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Retroreflectivity Database Study

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July 16, 2009

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16. Abstract

Pavement marking delineation is one method to provide positive driver guidance on all roadway types. There are a variety of pavement markings used by local and state transportation agencies in the United States. The type of pavement marking applied to a roadway surface is often a function of climatic conditions, funds available to apply and maintain the markings, and the anticipated performance of the markings. The Pennsylvania Department of Transportation (PennDOT) developed a program in 2005 designed to periodically collect pavement marking retroreflectivity data on longitudinal lines throughout the Commonwealth of Pennsylvania. The purpose of this program was to develop a comprehensive analysis database that could be used to create a pavement marking management system for both waterborne and durable (epoxy) pavement markings on a variety of roadway types. In order to develop a cost-effective pavement marking management system, the service life of pavement markings must be well understood. Consequently, the main objective of the present study was to estimate the service life of longitudinal pavement markings using pavement marking retroreflectivity data provided by PennDOT's Bureau of Highway Safety and Traffic Engineering. Various statistical models were specified to produce pavement marking degradation estimates that PennDOT can use to estimate re-stripe times for longitudinal pavement markings.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

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CHAPTER 1
INTRODUCTION

Pavement marking delineation is one method to provide positive driver guidance on all roadway types. There are a variety of pavement markings used by local and state transportation agencies in the United States. The type of pavement marking applied to a roadway surface is often a function of climatic conditions, funds available to apply and maintain the markings, and the anticipated performance of the markings.

The Pennsylvania Department of Transportation (PennDOT) developed a program in 2005 designed to periodically collect pavement marking retroreflectivity data on longitudinal lines throughout the Commonwealth of Pennsylvania. The purpose of this program was to develop a comprehensive analysis database that could be used to create a pavement marking management system for both waterborne and durable (epoxy) pavement markings on a variety of roadway types. In order to develop a cost-effective pavement marking management system, the service life of pavement markings must be well understood. Consequently, the main objective of the present study was to estimate the service life of longitudinal pavement markings using pavement marking retroreflectivity data provided by PennDOT's Bureau of Highway Safety and Traffic Engineering. Various statistical models were specified to produce pavement marking degradation estimates that PennDOT can use to estimate re-stripe times for longitudinal pavement markings.

The pavement marking retroreflectivity database developed by the Bureau of Highway Safety and Traffic Engineering consists of randomly selected roadway sections in eight PennDOT Engineering Districts and are comprised of two-lane and multi-lane highways. Pavement marking retroreflectivity measurements were recorded one or more times on each marking in a roadway section. The roadway sections included in the retroreflectivity database were designated as maintenance functional classifications (MFC) A, B, C, D, E, and F. These functional classes correspond to Interstates (A), other principal arterials (B and C), collectors (D), local streets (E), and ramps (F). The present analysis focused on durable markings (epoxy) applied on MFC A, B, and C roadways; waterborne paints applied on MFC A, B, and C roadways; and two separate analyses of waterborne paints applied on MFC D and E roadways. The first analysis is based on retroreflectivity data collected on pavement markings applied using a waterborne paint formulation that was evaluated on the 2002 National Transportation Product Evaluation Program (NTPEP) test deck located in Pennsylvania. A subsequent analysis was performed on retroreflectivity data based on a waterborne paint formulation evaluated on the 2005 NTPEP test deck in Pennsylvania. The results of the two MFC D and E analyses were compared to determine which waterborne paint formulation produced the longest service life estimates. PennDOT's current pavement marking management practice is to re-stripe waterborne paints on an annual basis, and to re-strip durable pavement markings on a biennial basis. Statistical models of retroreflectivity are developed in this study and then used to determine how long pavement markings in the Commonwealth remain at or above a minimum threshold level. The estimated service life could then be used to determine pavement marking re-stripe times.

This report is organized into four subsequent sections. Chapter 2 is a literature review of published pavement marking service life modeling methods and results. Also included are pavement marking cost estimates based on published literature. Chapter 3 is an outline of the statistical modeling methods used to estimate the service life of waterborne paint and durable pavement markings. Chapter 4 contains a description of the data used in the statistical analysis. Chapter 5 summarizes the analysis results. Chapter 6 includes conclusions from the research, including recommended mean pavement marking service estimates for waterborne paint and durable pavement markings. Methods to manage pavement marking systems in the Commonwealth are described in this chapter.

CHAPTER 2
LITERATURE REVIEW

The literature review is organized into two sections. The first includes a summary of the statistical methods that have been used to estimate the service life of pavement markings. The second section provides a summary of pavement marking installation and maintenance costs based on published literature.

PAVEMENT MARKING DEGRADATION MODELING

According to the Federal Highway Administration (FHWA) *Roadway Delineation Practices Handbook*, the service life of pavement markings is defined as "the time required for a pavement marking to become ineffective due to its having lost its luster, lost its retroreflectivity, or having been worn completely from the pavement" (Migletz et al., 1994). Based on this definition, there are several measures that could be used to define pavement marking service life. These may include, but are not limited to, material presence (i.e., durability), color, and visibility. Theoretically, anything that affects any one of these three components could directly influence the service life of the pavement marking material. Visibility of pavement markings is measured by the amount of light reflected back in the direction of the light source. This objective measure is called the coefficient of retroreflected luminance (R_L) (herein referred to as retroreflectivity) and is often considered a primary measure in assessing the service life of pavement markings.

There are many factors that can influence the service life of pavement markings. Weather and climatic conditions not only influence traffic flow, but also affect the service life of pavement markings *(*Abboud and Bowman, 2002; TXDOT, 2004; Cottrell, 1995). Cottrell (1995) assessed the impact of snow-removal activities on the durability of paint, thermoplastic, and waffle tape pavement markings. The study recommended the use of inlaid markings, underscoring the importance of snowplow activities. As pavement marking thickness increases, the more susceptible pavement markings are to snow blade abrasion or marking removal. Several researchers have indicated that traffic volume and composition are considered important variables to assess the service life of pavement markings *(*Migletz et al., 1994; Lee et al., 1999; Migletz et al., 2000), as higher traffic volumes can increase the rate of pavement marking degradation from increased vehicle-tire abrasion from vehicles passing over longitudinal lines.

The type of pavement (concrete versus asphalt) is an influencing factor when determining pavement marking service life. Associated with the type of pavement, variations in surface roughness, heat sensitivity, and surface porosity are known to affect the service life of pavement markings (TXDOT, 2004). No-track time is defined as the time required for the pavement marking material to dry so that a passenger car driven at a speed of 15 ±2 mph would not produce a track. This time varies with the material chemistry of the markings and the installation characteristics associated with it. Thus, no-track time may be considered a surrogate measure of visibility that represents material chemistry of the pavement marking.

Empirical studies have indicated that pavement marking retroreflectivity readings increase after the initial installation due to the late exposure of the embedded glass beads as the top surface wears due to snowplow and traffic activities (Abboud and Bowman, 2002; Lindly and Wijesundera, 2003; Norton and Kemp, 2002). This suggests that variation in glass bead characteristics may influence the overall service life of pavement markings, the reason being that the presence of glass beads contributes to the retroreflectivity level of a pavement marking. Thus, quantifying the glass bead retention capability of marking types over time could provide a better understanding of the service life of pavement markings (Rich et al., 2002). Glass beads used for the purpose of pavement marking retroreflectivity can be classified based on bead application and manufacturing properties (TXDOT, 2004). Application properties include quantity of beads, dispersion of exposed beads, and embedment depth. These are dependent on the applicator truck speed, bead drop rate, and viscosity of the binder material. Bead types are classified based on particle size gradation, refractive index, clarity, and roundness. Typically, smaller-grade beads are mixed with the pavement marking material prior to installation, while larger-grade beads are dropped on the markings during the application process. Bead coatings influence embedment depth and hence the measured retroreflectivity (TXDOT, 2004).

