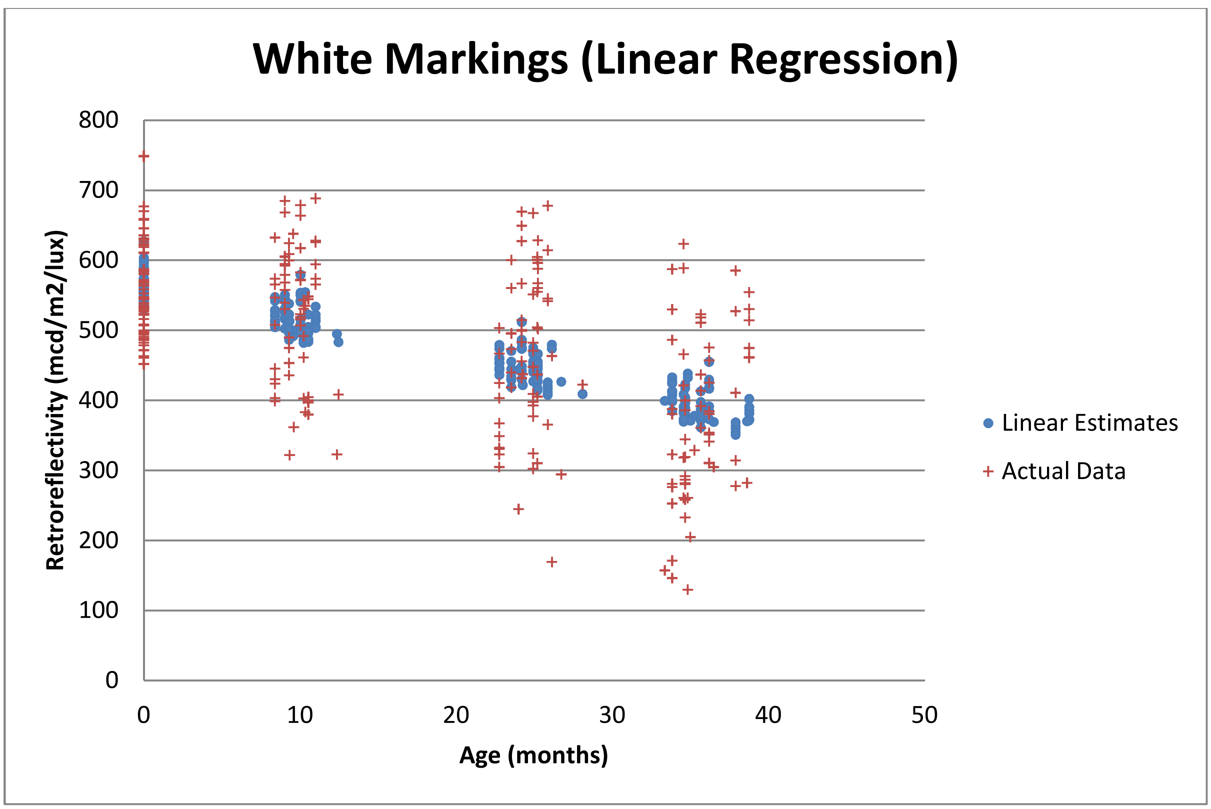

Figure 20 – Linear Regression estimates for White Markings: Initial Retroreflectivity and Age as Independent Variables

In order to ascertain how different initial retroreflectivity values influence where the model intercepts the Y axis, and also to compare the range of points in the model to the range formed by actual data points, different initial retroreflectivity values were tested from age zero until 40 months. For this analysis, with white markings, initial retroreflectivity values were set equal to 450 mcd/m^2/lux, 550 mcd/m^2/lux, 650 mcd/m^2/lux, and 750 mcd/m^2/lux. It can be noticed in Figure 21 that the regression lines occupy the middle region of the area formed by actual data points. The initial points as obtained from the model are not actual initial retroreflectivity values. This happens because the general linear model has a constant and a coefficient multiplying initial retroreflectivity causing that when age is equal to zero, retroreflectivity is not equal to initial retroreflectivity.

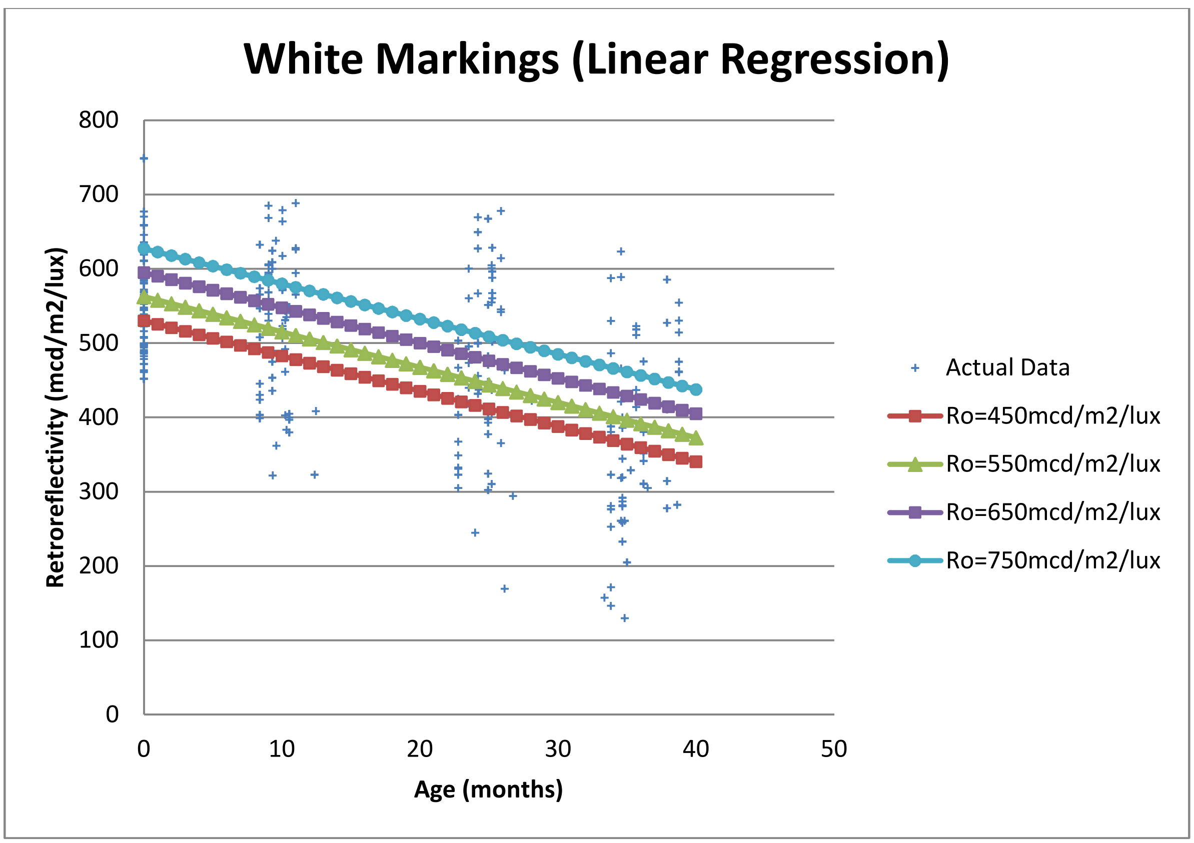

Figure 21 – White Markings Linear Regression for Different Initial Retroreflectivity Values: Initial Retroreflectivity and Age as Independent Variables

In trying to develop non-linear relationships between data and determine which models better represent retroreflectivity behavior over time in Alabama, a power regression model was developed. The comparison for white markings between actual data points and power model data points can be observed in Figure 22. In this case, as with the linear model, the range of data resulting from the power regression is narrower than the range of actual observations. The R^2 for this relationship, as shown in Table 23, was 0.335. Figure 23 shows that the power regression curves for initial retroreflectivity values of 450, 550, 650, and 750 mcd/m^2/lux also occupy the middle region of the area formed by actual data points; a similar pattern as was seen in Figure 23 for the linear model is apparent.

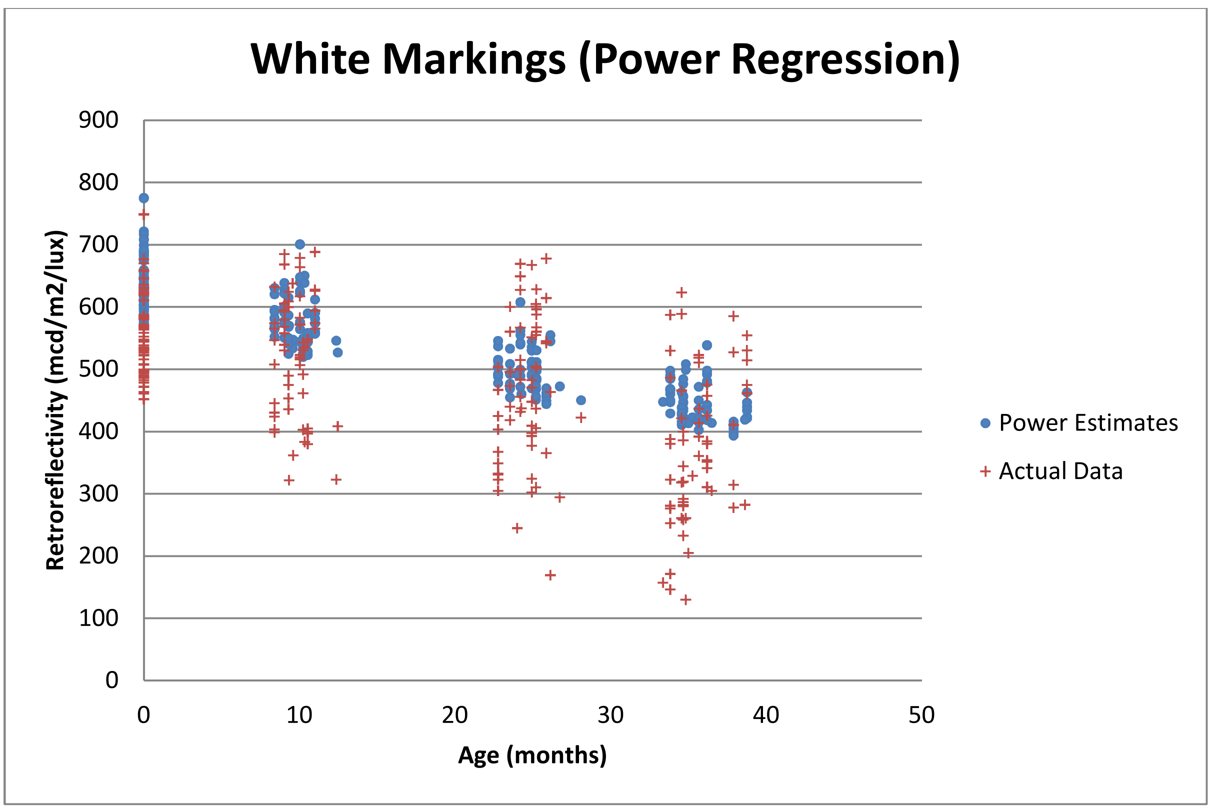

Figure 22 – Power Regression estimates for White Markings: Initial Retroreflectivity and Age as Independent Variables