Many research efforts have been published to estimate the service life of pavement markings in the United States based on statistical models (Martin et al., 1996; Andrady, 1997; Scheuer et al., 1997; Lu and Barter, 1998; Lee et al., 1999; Migletz et al., 2000; Migletz et al., 2001; Abboud and Bowman, 2002; Lindly and Wijesundera, 2003; Sarasua et al., 2003; Kopf, 2004; Zhang and Wu, 2006; Bahar et al., 2006; Sathyanarayanan et al., 2008). However, several of the studies used retroreflectivity data collected from retroreflectometers with measurement geometry of 15 meters. The current standard prescribes instrument measurement geometry of 30 meters (ASTM, 2005). The entrance and observation angles are 88.76 and 1.05 degrees, respectively. The focus of this literature review is to present details on relevant studies that involved retroreflectivity readings using the current measurement standard (Migletz et al., 2001; Lindly and Wijesundera, 2003; Sarasua et al., 2003; Kopf, 2004; Zhang and Wu, 2006; Bahar et al., 2006; Sathyanarayanan et al., 2008).

The FHWA sponsored a research study to quantify the service life of all-weather pavement markings using data from 19 different states across 85 study sites (Migletz et al., 2000; Migletz et al., 2001). First-order linear regression, second-order linear regression, and exponential decay models were considered to model pavement marking retroreflectivity as a function of cumulative traffic passages. A Laserlux mobile retroreflectometer was used to collect pavement marking retroreflectivity data on the following pavement markings types: epoxy, methyl-methacrylate (MMA), flat and profiled polyester, flat and profiled thermoplastics, profiled preformed tape, conventional paints, water-based paints, and standard and snow-plowable raised retroreflective pavement markers (RRPMs). Separate models were specified for each pavement marking material type, various roadway functional classes, and white and yellow lines. It was determined that 67 percent of the pavement markings included in the sample exhibited a degradation phenomenon that was consistent with a first-order linear regression model and that 25 percent of markings exhibited an exponential decay. Only 2 percent of the pavement marking retroreflectivity data exhibited a second-order degradation pattern, while the remaining pavement markings could not be fit to the data. Of interest to the present study were the service life estimates for epoxy and waterborne paint pavement markings. These estimates are provided in Table 1. As shown in Table 1, the average service life of epoxy materials was lower on freeways than on non-freeways. Yellow epoxy pavement markings had longer estimated service lives than white epoxy pavement markings. The service life estimates exhibited large variations within each pavement marking material type, suggesting that considerable variability exists in pavement marking retroreflectivity across the data collection sites.

Table 1. Epoxy and Waterborne Paint Pavement Marking Service Life Estimates (Migletz et al., 2001).

Roadway Type[a]	**Material**	**Number of Pavement Markings in Sample**	**Service Life Estimate (months)**	
			Average	**Range**
Freeway	White Epoxy	11	12.8	3.4 – 34.0
	Yellow Epoxy	7	23.2	12.6 – 47.5
	White Waterborne Paint	3	10.4	4.1 – 18.4
	Yellow Waterborne Paint	N/A	N/A	N/A
Non-freeway (Posted speed ≤ 40 mph)	White Epoxy	2	39.4	29.2 – 49.7
	Yellow Epoxy	2	43.9	34.7 – 53.1
	White Waterborne Paint	N/A	N/A	N/A
	Yellow Waterborne Paint	N/A	N/A	N/A
Non-freeway (Posted speed ≥ 45 mph)	White Epoxy	5	38.8	26.1 – 56.0
	Yellow Epoxy	6	44.1	35.8 – 57.8
	White Waterborne Paint	N/A	N/A	N/A
	Yellow Waterborne Paint	N/A	N/A	N/A

[a] Service life estimates are for roadways without retroreflective raised pavement markers or fixed roadway illumination.

Lindly and Wijesundera (2003) used a similar approach to model the degradation pattern of flat thermoplastic and profiled thermoplastic white edge-line pavement markings in Alabama. Pavement marking retroreflectivity data were collected using a mobile retroreflectometer at 6-month intervals over a 1-year period. They concluded that a first-order linear regression model and exponential decay model produced nearly identical goodness-of-fit to the pavement marking retroreflectivity data as a function of cumulative traffic passages.

Sarasua et al. (2003) developed a methodology to estimate the life cycle of pavement markings located on Interstate highways in South Carolina. The research included epoxy, thermoplastics, and tapes applied on asphalt and portland cement concrete pavements. A total of 149 sites were included in the pavement marking degradation models. The study considered the use of difference and percentage difference in retroreflectivity from the initial value as the dependent variable in modeling. Sarasua et al. (2003) included both linear and non-linear modeling techniques based on patterns observed in the data set. The non-linear model was used to predict the number of days required for the marking to reach a state of steady (i.e., linear) degradation. The initial increase in retroreflectivity after applying the pavement markings was likely due to the delayed exposure of glass beads after installation. Pavement marking age was used as the final independent variable for the model after considering traffic volume, temperature, and humidity as independent variables. In order to determine the service life of the markings, first the non-linear model was used to find the number of days for the initial increase in retroreflectivity, and subsequently the linear model was used to find the number of days required to reach a retroreflectivity threshold. The overall service life was calculated by summing the days predicted by the non-linear and linear models. The goodness-of-fit measures (R^2 values) for the specified models were between 20 and 80 percent. The authors concluded the following:

- Pavement surface type, pavement marking material type, and the frequency of maintenance activities are the most significant factors associated with the performance of the markings,
- Both thermoplastics and epoxy markings showed a substantial initial increase in retroreflectivity readings when newly applied,
- Retroreflectivity degradation exhibits an initial rise and then a steady decreasing trend, and
- AADT was not a statistically significant influential factor in retroreflectivity degradation.

Kopf (2004) collected pavement marking retroreflectivity data using a mobile retroreflectometer along roadways with longitudinal markings in Washington State. Separate models of pavement marking retroreflectivity were specified for different regions of the state to control for environmental effects. Additionally, separate models were also specified for different pavement marking colors (yellow or white) and traffic volume ranges. Best-fit trendlines were used to determine the degradation phenomenon of the waterborne and solvent-based pavement markings. The independent variable in all models was time (in days). In some instances, the best-fit trend line included a logarithmic or exponential transformation of the independent variable, while in other cases the best-fit trend line was a first-order linear regression model. The goodness-of-fit for the various models specified ranged from 3 to 69 percent. For waterborne paints, the service life estimates ranged from 3 to 25 months depending on the region, color of the marking, and average annual daily traffic. White pavement markings were generally found to have longer service life estimates than yellow pavement markings.

Bahar et al. (2006) developed pavement marking degradation models using inverse polynomial regression. These models were estimated using data from various NTPEP test decks across the United States. The inverse polynomial model contained only age (in months) in the specification suggesting that pavement marking retroreflectivity degradation is non-linear. It was determined that pavement surface type and average daily traffic (ADT) volume were not related to pavement marking retroreflectivity.