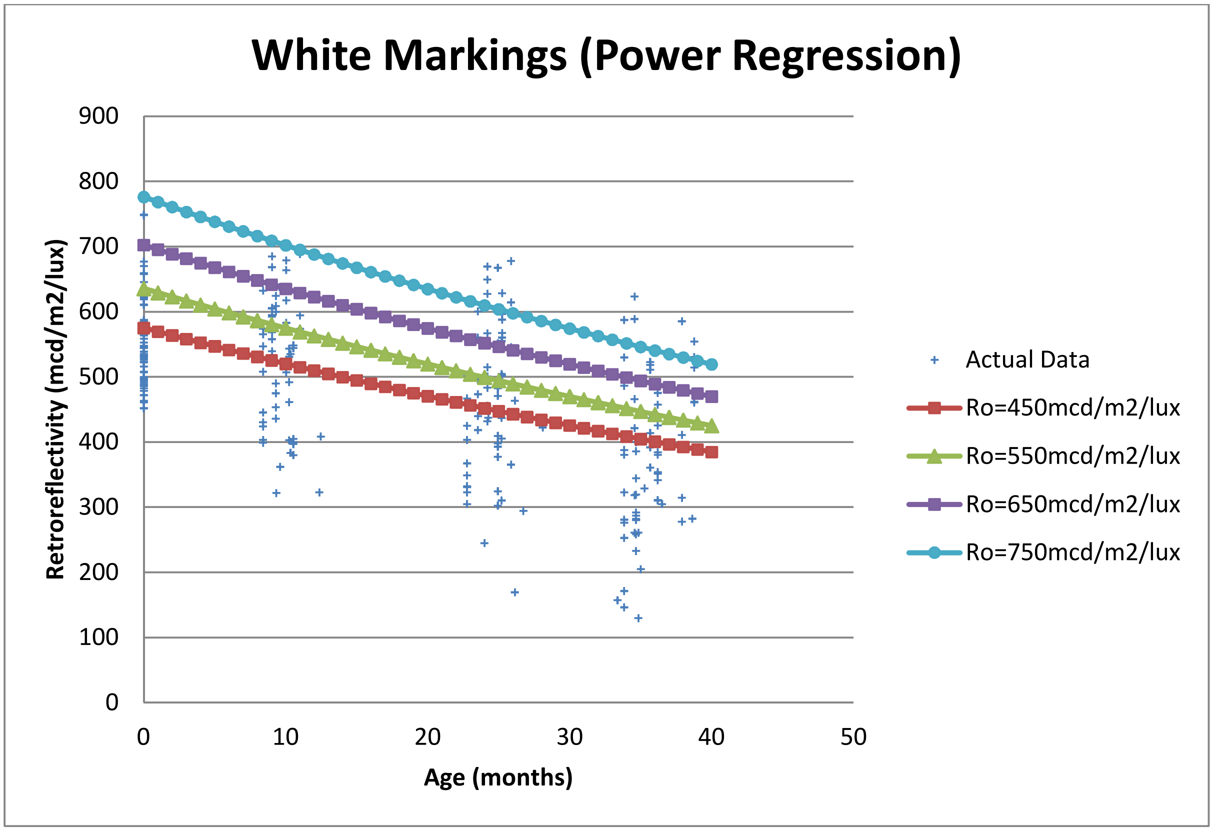

Figure 23 – White Markings Power Regression for Different Initial Retroreflectivity Values: Initial Retroreflectivity and Age as Independent Variables

A quadratic model was also developed in this section and applied to calculate retroreflectivity over time for age and initial retroreflectivity values of actual data. The comparison for white markings between actual data points and quadratic model data points can be observed in Figure 24. It is possible to observe that the range of data points from the quadratic regression is very similar to the range of actual observations, more so than was seen with the linear and power functions. The R^2 value for this relationship, as shown in Table 23, was 0.181. It can be observed in Figure 25 that points projected by the quadratic regression curves are in almost the entire region formed by the actual data points. There is high accuracy on where regression lines start, their initial points are very close to the observed initial retroreflectivity values. This happens because the constant in the quadratic model is not very high (1.231) and there is not a coefficient multiplying initial retroreflectivity.

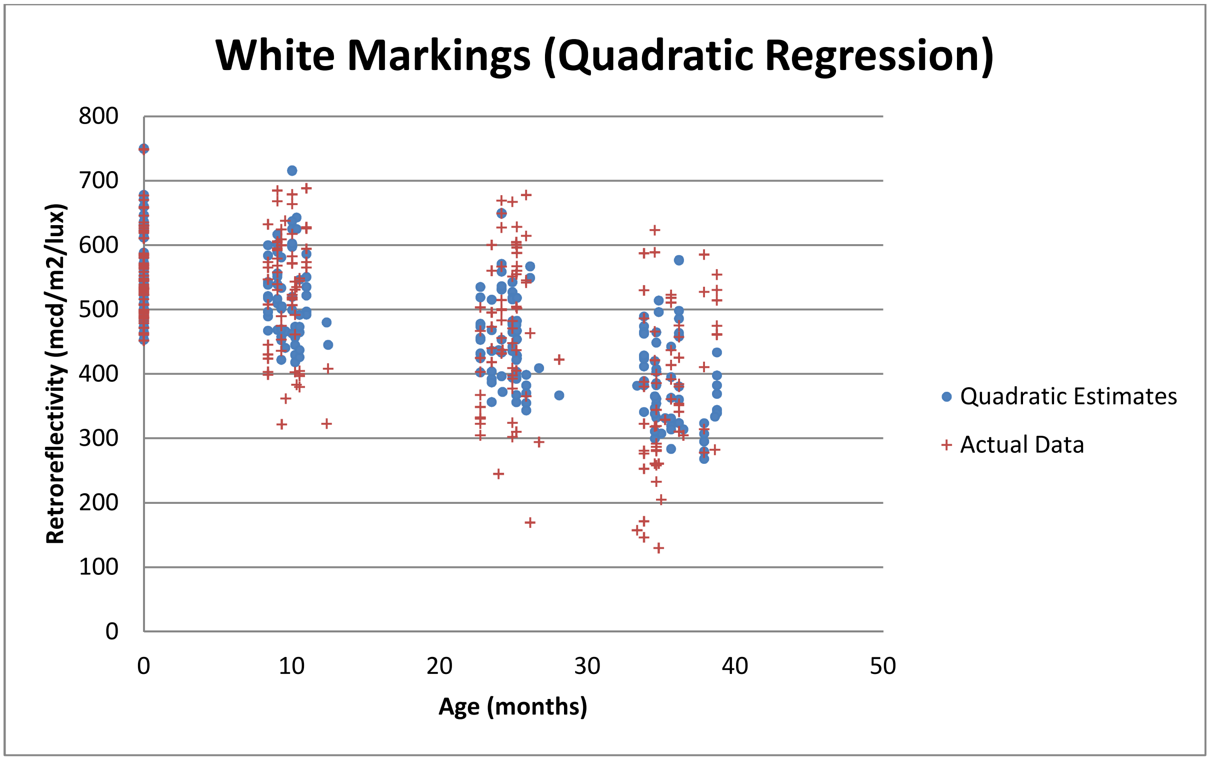

Figure 24 – Quadratic Regression estimates for White Markings: Initial Retroreflectivity and Age as Independent Variables

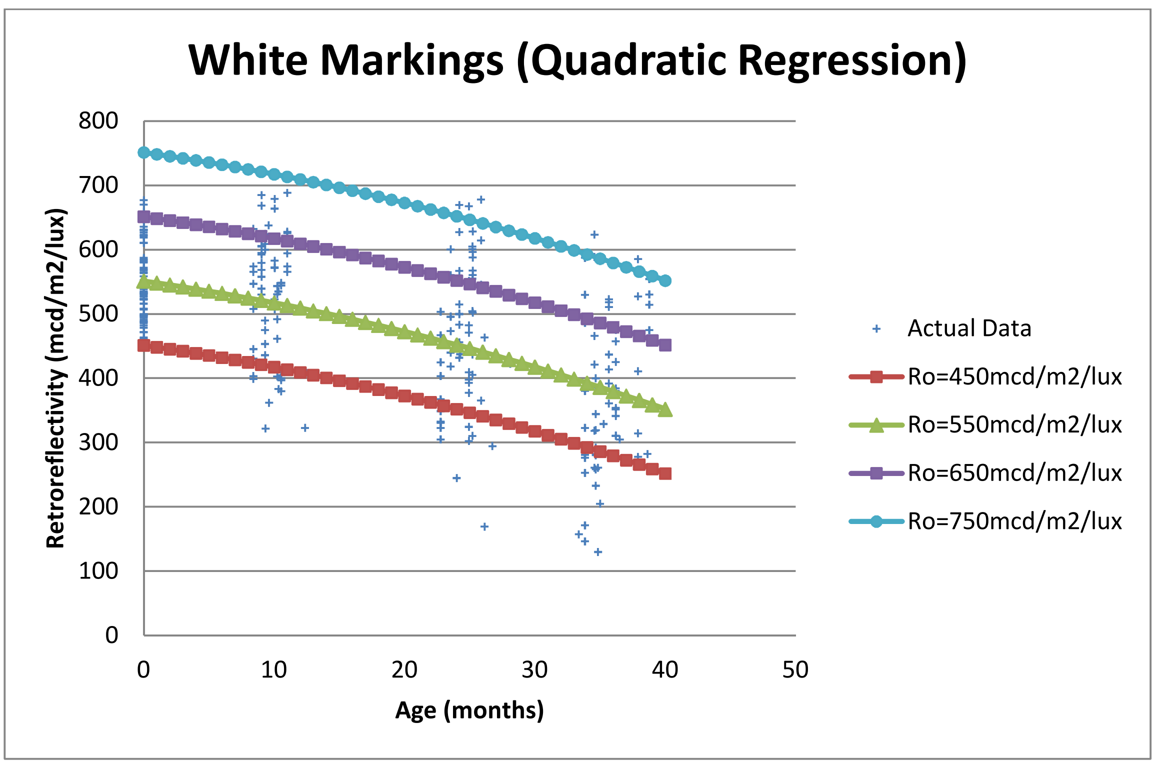

Figure 25 – White Markings Quadratic Regression for Different Initial Retroreflectivity Values: Initial Retroreflectivity and Age as Independent Variables

This study included an exponential model as well. The comparison for white markings between actual data points and exponential model data points can be observed in Figure 26. Figure shows that the range of data points estimated by the exponential regression is very similar to actual observations. The R^2 value for this relationship, as shown in Table 23, was 0.261.