Zhang and Wu (2006) used data from the Mississippi NTPEP test deck to estimate the service life of durable tapes, three-year waterborne paints, preformed thermoplastic and thermoplastic pavement markings. An autoregressive integrated moving average time series approach was recommended to model pavement marking retroreflectivity as a function of time (age in months). The difference in the observed and predicted values was less than 10 percent for all pavement marking types at 21 months and less than 15 percent for three of four pavement marking types at 24 months (predicted values were 31 percent different for durable tapes at 24 months). As noted by the authors, the models did not consider pavement surface type (asphalt or concrete), pavement marking color (yellow or white), or other factors that may be related to pavement marking retroreflectivity degradation; however, the modeling approach exhibited relatively good predictive power on data collected frequently over a 3-year period. The mean service life of 2-year paints, based on predictions from the time series models, was 26.7 months, and the mean service life of 3-year paints was 23.7 months.

Sathyanarayanan et al. (2008) analyzed 2-year waterborne paint pavement marking retroreflectivity data from the Pennsylvania NTPEP test deck using parametric (Weibull) duration models. Separate models were specified for pavement markings applied on asphalt and concrete pavements, white and yellow pavement markings, and at locations in the wheel path and skip line areas of the transverse NTPEP test deck markings. It was determined that white pavement markings have higher retroreflectivity levels than yellow pavement markings. A minimum pavement marking retroreflectivity threshold of 100 mcd/m^2/lux was used to define the service life. The median survival time for white pavement markings at the skip line location on the test deck was approximately 20 months, suggesting that only 50 percent of these markings had retroreflectivity levels above 100 mcd/m^2/lux at 20 months. The median survival time for yellow pavement markings in the skip line area was approximately 12 months. Finally, the median survival times for white and yellow markings in the wheel path location along the test deck were approximately 9.5 and 6.5 months, respectively. The difference in degradation between markings applied on asphalt and concrete was nominal.

Based on the existing literature, a variety of modeling methods have been used to predict the degradation phenomenon of pavement markings. The pavement marking type and color, pavement surface type, traffic volume, snow removal activities, and other spatial and temporal variables have all been shown by some researchers to be associated with pavement marking retroreflectivity; however, the variable most strongly associated with pavement marking degradation is time.

COST OF PAVEMENT MARKINGS

There are many marking materials available for the purpose of providing longitudinal delineation on roadways. Among them, waterborne paints, thermoplastics, epoxies and tapes are used most commonly (Migletz and Graham, 2002). Paints are generally considered non-durable markings because their service life is generally equal to 1 year or less. Durable pavement markings typically have an expected service life greater than 1 year. Pavement markings are also categorized into four different styles based on the application method used to apply the markings to the pavement surface. These include flat, inlaid, profiled, or patterned markings that may be applied using spray applicators, extrusion methods, or heat-fused procedures. Not all styles and application techniques can be used for all materials. Nevertheless, a variety of pavement marking materials and application methods are currently available; application costs vary considerably based on the pavement marking material and application procedure used to apply the markings.

According to Cuelho et al. (2003), pavement marking costs are determined based on the cost of the materials, equipment, time required for installation, volume of markings used, and whether or not the markings are installed by a private firm or public agency. The overall cost-effectiveness of pavement markings includes the material, installation, maintenance, road user, and life-cycle costs over a prescribed design period.

Table 2 presents cost data for several common pavement markings that are currently used for longitudinal delineation purposes in the United States (Donnell et al., 2005). Of interest to the present study, waterborne paints have a mean cost of $0.06 per linear foot while epoxy markings have a mean cost of $0.26 per linear foot.

Table 2. Range of Pavement Marking Costs in the United States (Donnell et al., 2005).

Pavement Marking Material	**Min. ($/lf)**	**Max. ($/lf)**	**Median ($/lf)**	**Mean ($/lf)**	**Sample Size**
Solvent based paints	0.02	0.15	0.05	0.05	11
Waterborne paints	0.02	0.20	0.04	0.06	21
Polyester	0.05	0.30	0.08	0.13	3
Spray thermoplastics	0.10	0.40	0.19	0.23	5
Epoxy	0.09	0.40	0.27	0.26	12
Flat thermoplastics	0.08	0.85	0.32	0.38	11
Modified urethane	0.43	0.43	0.43	0.43	1
Polyurea	0.43	0.90	0.70	0.68	4
Profiled thermoplastics	0.35	1.30	0.55	0.73	3
Flat methyl methacrylate	0.25	1.53	0.85	0.86	6
Profiled methyl methacrylate	1.12	1.75	1.44	1.44	2
Flat preformed tapes	0.12	2.65	1.65	1.67	14
Cold plastics	2.12	2.12	2.12	2.12	1
Profiled tapes	1.50	3.10	2.10	2.23	3
White cement material (WCM)	3.51	3.51	3.51	3.51	1
Inlayed methyl methacrylate	4.00	4.00	4.00	4.00	1

Note: The costs provided in the table are in units of dollars per linear foot ($/lf). The data used to populate the cells in the table are from reports published between 1997 and 2003, and a survey that was administered in 2005. As such, the costs should be interpreted with caution.

SUMMARY

Nighttime visibility is considered a critical component of pavement marking performance. Retroreflectivity is the primary nighttime visibility measure used to assess the service life of pavement markings and is currently measured using a 30-m geometry retroreflectometer. Either handheld or mobile retroreflectometers can be used to measure pavement marking retroreflectivity; however, each has advantages and disadvantages associated with their use. The Highway Innovative Technology Evaluation Center (HITEC, 2001) evaluated four 30-m handheld and two mobile pavement marking retroreflectometers. Several performance characteristics were used in the evaluation procedure, including retroreflectivity measurement (i.e., bias, repeatability, and reproducibility), physical characteristics, operational procedures, economic issues, and service requirements. Handheld devices are less expensive than mobile devices, have a greater measurement range, and can be set up more quickly than a mobile device. Mobile devices can take many more measurements per unit time, or over a greater geographic area, than the handheld devices. Most retroreflectometers have been modified and refined since the HITEC testing (2001) was completed; the following results, however, were reported from the evaluation:

- Devices deviate more from designated values at lower retroreflectivity levels;
- The handheld and mobile devices do not significantly differ with respect to measurement bias;
- All devices generally performed very well in the repeatability test;
- The mobile devices appear to produce better reproducibility results when compared to the handheld devices; and,
- The handheld devices appear to produce better field measurement results when compared to mobile devices.

A variety of factors can influence the degradation of pavement markings. These include traffic volumes, weather, pavement surface type, pavement marking color, frequency of snow plow activities, and installation practices. The combined effects and the degree of influence of each of these factors are still not clear. Several studies have estimated statistical models of pavement marking degradation using regression analysis, time series models, and survival analysis. The most common method to estimate pavement marking retroreflectivity degradation is linear regression. Due to the inherent variability in pavement markings applied on roadways, the estimated service life of the same pavement markings varies considerably across geographic regions.

In the published retroreflectivity service life literature, state transportation agencies have used a minimum threshold value of 100-150 mcd/m^2/lux to define the end of the useful pavement marking service life. Recent research by DeBallion et al. (2007) has proposed minimum threshold retroreflectivity levels, shown in Table 3; however, these levels have not yet been adopted by the FHWA for inclusion in the *Manual on Uniform Traffic Control Devices* (2003).

Table 3. Proposed Minimum Levels of Pavement Marking Retroreflectivity (DeBallion et al., 2007).

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

Notes:
All retoreflectivity values are reported in units of mcd/m^2/lux.
RRPMs are retroreflective raised pavement markers.

To improve pavement marking management, reliable pavement marking service life models must be developed and accompanied by life-cycle cost analysis. Although paint-based pavement markings have the lowest installation costs, it is important to consider the long-term cost trade-offs of these and other durable markings. Furthermore, it should be noted that as pavement marking materials continue to evolve, the service life and the cost of the marking material is subject to change. As such, it is important to consistently monitor pavement marking performance and continually update life-cycle costs to improve pavement making system management.

CHAPTER 3
ANALYSIS METHODOLOGY

This section describes the analysis methods that were used to model the degradation of pavement markings over time. The methods considered in the present study were ordinary least squares (OLS) linear regression and panel data methods. The former was used as it represents the most common statistical modeling method used to estimate pavement marking retroreflectivity over time. However, as will be described later, when repeated observations (i.e., retroreflectivity) are recorded on the same pavement marking sample over a period of time, the correlation that exists between each observation should be considered. To address this issue, a panel data modeling approach was also considered in the present study. The OLS linear regression and panel data modeling approaches are both described in the following sections, and the method used to select the most appropriate model is provided.

ORDINARY LEAST SQUARES LINEAR REGRESSION MODEL

The general form of the OLS linear regression model is as follows:

$$Retro_i = \beta X_i + \varepsilon_i \qquad (1)$$

where: $Retro_i$ = retroreflectivity for pavement marking type *i* (mcd/m^2/lux);
β = parameters to be estimated;
X_i = vector of explanatory variables for pavement marking type *i*;
ε_i = disturbance term for pavement marking type *i*.

In the present study, the pavement marking retroreflectivity was recorded for each pavement marking type on randomly selected roadway segments. The OLS estimator assumes the following (Gujarati, 2003):

- The explanatory variables are nonstochastic;
- No omitted or irrelevant variables are included in the model specification;
- The disturbance has a mean value of zero;
- Homoskedastic disturbances;
- No autocorrelation between disturbances;
- No perfect multicollinearity;
- Correctly specified model; and
- Zero covariance between the disturbance and explanatory variables.

Violating the assumptions of the OLS estimator can result in biased, inconsistent, or inefficient parameter estimates. As such, several diagnostic measures were applied to test the OLS assumptions. A histogram of the residuals was used to graphically inspect the normality assumption. A Breusch-Pagan/Cook-Weisburg test was used to assess the residuals for heteroskedasticity. The null hypothesis (χ^2 test) is that the residuals have a constant variance. The autocorrelation assumption was tested using the Durbin-Watson statistic. Values near two indicate that no autocorrelation exists among the residuals. Variance inflation factors (VIFs) were used to determine the presence of multicollinearity. VIFs are a measure of multicollinearity among the explanatory variables in a model – generally, values exceeding 10 indicate that multicollinearity is present (Neter et al., 1996). When assumption violations resulted from the analysis, remedial measures were taken.

PANEL DATA ANALYSIS

Panel data models combine cross-section and time series data. In the case of pavement marking retroreflectivity data, a pavement marking type in each roadway section is considered a cross-sectional unit which is observed over time. The primary advantage of panel data is that these data can account for the heterogeneity of pavement marking line types measured in each roadway section that affect the degradation phenomenon of each line over time (Kennedy, 2003). Panel data models are estimated using either a fixed effects or random effects estimator. The fixed effects estimator accounts for the different intercepts for each cross-sectional unit by including dummy variables in the model specification. The disadvantages of such an estimator are that a considerable loss in degrees of freedom results if the number of cross-sectional units is large, and the explanatory variables that do not vary within an individual cross-sectional unit cannot be included in the model specification. Alternatively, a within-effects group model uses deviations from group means to eliminate the need for including several dummy variables to address individual cross-section unit effects. The random effects estimator can be used to overcome the two limitations of the fixed effects estimator. Like the fixed effects estimator, the random effects estimator produces a different intercept for each cross-sectional unit; however, these intercepts are considered randomly drawn from a normal distribution and are treated as part of the error term. As such, the random effects panel data model contains an overall intercept, explanatory variables with the coefficients of interest, and a composite error term that contains a random intercept and the random error term (Kennedy, 2003). The random effects model is estimated using generalized least squares (GLS) while the fixed effects model is estimated using the OLS estimator. The general form of a one-way error components panel data model is shown in equation 2.

$$\mathrm{Re}tro_{it} = \alpha + \beta x'_{it} + \mu_i + \nu_{it},\ i = 1, 2, \ldots, n;\ t = 1, 2, \ldots, T \quad (2)$$

where: $Retro_{it}$ = pavement marking retroreflectivity for pavement marking type i at time t (mcd/m^2/lux);
α = scalar;
β = vector of estimable parameters;
x'_{it} = vector of explanatory variables;
μ_i = unobserved cross-sectional specific effect;
ν_{it} = random error term.

An advantage of the fixed effects model is that the error terms may be correlated with the individual cross-section specific effects. The assumption of constant variance of the random disturbances also applies. Statistical inference based on the fixed effects panel model is conditioned on the *n* pavement markings and *T* time periods in the model specification. An F-test was used to test the significance of the cross-sectional fixed effects. The null hypothesis is that the individual cross-section specific effects are equal to zero.

The Hausman specification test can be used to determine the appropriateness of a fixed or random effects panel model. The test determines if there is significant correlation between the unobserved individual-specific random effects and the explanatory variables. Under the null hypothesis, OLS in the fixed effects model and GLS in the random effects model are consistent, but OLS is inefficient. Under the alternative hypothesis, OLS is consistent while GLS is not (Greene, 2008). A rejection of the null hypothesis results in the conclusion that the fixed effects model is preferred over the random effects model.

The decision tree used to select the appropriate statistical model and level of data aggregation to predict the degradation pattern of pavement marking retroreflectivity is shown in Figure 1. As will be described in the subsequent chapter, quality control checks were undertaken to ensure that the retroreflectivity degradation patterns were consistent with published research (i.e., general decreasing trend in retroreflectivity over time, or a short period of retroreflectivity increase followed by a decrease thereafter). Then, a modeling taxonomy was created based on the available data (white versus yellow markings, concrete versus asphalt pavement surfaces, etc.). Separate OLS linear regression models were estimated based on the analysis taxonomy. A Chow test was used to test for any differences in pavement marking degradation patterns at each level in the analysis taxonomy to determine the level of data aggregation that could be employed to estimate a final model of pavement marking retroreflectivity. In other words, the Chow test is a method to test for parameter constancy from different datasets. The null hypothesis in the Chow test is that the regression parameters are equal. The test follows an F-distribution with k (number of parameters) and $N_1 + N_2 - 2$ degrees of freedom, where N_1 and N_2 represent the sample size included in two different datasets.

Once the level of data aggregation was determined the next step was to select the appropriate statistical model to predict the pavement marking retroreflectivity and determine service life estimates based on a minimum retroreflectivity threshold. A fixed effects model was estimated first and an F-test was used to test for the significance of the cross-sectional effects in the panel dataset. If the cross-sectional effects were not statistically different from zero in the present sample, the OLS model was used to estimate the regression parameters. If the cross-sectional effects were statistically different than zero, a random effects panel model was estimated. As noted previously, the Hausman test was used to determine the most appropriate panel data estimator. It must be noted that in the case of disaggregate data, these steps were repeated for each subset of the data to determine the most appropriate statistical model.

Once the appropriate statistical models were identified, the analyses concluded by computing mean service life estimates for each pavement marking type. Mean service life estimates were computed based on setting the pavement marking retroreflectivity level equal to both 75 and 100 $mcd/m^2/lux$ and computing the time to reach this level using the appropriate statistical model.