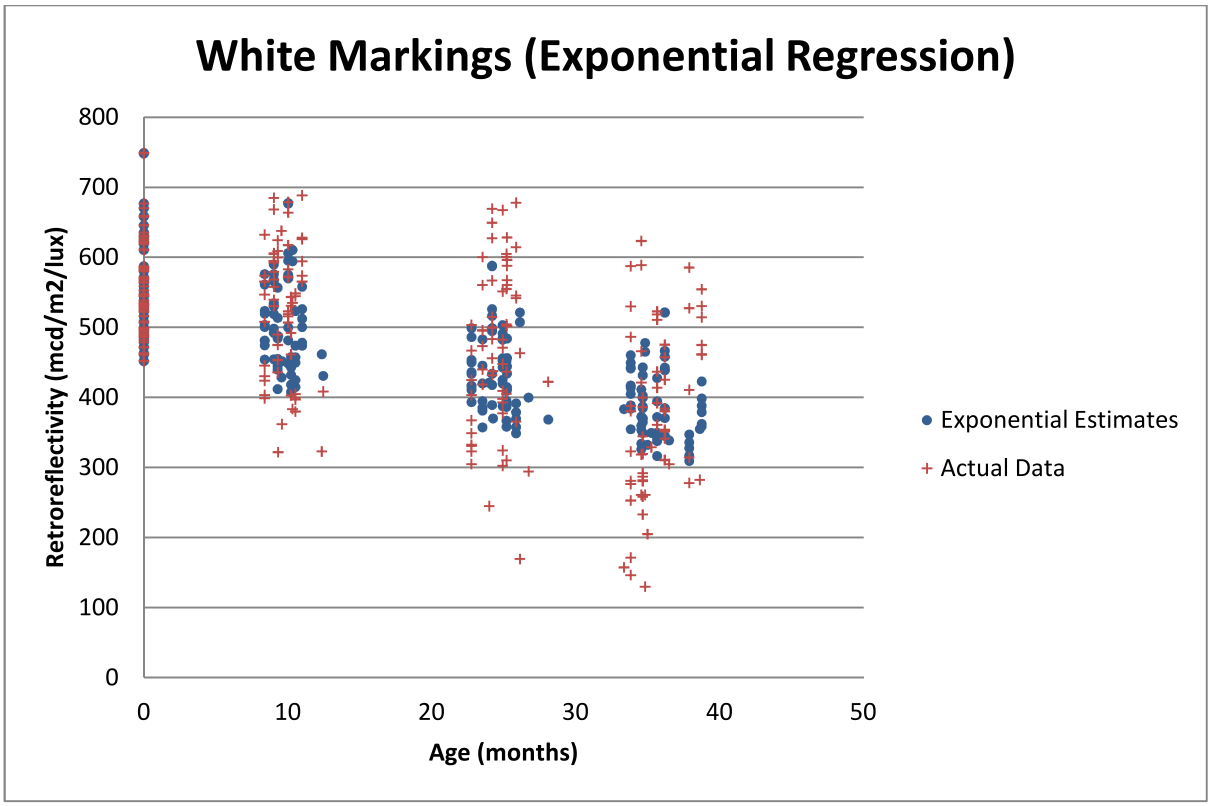

Figure 26 – Exponential Regression estimates for White Markings: Initial Retroreflectivity and Age as Independent Variables

Figure 27 shows that the exponential regression curves occupy almost all the area formed by actual data points. Unlike the other model forms developed, the initial points of the exponential model are exactly initial retroreflectivity values. This happens because when age is equal to zero, the exponential function of age has a value of one.

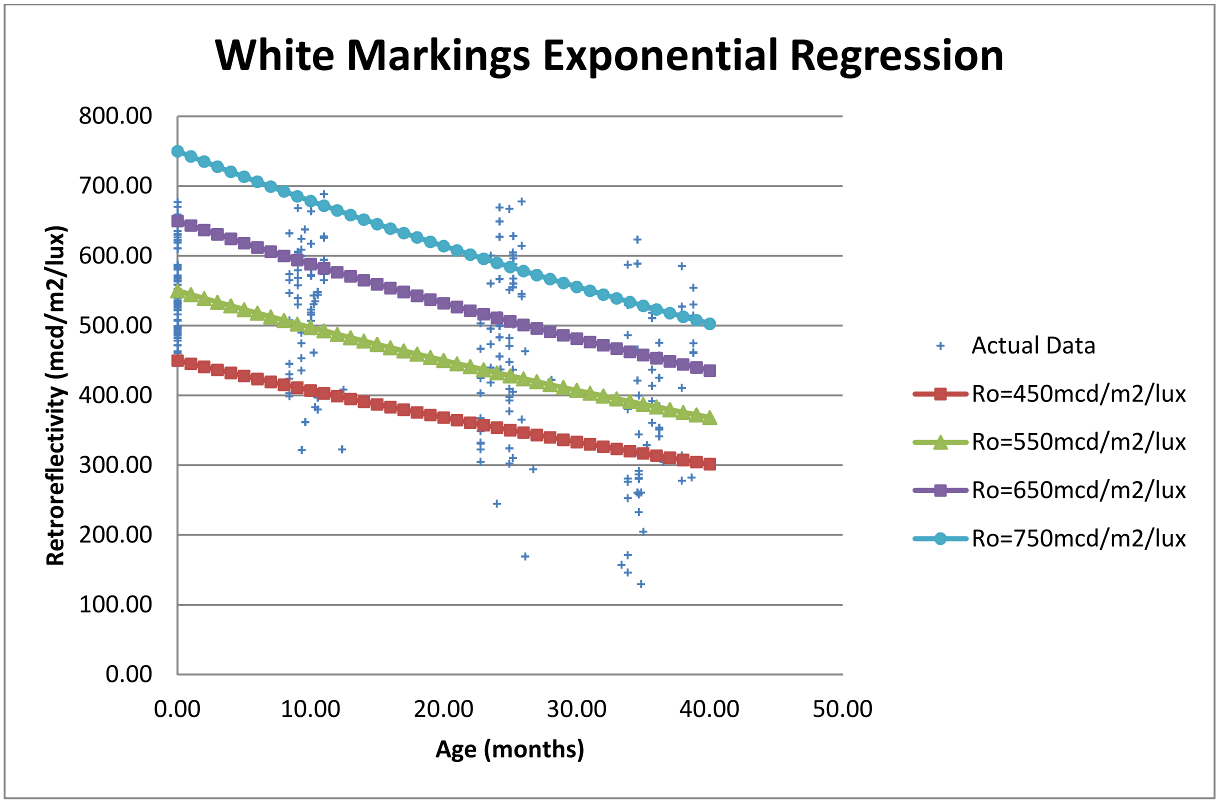

Figure 27 – White Markings Exponential Regression for Different Initial Retroreflectivity Values: Initial Retroreflectivity and Age as Independent Variables

The same process was conducted for yellow markings. Adopted initial retroreflectivity values, to verify the behavior of the developed models in the area occupied by actual observations, were equal to 350 mcd/m^2/lux, 400 mcd/m^2/lux, 450 mcd/m^2/lux, and 500 mcd/m^2/lux. Conclusions were the same as the observed for white markings. Detailed charts are presented in Appendix C.

4.4.2. Approach Two: Initial Retroreflectivity, Age of Marking, and Traffic Volume as Independent Variables

With three independent variables, only a linear model was developed by color, as it is usually seen in the literature. Figure 28 shows the data estimated by the linear regression compared to actual data. Figure 29 illustrates estimated data for initial retroreflectivity values equal to 450, 600, and 750 mcd/m^2/lux and AADT equal to 350, 7000, and 18000 veh/day. These values were observed to be the minimum, average, and maximum values of actual initial retroreflectivity for white markings and traffic volume data, respectively, for the 15 study sites. Both figures show that the initial points of the model are not actual initial retroreflectivity values, because the linear model has a constant and a coefficient multiplying initial retroreflectivity and AADT causing that when age and AADT are equal to zero, retroreflectivity is not equal to initial retroreflectivity. However, this linear regression estimated values for retroreflectivity closer to actual values than the linear model that did not consider AADT as an independent variable; this can be verified by comparing Figures 28 and 29 to Figures 20 and 21, and also Table 24 to Table 23, which shows a higher R^2 value (0.398) for the regression considering AADT. The same procedure was applied to yellow markings for initial retroreflectivity values equal to 350, 425, and 500 mcd/m^2/lux, and the conclusions were similar; details can be seen in Appendix D.