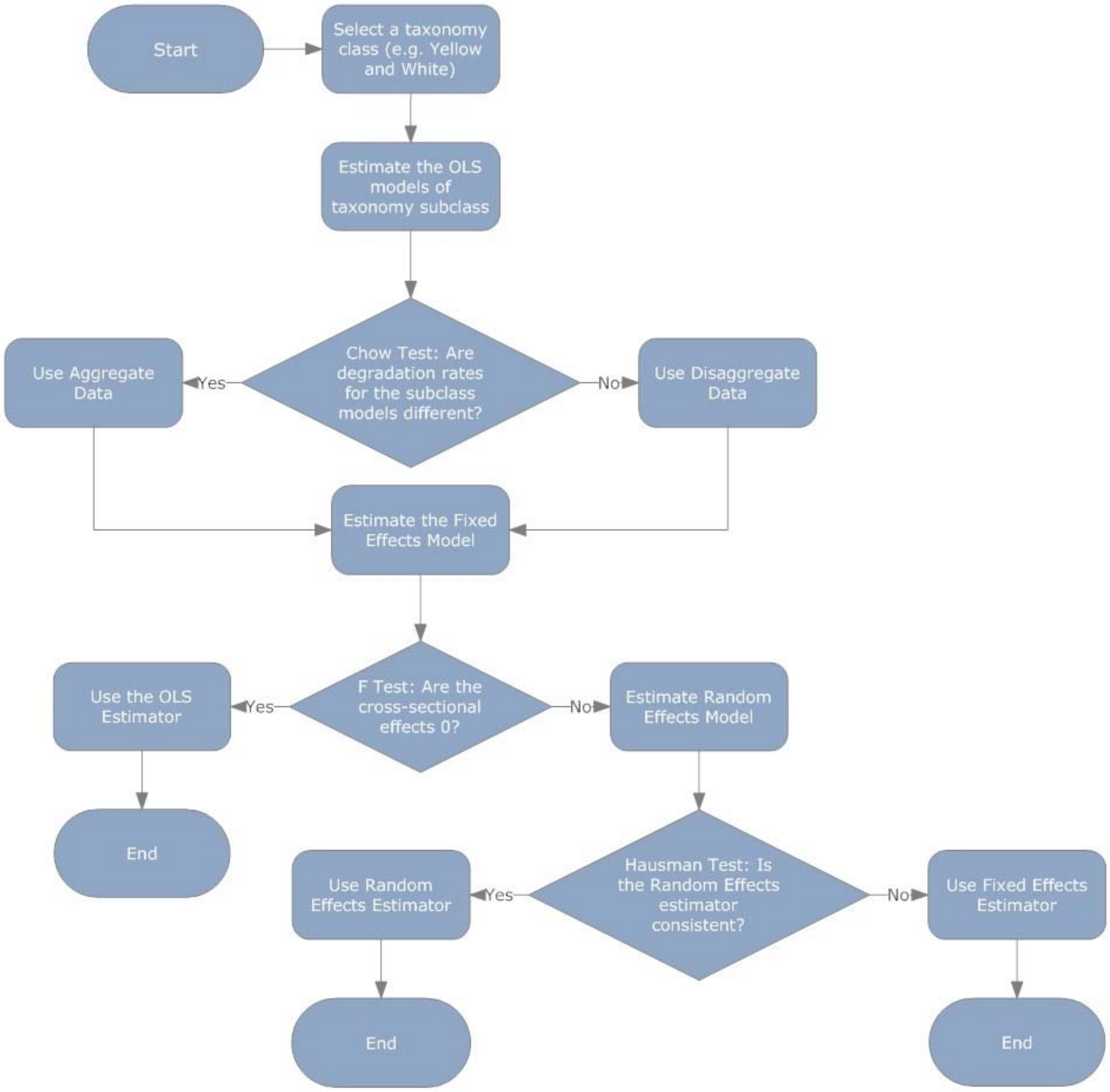

Figure 1. Decision Tree Used to Select Pavement Marking Degradation Model.

CHAPTER 4
EMPIRICAL SETTING

This chapter describes the data collected by PennDOT and a contractor for use in the statistical analysis. Four sections are included in this chapter. The first describes the data quality control checks that were undertaken on the retroreflectivity measurements provided by PennDOT. The following three sections describe the retroreflectivity data collected on various functional class roadways and two different pavement marking types. These include epoxy markings applied on MFC A, B, and C roadways; waterborne paints applied on MFC A, B, and C roadways; and waterborne paints applied on MFC D and E roadways. All retroreflectivity data on MFC A, B, and C roadways were collected using a mobile retroreflectometer, while all pavement markings on MFC D and E roadways were collected using a handheld retroreflectometer.

DATA QUALITY CONTROL CHECKS

The degradation of pavement marking retroreflectivity over time follows two general patterns. The first pattern is where the retroreflectivity decreases over time. The second pattern that is commonly observed occurs when the retroreflectivity initially increases over a short period of time immediately after installation, likely due to delayed glass bead exposure, and then a steady decrease in retroreflectivity is observed thereafter. Each dataset provided by PennDOT was examined for such patterns. Any other degradation pattern was regarded as inconsistent with previous research results. Point by point inspection of the data and graphical degradation plots were used to determine the consistency of the dataset. These plots are shown in Appendixes A through D at the end of this report. All data inconsistencies were shared with PennDOT in an effort to determine why irregular patterns in the degradation plots were observed. In most cases, all irregular degradation patterns were resolved. If it was not clear why an irregular pattern existed in the datasets provided by PennDOT, these data were eliminated from the statistical analysis.

EPOXY PAVEMENT MARKINGS

Each of PennDOT's 11 Engineering Districts was asked to select roadway sections in which periodic pavement marking retroreflectivity measurements could be recorded over time for use in this study. A total of 35 roadway segments classified as MFC A, B, or C were available for the present analysis. Of these, 14 were classified as MFC A and each included a white edgeline, white skip line, and yellow edgeline. A total of 16 roadway segments were classified as MFC B roadways. Thirteen of these roadways contained a white edgeline, white skip line, and yellow edgeline; the other three roadway segments were two-lane undivided highways and contained only a white edgeline and yellow centerline. The five remaining pavement marking sections were classified as MFC C roadways. Three segments included a white edgeline, white skip line, and yellow edgeline; the other two were undivided roadways with a white edgeline and yellow centerline.

All pavement marking types were reflectorized, two-component epoxy. These durable pavement markings were applied by PennDOT contractors with a wet-film thickness of 20 mils ± 1 mil. Glass beads were applied using a double-drop method with a minimum rate of 10 lb/gal of PennDOT Type A beads and 10 lb/gal of PennDOT Type B beads. PennDOT standards specify a minimum initial retroreflectivity of 250 mcd/m^2/lux for white markings and 200 mcd/m^2/lux for yellow markings, measured using a retroreflectometer conforming to ASTM E1710 with a 30-m geometry within 21 days after installation.

Retroreflectivity measurements were taken by BC Traffic Engineering, Inc. with a mobile retroreflectometer containing a 30-m geometry during the period between May 2007 and May 2008. Mobile retroreflectometers are capable of taking nearly 70,000 pavement marking retroreflectivity readings every hour while traveling at highway speeds. Each roadway segment contained in the MFC A, B, and C pavement marking retroreflectivity database provided by PennDOT was nominally one-half mile long. As such, more than 500 pavement marking retroreflectivity measurements were recorded for each line type in a roadway segment. PennDOT entered the average pavement marking retroreflectivity for each line type in a roadway segment for use in the present analysis. All measurements obtained in the sampling area were taken in the direction of traffic flow. The range and standard deviation of the pavement marking retroreflectivity measurements were not recorded.