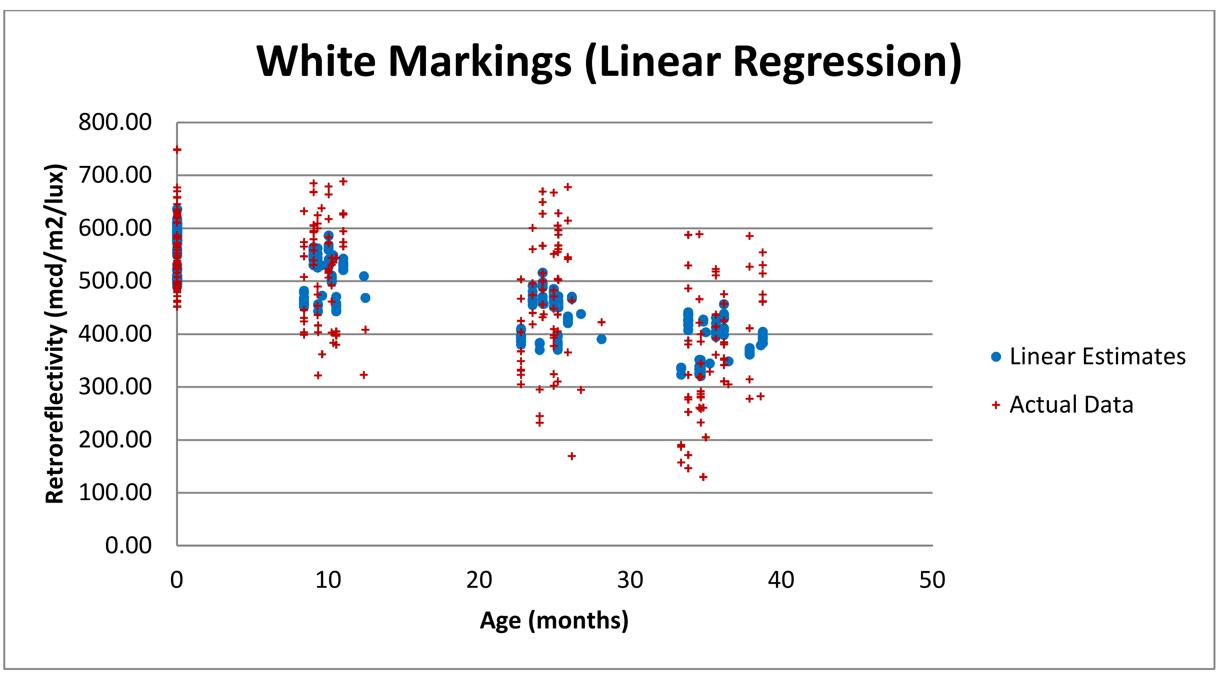

Figure 28 – Linear Regression estimates for White Markings: Initial Retroreflectivity, Age, and AADT as Independent Variables

Figure 29 – White Markings Linear Regression for Different Initial Retroreflectivity and AADT Values: Initial Retroreflectivity, Age, and AADT as Independent Variables

4.4.3. Service Life

Another important issue to be considered is service life. Considering as thresholds for minimum retroreflectivity 150 mcd/m^2/lux for white markings and 100 mcd/m^2/lux for yellow markings, the predicted service life using each developed model in this section was calculated. Table 25 shows estimated service life for different values of initial retroreflectivity, considering initial retroreflectivity and age of marking as independent variables (approach one). It can be observed in Table 26 estimated service life also considering traffic volume as an independent variable (approach two).

Table 25 – Predicted Service Life: Initial Retroreflectivity and Age as Independent Variables

Model	Color	Predicted Service Life (months)	Considered Initial Retroreflectivity ($mcd/m^2/lux$)	Minimum Retroreflectivity Threshold ($mcd/m^2/lux$)
White	Linear	81	450	150
	Power	134		
	Quadratic	54		
	Exponential	110		
	Linear	87	550	
	Power	144		
	Quadratic	65		
	Exponential	130		
	Linear	94	650	
	Power	154		
	Quadratic	74		
	Exponential	147		
	Linear	101	750	
	Power	164		
	Quadratic	83		
	Exponential	161		
Yellow	Linear	59	350	100
	Power	85		
	Quadratic	51		
	Exponential	74		
	Linear	61	400	
	Power	88		
	Quadratic	58		
	Exponential	82		
	Linear	62	450	
	Power	92		
	Quadratic	64		
	Exponential	89		
	Linear	63	500	
	Power	95		
	Quadratic	70		
	Exponential	95		

Table 26 – Predicted Service Life: Initial Retroreflectivity, Age, and AADT as Independent Variables

Color	Model	Predicted Service Life (months)	Considered AADT (veh/day)	Considered Initial Retroreflectivity (mcd/m^2/lux)	Minimum Retroreflectivity Threshold (mcd/m^2/lux)
White	Linear	86	350	450	150
		79	7000		
		68	18000		
		93	350	600	
		86	7000		
		75	18000		
		99	350	750	
		93	7000		
		82	18000		
Yellow	Linear	60	350	350	100
		57	7000		
		53	18000		
		61	350	425	
		58	7000		
		54	18000		
		61	350	500	
		59	7000		
		54	18000		

It could be observed in the literature that the service life for white thermoplastic markings was in a range between 22.6 and 102 months. It is important to notice that the maximum service life was a function of an initial retroreflectivity equal to 375 mcd/m^2/lux. Table 25 shows that the maximum service life for white markings is 166 months, but it considers an initial retroreflectivity of 750 mcd/m^2/lux, higher than the values found in the literature.

For yellow thermoplastic markings, service life in the literature was in a range between 24.7 and 103 months. The maximum service life considered an initial retroreflectivity equal to 135 mcd/m^2/lux. Table 25 shows that the maximum service life for yellow markings is 96 months, but it considers an initial retroreflectivity of 500 mcd/m2/lux, higher than the values found in the literature. Therefore, values shown on Table 25 are considered consistent with what was found in the literature. Some high estimation for service life may be due to the high initial retroreflectivity values from actual observations.

It can be observed in Table 26 the estimated service life values for different initial retroreflectivity and AADT values, considering three independent variables (approach two). Similar conclusions from service life estimated by approach one were found.

4.5. Summary of Chapter Four

Chapter Four presented the results regarding the application of methodology described in Chapter Three. The analysis to verify if measures of markings met specifications showed that the most consistent property was chromaticity, with 94.04% of total measurements passing minimum required values. Thickness and luminance measurements presented 79.53% and 75.77%, respectively, of total observations meeting specifications. The property which presented fewer measurements passing minimum required values was retroreflectivity, with 69.40% observations meeting specifications.

The statistical analysis of observations in the 40 projects of the 2007 database showed that the most consistent property was luminance, with the lowest coefficients of variation. Thickness was found to be the less consistent one, because some standard deviations are almost half of, or more than the mean value, and coefficient of variation could be as high as 55.13%. Retroreflectivity also had very dispersed observations, with a high coefficient of variation of 43.44% among the four color/class categories, and also very different means when contrasting all classes and types.

Modeling of retroreflectivity over time was performed and all observations of the 15 projects that had data for four years allowed the development of 76 curves for solid white markings, 17 for broken white, 67 for solid yellow and 32 for broken yellow markings. Four models were developed, by color, based on the observations of these 15 projects. Considering initial retroreflectivity and age of marking as independent variables, for white markings the R^2 values were 0.325 for linear, 0.335 for power, 0.181 for quadratic, and 0.261 for exponential models; for yellow markings, the R^2 values were 0.465 for linear, 0.480 for power, 0.320 for quadratic, and 0.440 for exponential models. Considering also AADT as an independent variable, the R^2 values were 0.398 for white and 0.479 for yellow models, both linear.

The benefit/cost method analyzed in this Chapter did not provide good results, especially because the service life, determined by when retroreflectivity reaches the minimum threshold value of 150 mcd/m^2/lux for white markings and 100 mcd/m^2/lux for yellow markings, was much higher than the observed values for markings in literature and, therefore, not reliable.

Chapter Five

Conclusions and Recommendations

5.1. Conclusions

The documentation of 2007 ALDOT Special Provisions changes showed that no significant modifications related to specifications were observed; text modifications constituted the changes among different Special Provisions. An examination of the 2007 database containing 7,840 observations for 40 projects in Alabama to determine whether thickness, retroreflectivity, luminance, and color complied with ALDOT specifications found that 79.53% of the observations complied with thickness specifications, 69.40% were according to retroreflectivity standards, 75.77% conformed to luminance specifications, and 94.03% were according to color standards.

A statistical analysis was performed for all observations among the 40 projects, based on mean, standard deviation, and coefficient of variation, by color and type (class) of markings for thickness, retroreflectivity, and luminance. Results showed that luminance measures were consistent, with highest coefficient of variation of 18.33%. Thickness values were not very consistent within each color/type group, with a coefficient of variation as high as 55.13%, but means between groups were similar, varying from 0.065 to 0.117 in. Retroreflectivity, however, presented huge variations within groups, with standard deviation as great as 141.383 mcd/m^2/lux, and between groups, with mean varying from 202 to 496 mcd/m^2/lux.

Retroreflectivity modeling was also executed in this thesis. Joining retroreflectivity data from the 2007 database and subsequent ALDOT data on retroreflectivity from 2008 to 2010, it was possible to create models of retroreflectivity over time. Only 15 projects had measurements of retroreflectivity for the same locations from 2007, 2008, 2009, and 2010 databases, which represented 76 observations for solid white markings, 17 for broken white, 67 for solid yellow, and 32 for broken yellow markings. Since only four years of data exist, the created curves had to be extrapolated to reach minimum retroreflectivity values (until the end of service life). In order to accomplish this, the most relevant models in the literature were applied to the data to evaluate model fit. The Thamizharasan et al. and Sitzabee et al. were the models that best represented actual data from ALDOT projects. To determine best-fitting models, comparisons of area under curve ratio, average model error and average percent error between model curve and actual curve were performed.

When extrapolating actual data based on the best-fitting models in the literature, it was found that service life was about twice the common values for thermoplastic materials found in the literature, and sometimes higher than typical pavement service life, being as high as 250 months (almost 21 years). Cost data was obtained from and organized based on the Tabulation of Bids, from ALDOT. However, without retroreflectivity curves that yielded realistic service lives, it was not possible to calculate benefits based on this model. In addition, benefit/cost relationships given by this method did not provide meaningful and applicable results for the observations of the 15 projects in Alabama, since there was only one type of material, thermoplastic Class 2, and this benefit/cost analysis is most appropriate when comparing different materials.

New models needed to be developed to represent actual points from projects in Alabama more realistically. The modeling of retroreflectivity over time considered retroreflectivity as the dependent variable; age and initial retroreflectivity were considered as the independent variables for the first modeling approach and traffic volume was also considered for a second modeling approach. Models developed when considering age and initial retroreflectivity as independent variables were linear, power, quadratic, and exponential, for each color. For white markings, there were 63 different locations and for yellow markings, 42. White markings had R^2 values equal to: 0.325 (linear), 0.335 (power), 0.181 (quadratic), and 0.261 (exponential); yellow markings had R^2 values equal to: 0.465 (linear), 0.480 (power), 0.320 (quadratic), and 0.440 (exponential). For the consideration of AADT as an additional independent variable, linear models were developed for the same locations by color and R^2 values were 0.398 for white markings and 0.479 for yellow markings. In the literature, R^2 values from models for white markings vary from 0.007 to 0.600 and from 0.003 to 0.600 to yellow markings; the R^2 values of the models developed in this study are higher than most models in the literature.

5.2. Recommendations

The linear model considering age of marking, initial retroreflectivity, and traffic volume as independent variables had the highest R^2 value among all predicted models for white markings. For yellow markings, the power model considering age of marking and initial retroreflectivity as independent variables and the linear model considering traffic volume as an additional independent variable, yielded R^2 values equal to 0.480. The linear model considering the three independent variables to estimate retroreflectivity over time was found to be the most adequate when representing Alabama data because of the simplicity in its equation, the capacity to well-represent retroreflectivity for a time equal to zero, and the highest R^2 values among predicted models.

5.3. Recommendations for Subsequent Studies

Limitations to the present study can be noticed throughout this thesis. From all 40 projects applied in 2007 in Alabama, only 15 had retroreflectivity data, which were used to develop models. In addition, historical retroreflectivity measurements were made only from 2007 to 2010. This means that models can be improved if data are provided for new locations and measurements continue for the existing sites. New sites can also be added to increase sample size and provide more accurate results.

The wide range of initial retroreflectivity values for different observations of the 15 projects was something that also deserves further investigation. A detailed analysis of the equipment used to measure each observation and development of adjustment factors between measures from one retroreflectometer to another can be ways to explain potential source of variability.

Another point to be considered is which variables influence retroreflectivity behavior. In this thesis, age of marking, initial retroreflectivity, and traffic volume were the considered independent variables. However, additional variables might be analyzed to improve models. It was observed in the literature that white edgeline markings generally had longer predicted service lives than all other pavement marking types and the shortest mean predicted service life was most often computed for the yellow centerline markings, showing that position of marking on pavement may be considered when predicting retroreflectivity. In addition, it was observed in the literature that there was considerable variability in the predicted service life across different engineering divisions, which shows the importance of geographic location when developing models to predict service life. The impact of different vehicle types was also mentioned in the literature, and it was found that roadways with higher truck traffic volumes decrease pavement markings service life due to abrasion between the tires and the markings; therefore, vehicle type might also be an independent variable to predict retroreflectivity. A benefit/cost analysis is useful, especially if information of other types of markings is available; comparison between different materials to determine the most appropriate to Alabama conditions can be interesting.

Pay adjustment factors procedure in the 2008 ALDOT *Standard Specifications for Highway Construction* does not provide consistent justification on how the percentage that the stripe will be paid for was established. The stripe is accepted without a price adjustment for retroreflectivity 85% or greater than the minimum required value; for retroreflectivity less than 85% and greater than 50% the target value, the stripe is paid for at a percentage equal to the percentage determined from the measurements; for retroreflectivity less than 50%, the stripe needs to be removed. This procedure could be refined; therefore, the development of pay adjustment factors may also be another suggestion for future studies. This analysis can be based on the data that did not meet minimum requirements as well as those that did in the 2007 ALDOT database, in addition to a study considering benefit/cost models.

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Appendix A

Project STPSA-0185(500): Pictures


GREENVILLE
CITY LIMIT


NORTH
263
NORTH
185

Appendix B

List of Mileposts by Project

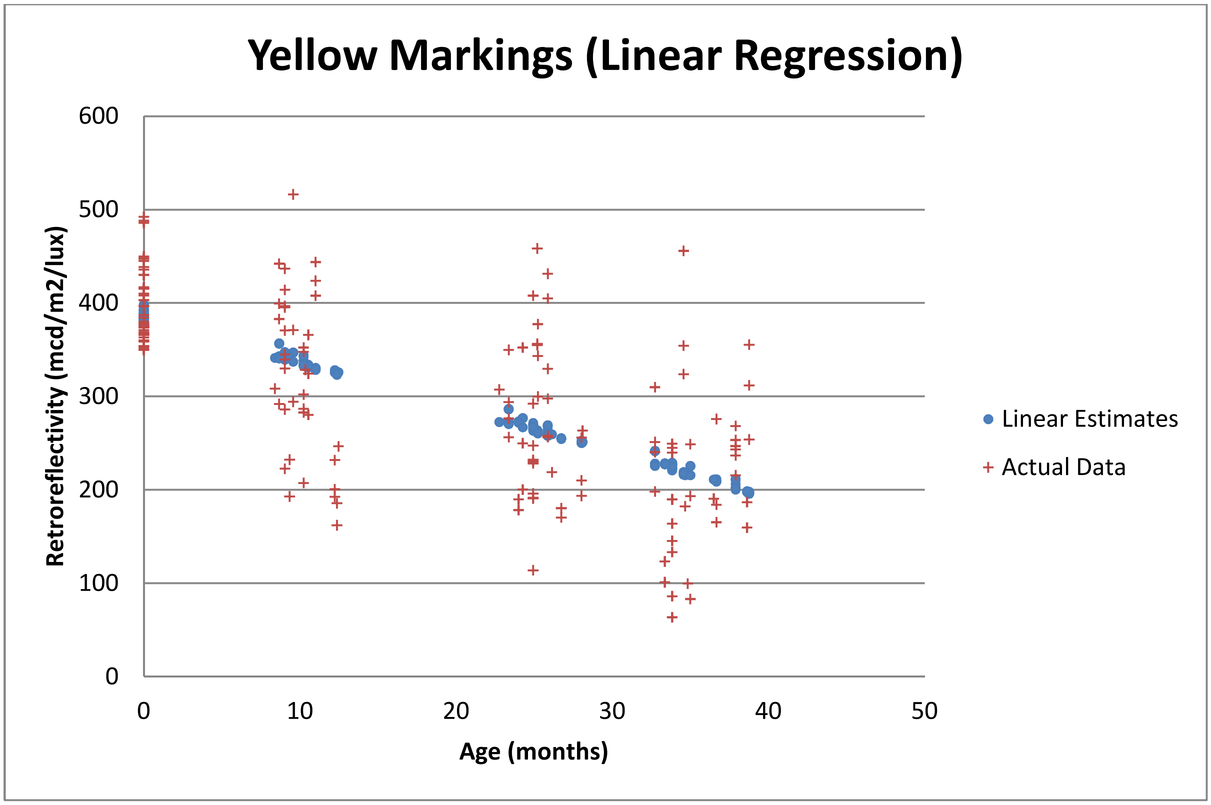
Project	MP			
	Solid White	**Broken White**	**Solid Yellow**	**Broken Yellow**
99-302-391-101-701	25.7	-	25.7	
	26.2	-	26.2	
	27	-	27	
	28	-	28	
99-302-437-171-706	53	53	53	
99-303-595-003-709	244	-	244	244
	245	-	245	245
99-305-632-069-702	157.1	-	-	157.1
	158	-	158	-
	159	-	159	159
	160	-	160	-
	161	-	161	161
	162.1	-	162.1	-
	163.1	-	163.1	-
	164	-	164	-
	165	-	165	-
	166	-	166	-
	167	-	167	-
99-307-164-167-701	1	-	-	1
	2	-	2	-
	3	-	-	3
	4	-	-	4
	5	-	-	5
	6	-	6	-
99-307-346-010-701	216	216	216	-
	217	-	217	217

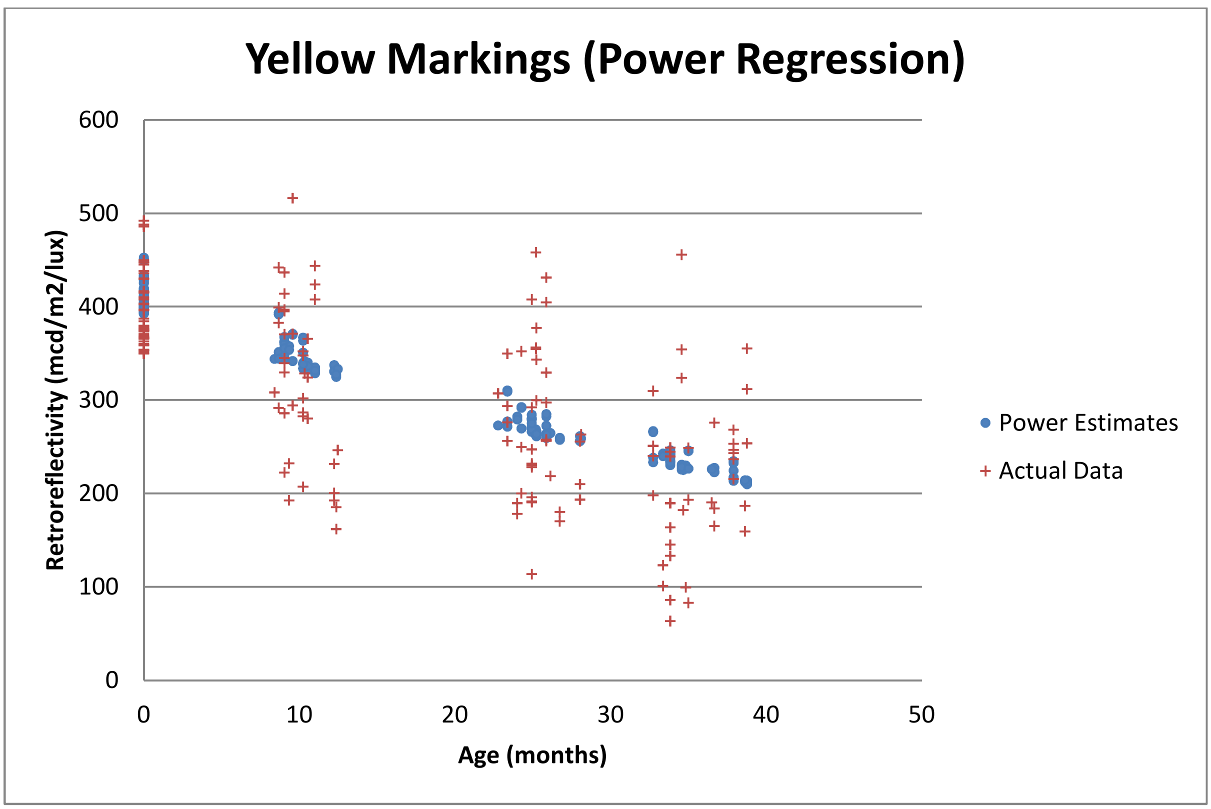
EB-0016(505)	60	-	60	-
	61	-	61	61
	62	-	62	-
	63	-	63	63
	64	-	64	-
	65	-	65	65
	66	-	66	66
	67	-	67	67
	68	-	-	68
	69	-	69	69
	70	-	70	70
	71	-	71	-
	72	-	72	-
	73	-	73	-
	74	-	74	-
	75	-	-	75
	76	-	-	76
EB-0035(506)	-	23	23	23
	-	24	24	24
	-	25	25	-
EB-0074(513)	76	76	76	-
	77	77	77	77
NHF-STPSAF-0053(525)	32	32	32	-
	33	33	33	-
	34	34	34	-
	35	35	35	-
	36	36	36	-
STPSA-0001(529)	267	267	267	-
	268	268	268	-
	269	269	269	-
	270	270	270	-
	271	271	271	-