The installation date of each pavement marking was recorded in a PennDOT-maintained database as was the date of each pavement marking measurement. This permitted the age of the pavement marking to be known when the retroreflectivity measurements were recorded. Generally, four pavement marking retroreflectivity measurements were recorded over the 1-year data collection period. The measurements were not generally taken at equally-spaced intervals or at consistent time periods after the date of installation. In addition to the age and pavement marking retroreflectivity data, the traffic volume (average daily traffic), pavement marking color, pavement surface type (concrete or asphalt), route, county, segment, and snow zone region data were recorded by PennDOT. Snow zone regions were determined by PennDOT using historical weather data and are shown in Figure 2. The snow zones were grouped into three categories. These were denoted as snow zones A, B, and C. Snow zone A has historical snowfall amounts of 0 to 40 inches annually. Snow zones B and C have historical annual snowfall amounts of 40 to 60 inches, and 60 to 100 inches, respectively.

The statistical analysis taxonomy is depicted in Figure 3. At the most disaggregate level of analysis (bottom row of Figure 3 corresponding to each pavement marking type), statistical models were estimated to determine if the pavement marking degradation phenomenon (i.e., slope of regression line) varied by pavement marking or pavement surface type. This was done because several past research studies have indicated that pavement marking retroreflectivity differs for different pavement marking types (see Migletz et al. [2001]; Scheuer et al. [1999]; Hawkins et al. [2002]) and different pavement marking surfaces (Sarasua et al., 2003). The Chow test was used to assess the constancy of the time (age) and intercept variables in the model. If the time parameter was not statistically significant in the sample, an aggregate model (see top row of Figure 3) was estimated, using all of the epoxy retroreflectivity data provided by PennDOT. In this model, indicator variables for various pavement marking types were included in the model specification if the intercepts from the Chow test were statistically different. It should be noted that further levels of disaggregation were not considered (e.g., separate models for each Engineering District) for the epoxy pavement marking analysis.

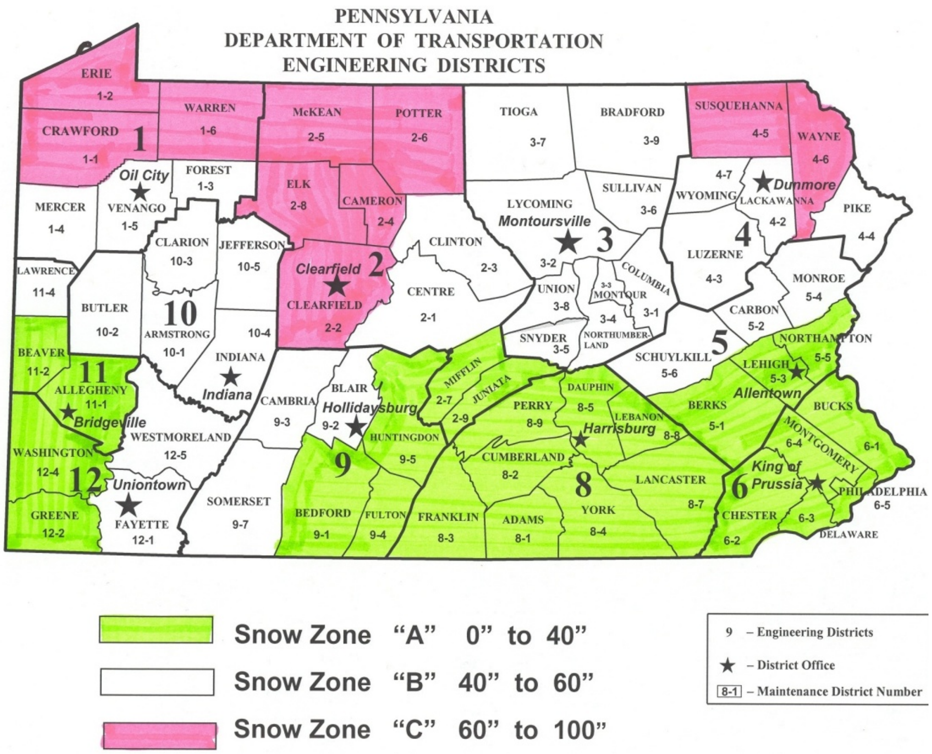

Figure 2. Snow Zone Map.

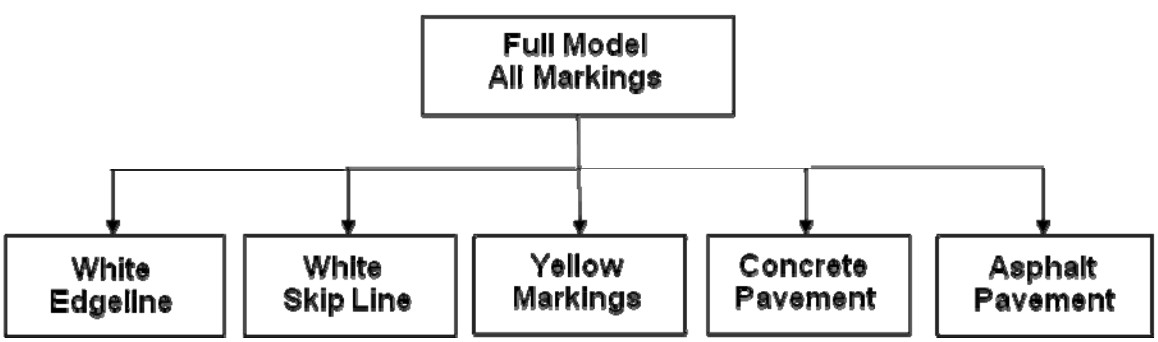

Figure 3. Epoxy Pavement Marking Retroreflectivity Analysis Taxonomy.

Descriptive statistics for each of the variables included in the statistical analysis are shown in Table 4. The continuous variables summarized in Table 4 indicate that the retroreflectivity levels ranged from 53 to 568 mcd/m^2/lux. The average daily traffic on the roadways included in the analysis ranged from nearly 300 to 41,000 vehicles per day. It should be noted that these average daily traffic values represent the amount of traffic per day that passes each pavement marking type along a roadway segment. For a white edgeline, it was assumed that one-half of the directional average daily traffic would occupy the right-lane of a multi-lane highway that has two lanes in each direction of travel. On a two-lane undivided roadway, it was assumed that the directional average daily traffic would pass the white edgeline pavement marking. On multi-lane highways with a white skip line, it was assumed that the entire directional average daily traffic would pass the skip line marking. On two-lane undivided highways, it was assumed that the directional average daily traffic would pass the yellow edgeline. On a multi-lane highway with two travel lanes per direction, it was assumed that one-half of the directional average daily traffic would pass the yellow edgeline pavement marking. The directional average daily traffic data were compiled using PennDOT's interactive traffic management system database.

Retroreflectivity measurements were recorded at intervals ranging from 1 day after installation to 1,434 days after installation. The relatively low proportion of white skip line data is based on the fact that not all of the roadway segments in this MFC A, B, and C database were divided highways. The snow zone data were developed using several years of historical data compiled by PennDOT.

Table 4. Descriptive Statistics of Explanatory Variables used in Epoxy Model Specifications.