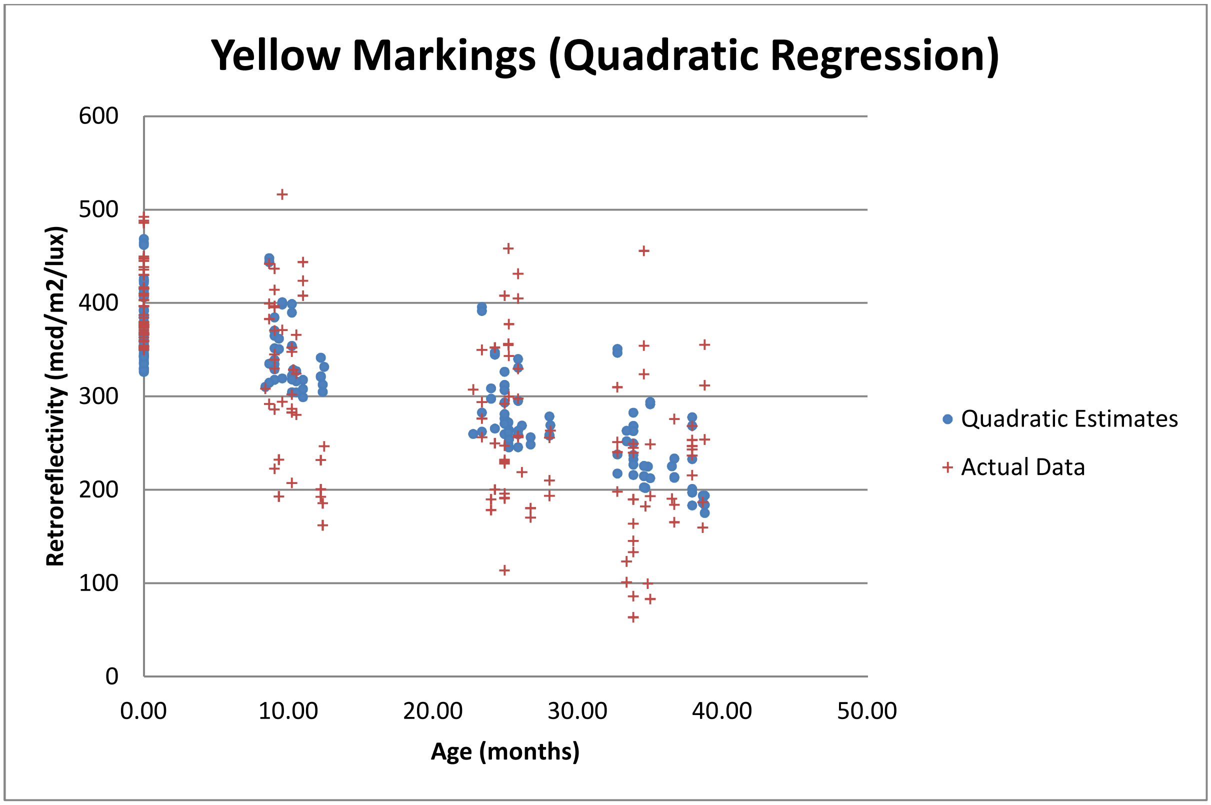
STPSA-0021(515)	98	-	98	-
	99	-	99	99
	100	-	100	-
	101	-	-	101
	102	-	102	102
	103	-	103	-
	104	-	104	-
	105	-	105	-
	106	-	-	-
	107	-	107	-
	108	-	108	108
STPSA-0079(505)	-	-	72	-
	-	-	73	-
	-	-	-	74
	-	-	-	75
	-	-	76	-
	-	-	77	-
	-	-	-	78
	-	-	79	-
	-	-	80	-
	-	-	-	81
STPSA-0089(500)	1	-	1	-
	2	-	2	-
	3	-	-	3
STPSA-0185(500)	8	-	-	-
	9	-	-	-
	10	-	-	-
	11	-	-	-
	12	-	-	-
	13	-	-	-
	14	-	-	-

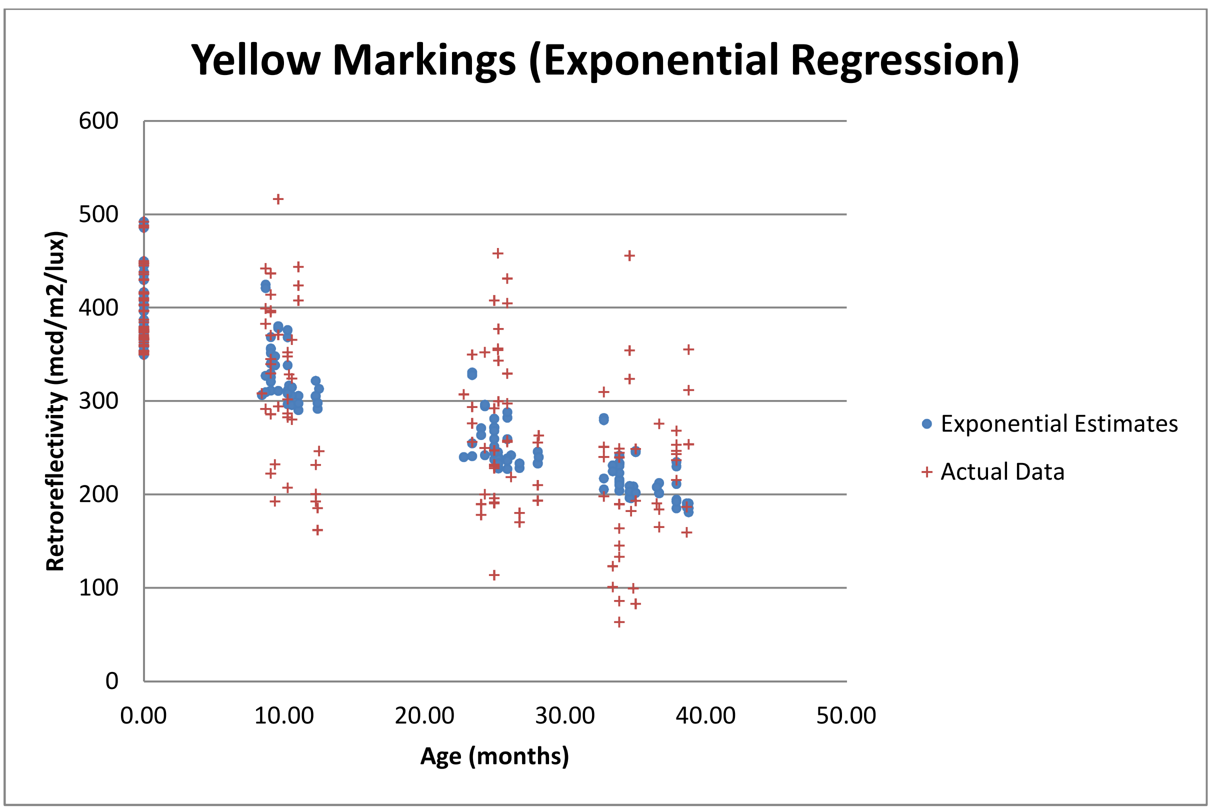
Appendix C

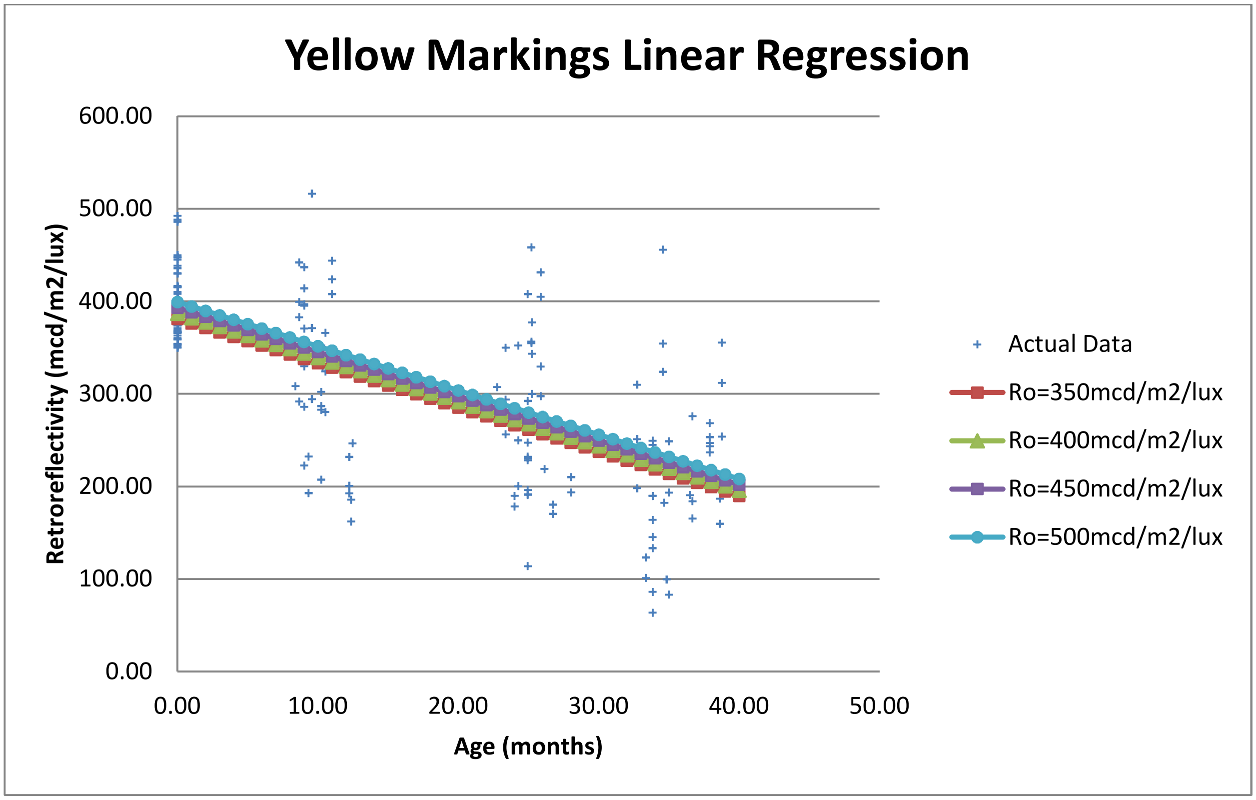
Retroreflectivity Modeling for Yellow Markings: Initial Retroreflectivity and Age as Independent Variables

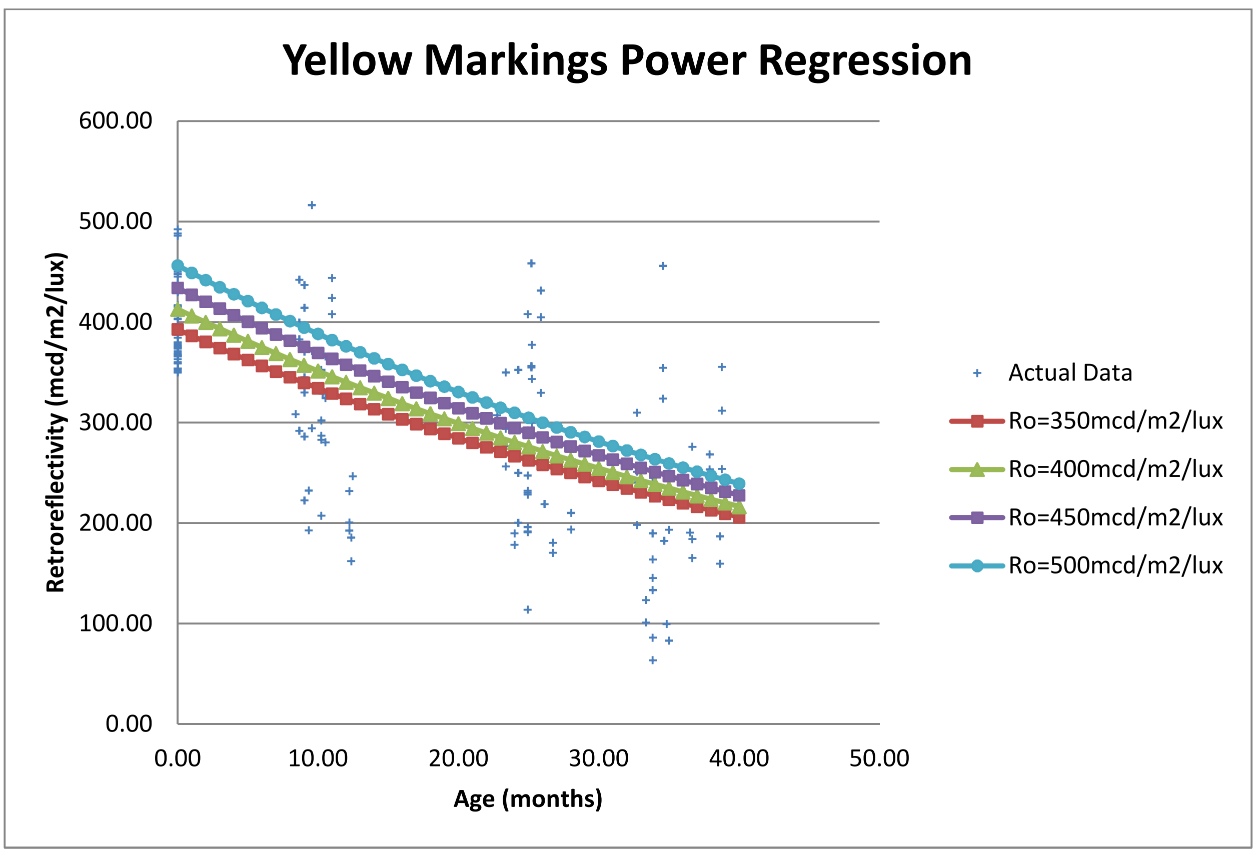

Yellow Markings (Linear Regression)
Retroreflectivity (mcd/m2/lux)
600
500
400
300
200
100
0
0
10
20
30
40
50
Age (months)
Linear Estimates
Actual Data

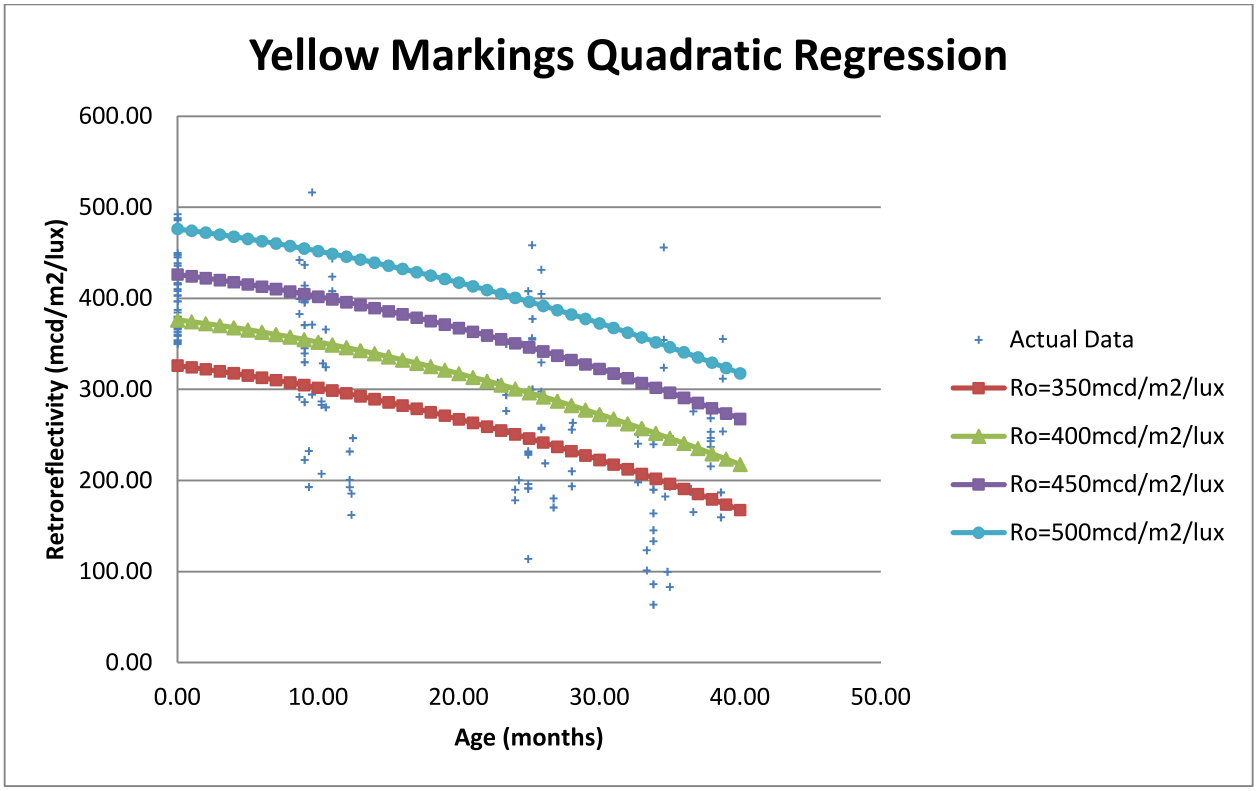

Yellow Markings (Power Regression)
Retroreflectivity (mcd/m2/lux)
600
500
400
300
200
100
0
0
10
20
30
40
50
Age (months)
Power Estimates
Actual Data

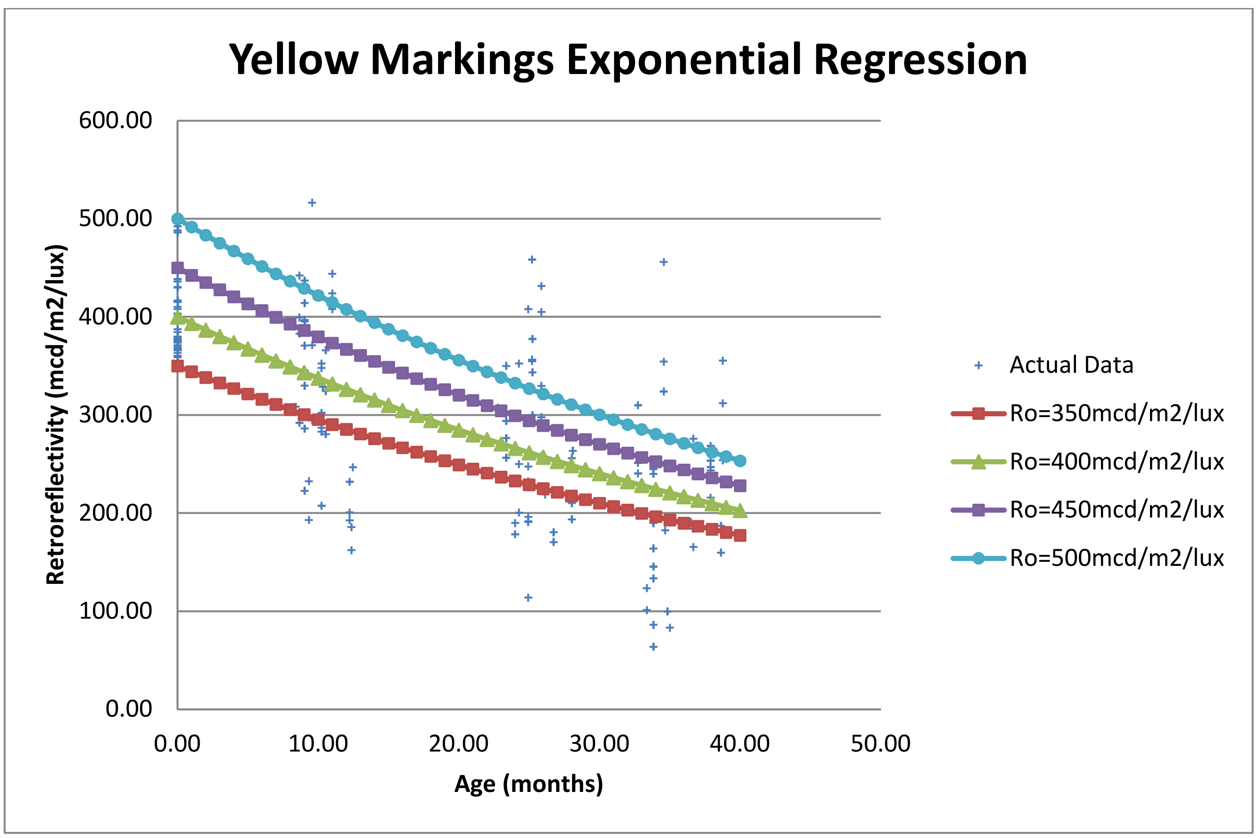

Yellow Markings (Quadratic Regression)
600
500
400
300
200
100
0
0.00
10.00
20.00
30.00
40.00
50.00
Retroreflectivity (mcd/m2/lux)
Age (months)
Quadratic Estimates
Actual Data