Continuous Variable Name	**Mean**	**Standard Deviation**	**Minimum**	**Maximum**
Retroreflectivity (mcd/m^2/lux)	172.54	77.80	53	568
Average daily traffic (veh/day)	4,679	6,218	285	40,939
Time (days)	458.66	371.277	3	1434

Categorical Variable Name	**Categories**	**Proportion of Sample in Category**
Pavement marking type	White Edgeline	36.8
	White Skip Line	26.6
	Yellow Line	36.6
Pavement surface type	Concrete	26.8
	Asphalt	73.2
Maintenance functional class	MFC A	40.8
	MFC B	45.2
	MFC C	14.0
Snow zones	0-40 inches annually	25.2
	40-60 inches annually	58.2
	60-100 inches annually	16.6
Number of observations = 424		

WATERBORNE PAINT PAVEMENT MARKINGS (MFC A, B, AND C)

A random sample of MFC A, B, and C roadway segments with waterborne paints were selected by each of PennDOT's Engineering Districts for data collection. A total of 51 roadway segments were available for the statistical analysis. Of these, 15 were classified as MFC A and each included a white edgeline, white skip line, and yellow edgeline. A total of 14 roadway segments were classified as MFC B roadways. Eight of these roadways contained a white edgeline, white skip line, and yellow edgeline; the remaining six roadway segments contained only a white edgeline and yellow centerline. A total of 22 of the 51 roadway segments were classified as MFC C roadways. Three of these 22 roadway segments contained a white edgeline, white skip line, and yellow edgeline; the remaining 19 segments contained only a white edgeline and yellow centerline. All pavement markings in this dataset were waterborne paint with PennDOT Type A glass beads applied at 7 lb per gallon of paint. Additionally, all waterborne pavement markings were applied by PennDOT maintenance forces with a wet-film thickness of 15 mils $\pm$ 1 mil, except white edgeline markings, which were applied with a wet-film thickness of 12 mils $\pm$ 1 mil. PennDOT standards specify a minimum initial retroreflectivity of 250 mcd/m^2/lux for white and 165 mcd/m^2/lux for yellow waterborne markings.

Retroreflectivity measurements on MFC A, B, and C roadway segments were taken by BC Traffic Engineering, Inc. with a mobile retroreflectometer containing a 30-m geometry. Each roadway segment contained in the MFC A, B, and C pavement marking retroreflectivity database provided by PennDOT was nominally one-half mile long. All measurements obtained in the sampling area were taken in the direction of traffic flow.

The installation date of each pavement marking was recorded in the PennDOT database, as was the date of each pavement marking measurement. These dates were used to determine the age of the pavement markings when the retroreflectivity measurements were recorded. It was common for four or five pavement marking retroreflectivity measurements to be taken over a 1-year period between May 2007 and May 2008. In addition to the age and pavement marking retroreflectivity data, the traffic volume (average daily traffic), pavement marking color, pavement surface type (concrete or asphalt), route, county, segment, and snow zone region data were recorded by PennDOT. Snow zone regions were defined as shown in Figure 2.

The analysis taxonomy that was used for the epoxy markings (see Figure 3) was also used for the MFC A, B, and C analysis of waterborne paints.

A total of 579 pavement marking measurements were included in the analysis sample after excluding markings that exhibited irregular degradation patterns. Nearly all of the pavement markings were applied in 2007 using the paint formulation based on the 2005 PennDOT National Transportation Product Evaluation Program (NTPEP) test deck. Descriptive statistics for each of the variables included in the final statistical analyses are shown in Table 5. The continuous variables summarized in Table 5 indicate that the retroreflectivity levels ranged from 34 to 381 mcd/m^2/lux. The low values suggest that the pavement marking material may not have been fully present during the measurement period. The average daily traffic on the roadways included in the analysis ranged from 900 to 57,900 vehicles per day. It should be noted that these average daily traffic values represent the amount of traffic per day that passes each pavement marking type along a roadway segment. For a white edgeline, it was assumed that one-half of the directional average daily traffic would occupy the right lane of a multi-lane highway that has two lanes in each direction of travel. On a two-lane undivided roadway, it was assumed that the directional average daily traffic would pass the white edgeline pavement marking. On multi-lane highways with a white skip line, it was assumed that the entire directional average daily traffic would pass the skip line marking. On two-lane undivided highways, it was assumed that the directional average daily traffic would pass the yellow edgeline. On a multi-lane highway with two travel lanes per direction, it was assumed that one-half of the directional average daily traffic would pass the yellow edgeline pavement marking. The directional average daily traffic data were compiled using PennDOT's interactive traffic management system database.

Retroreflectivity measurements were recorded at intervals ranging from 1 day after installation to 600 days after installation. The relatively low proportion of white skip line data is based on the fact that approximately half of the roadway segments were divided highways.

Table 5. Descriptive Statistics of Explanatory Variables used in MFC A, B, and C Waterborne Paint Model Specifications.

Continuous Variable Name	**Mean**	**Standard Deviation**	**Minimum**	**Maximum**
Retroreflectivity (mcd/m^2/lux)	170.93	74.93	34	381
Average daily traffic (veh/day)	12060.79	10318.04	900	57,900
Time (days)	180.62	129.05	1	600
Categorical Variable Name	**Categories**		**Proportion of Sample in Category**	
Pavement marking type	White Edgeline		38.90	
	White Skip Line		21.20	
	Yellow Line		39.90	
Pavement surface type	Concrete		28.70	
	Asphalt		71.30	
Maintenance functional class	MFC A		34.70	
	MFC B		29.60	
	MFC C		35.60	
Snow zones	0-40 inches annually		44.20	
	40-60 inches annually		36.10	
	60-100 inches annually		19.70	
Number of observations = 579				

WATERBORNE PAINT PAVEMENT MARKINGS (MFC D and E)

Two separate statistical analyses were undertaken on the retroreflectivity data recorded on MFC D and E roadway segments with waterborne paints. The first included a random sample of pavement markings that were applied using a paint formulation that was tested on the 2002 Pennsylvania NTPEP test deck. A second, different set of randomly sampled roadway segments were analyzed that included pavement marking retroreflectivity data based on a paint formulation that was tested on the 2005 Pennsylvania NTPEP test deck. Each of these separate datasets is described in the next two subsections.

Retroreflectivity Sample Based on 2002 NTPEP Paint Formulation

PennDOT Engineering Districts identified a random sample of 47 roadway segments where retroreflectivity measurements were recorded periodically during 2005 and 2006. Each MFC D and E roadway section consisted of a white edgeline and a double yellow centerline. Both pavement marking types are waterborne paint with PennDOT Type A glass beads applied at 7 lb per gallon of paint. All waterborne pavement markings were applied by PennDOT maintenance forces with a wet-film thickness of 15 mils ± 1 mil, except white edgeline markings, which were applied with a wet-film thickness of 12 mils ± 1 mil. PennDOT standards specify a minimum initial retroreflectivity of 250 $mcd/m^2/lux$ for white markings and 165 $mcd/m^2/lux$ for yellow markings.

Retroreflectivity measurements on MFC D and E roadway sections were taken with a handheld retroreflectometer with a 30-m geometry. The sampling plan used to collect the retroreflectivity measurements is shown in Figure 4. For white edgeline and double yellow centerline markings, 20 retroreflectivity measurements were averaged over a longitudinal length of at least 300 ft and this average was recorded in a pavement marking retroreflectivity database developed by PennDOT; the range of retroreflectivity values and standard deviation were not recorded by PennDOT. All measurements obtained in the sampling area were taken in the direction of traffic flow, except on the centerline of two-lane roads, where the required number of measurements was made in each direction. For the purposes of this analysis, each yellow marking was treated as a separate marking; therefore, a double yellow centerline occupying the sampling section in the analysis contained two mean retroreflectivity measurements.