Yellow Markings (Exponential Regression)
600
500
400
300
200
100
0
0.00
10.00
20.00
30.00
40.00
50.00
Retroreflectivity (mcd/m2/lux)
Age (months)
Exponential Estimates
Actual Data


Yellow Markings Linear Regression
Retroreflectivity (mcd/m2/lux)
600.00
500.00
400.00
300.00
200.00
100.00
0.00
0.00
10.00
20.00
30.00
40.00
50.00
Age (months)
Actual Data
Ro=350mcd/m2/lux
Ro=400mcd/m2/lux
Ro=450mcd/m2/lux
Ro=500mcd/m2/lux

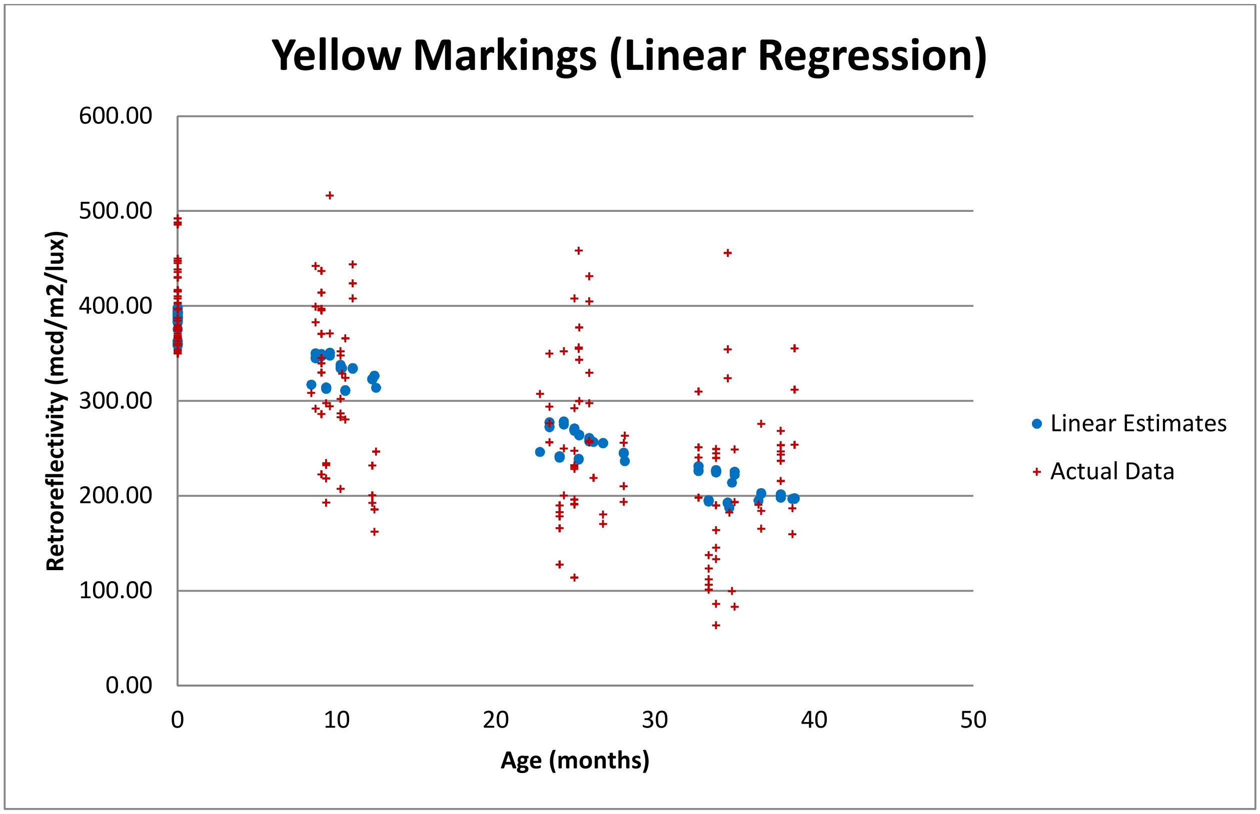

Yellow Markings Power Regression
Retroreflectivity (mcd/m2/lux)
600.00
500.00
400.00
300.00
200.00
100.00
0.00
0.00
10.00
20.00
30.00
40.00
50.00
Age (months)
Actual Data
Ro=350mcd/m2/lux
Ro=400mcd/m2/lux
Ro=450mcd/m2/lux
Ro=500mcd/m2/lux

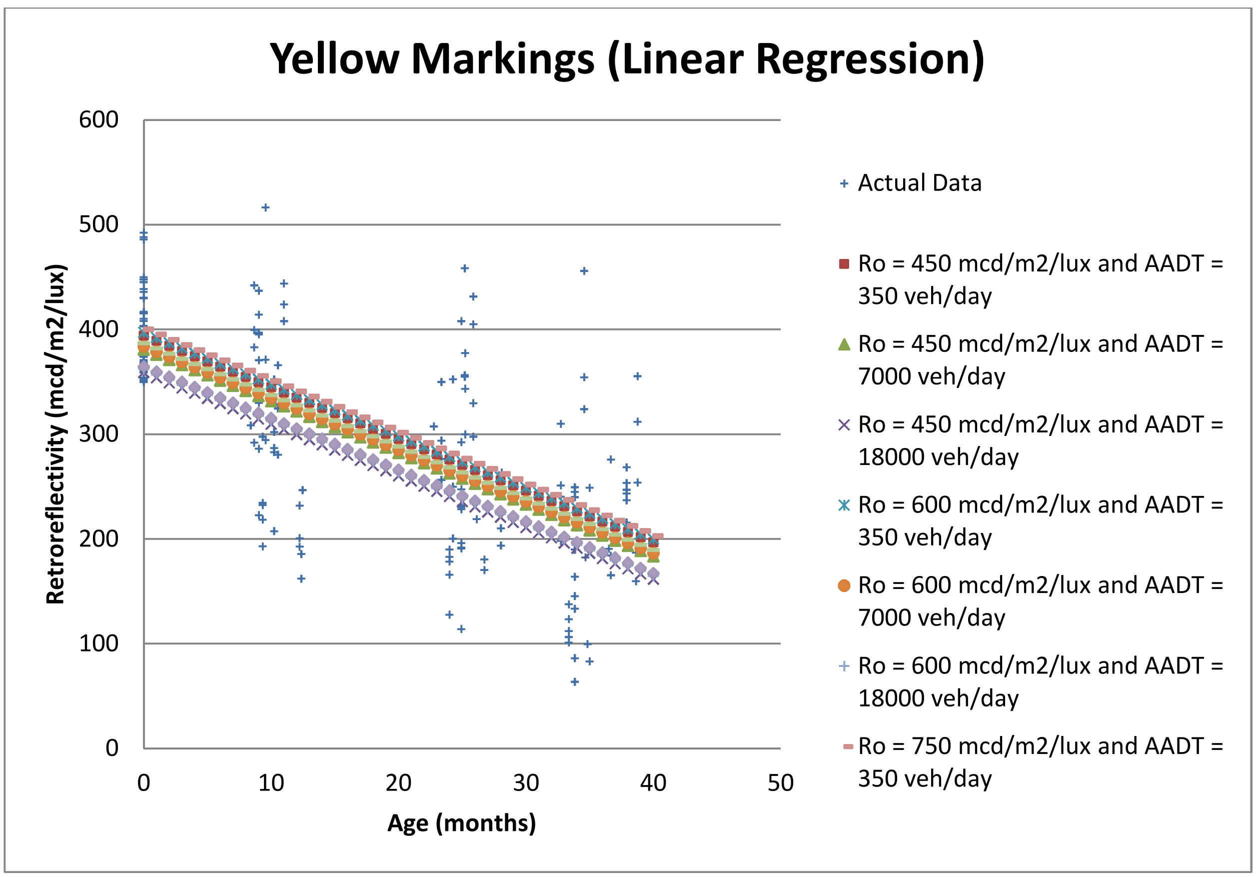

Yellow Markings Quadratic Regression
Retroreflectivity (mcd/m2/lux)
Age (months)
600.00
500.00
400.00
300.00
200.00
100.00
0.00
0.00
10.00
20.00
30.00
40.00
50.00
Actual Data
Ro=350mcd/m2/lux
Ro=400mcd/m2/lux
Ro=450mcd/m2/lux
Ro=500mcd/m2/lux


Yellow Markings Exponential Regression
Retroreflectivity (mcd/m2/lux)
Age (months)
600.00
500.00
400.00
300.00
200.00
100.00
0.00
0.00
10.00
20.00
30.00
40.00
50.00
Actual Data
Ro=350mcd/m2/lux
Ro=400mcd/m2/lux
Ro=450mcd/m2/lux
Ro=500mcd/m2/lux

Appendix D

Retroreflectivity Modeling for Yellow Markings: Initial Retroreflectivity, Age, and Traffic Volume as Independent Variables


Yellow Markings (Linear Regression)
Retroreflectivity (mcd/m2/lux)
600.00
500.00
400.00
300.00
200.00
100.00
0.00
0
10
20
30
40
50
Age (months)
Linear Estimates
Actual Data


Yellow Markings (Linear Regression)
Retroreflectivity (mcd/m2/lux)
600
500
400
300
200
100
0
0
10
20
30
40
50
Age (months)
Actual Data
Ro = 450 mcd/m2/lux and AADT = 350 veh/day
Ro = 450 mcd/m2/lux and AADT = 7000 veh/day
Ro = 450 mcd/m2/lux and AADT = 18000 veh/day
Ro = 600 mcd/m2/lux and AADT = 350 veh/day
Ro = 600 mcd/m2/lux and AADT = 7000 veh/day
Ro = 600 mcd/m2/lux and AADT = 18000 veh/day
Ro = 750 mcd/m2/lux and AADT = 350 veh/day