The installation date of the pavement marking was recorded in the database as was the date of each pavement marking retroreflectivity measurement. This permitted the age of the pavement marking to be known when the retroreflectivity measurements were recorded. It was common for at least three separate pavement marking measurements to be taken over a 1-year period prior to re-striping each pavement marking. The measurements were not generally taken at equally spaced time intervals or at consistent time periods after the date of installation. In addition to the age and pavement marking retroreflectivity data, the traffic volume (average daily traffic), pavement marking color, pavement surface type (concrete or asphalt), route, county, segment, offset, and snow zone region data were recorded by PennDOT and added to the analysis database. The analysis taxonomy used to analyze the data is shown in Figure 5.

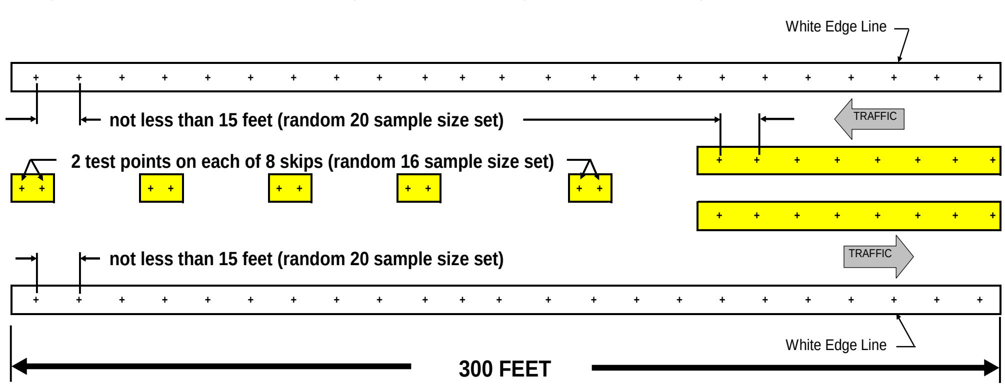

Figure 4. Pavement Marking Retroreflectivity Sampling Plan.

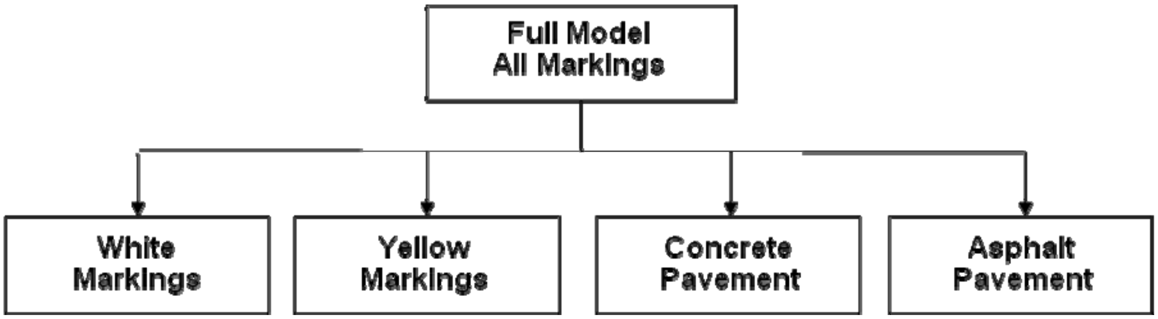

Figure 5. Analysis Taxonomy Used for MFC Waterborne Paints based on 2002 NTPEP Paint Formulation.

Descriptive statistics for each of the variables included in the statistical analysis are shown in Table 6. The continuous variables summarized in Table 6 indicate that the retroreflectivity levels ranged from 27 to 311 mcd/m^2/lux. The low values suggest that the pavement marking material may not have been fully present during the measurement period. The average daily traffic on the roadways included in the analysis ranged from 104 to 10,058 vehicles per day. Retroreflectivity measurements were recorded at intervals ranging from 1 day after installation to 433 days after installation. The high proportion of yellow measurements is the result of the double yellow centerlines being measured separately. Because nearly 75 percent of pavements in Pennsylvania are asphalt, the low proportion of measurements taken on concrete pavements was expected. However, the sample did include 42 retroreflectivity observations on concrete roadways, so separate models of retroreflectivity for asphalt and concrete roadways were specified to determine if the degradation process varied. The snow zone data were developed using several years of historical data compiled by PennDOT. The snow zones were grouped into three categories, as shown in Figure 2.

Table 6. Descriptive Statistics of Explanatory Variables used in MFC D and E Statistical Models based on 2002 NTPEP Paint Formulation.

Continuous Variable Name	Mean	Standard Deviation	Minimum	Maximum
Retroreflectivity (mcd/m^2/lux)	153	55	27	311
Average daily traffic (veh/day)	2,038	2,407	104	10,058
Time (days)	173	125	1	433
Categorical Variable Name	**Categories**		**Proportion of Sample in Category**	
Color	White		23	
	Yellow		77	
Pavement surface type	Concrete		6	
	Asphalt		94	
Maintenance functional class	MFC D		68	
	MFC E		32	
Installation year	2005		56	
	2006		44	
Snow zones	0-40 inches annually		46	
	40-60 inches annually		36	
	60-100 inches annually		17	
Number of observations = 659				

Retroreflectivity Sample Based on 2005 NTPEP Paint Formulation

PennDOT Engineering Districts identified a random sample of 44 MFC D and E roadway segments to collect pavement marking retroreflectivity data during 2007. These pavement markings were applied using a paint formulation that was evaluated on the 2005 NTPEP Pennsylvania test deck. All other pavement marking specifications (i.e., minimum initial retroreflectivity, bead application rate, and minimum wet-film thickness) were the same as those for the 2002 paint formulation described above. The retroreflectivity sampling plan was the same as provided in Figure 5. All retroreflectivity measurements were recorded with a handheld retroreflectometer (30-m geometry) by PennDOT staff. In general, three or four measurements were recorded over the 1-year data collection period on most pavement markings. Descriptive statistics of the data are provided in Table 7. As shown in Table 7, the mean retroreflectivity of the sample was 138 mcd/m^2/lux, with a minimum of 11 mcd/m^2/lux and a maximum of 311 mcd/m^2/lux. The average age of the pavement markings included in the sample was 214 days. Average daily traffic volumes on the roadway segments ranged from 50 to 10,240 vehicles per day, with a mean of 1,474 vehicles per day. Approximately 75 percent of the markings were yellow, which was expected, since retroreflectivity levels were recorded on both centerline stripes in each roadway segment. Nearly the entire sample was applied on asphalt roadway surfaces, so the analysis taxonomy used for the MFC D and E analysis shown in Figure 5 was modified because the sample of retroreflectivity measurements recorded on concrete pavements included only 11 observations. As such, separate models for white and yellow pavement markings were the only disaggregate-level models considered.

Table 7. Descriptive Statistics of Explanatory Variables used in MFC D and E Statistical Models based on 2005 NTPEP Paint Formulation.

Continuous Variable Name	Mean	Standard Deviation	Minimum	Maximum
Retroreflectivity (mcd/m^2/lux)	138	73	11	311
Average daily traffic (veh/day)	1,474	1,866	50	10,240
Time (days)	214	145	3	483

Categorical Variable Name	Categories	Proportion of Sample in Category
Color	White	25
	Yellow	75
Maintenance functional class	MFC D	66
	MFC E	34
Pavement surface type	Asphalt	98
	Concrete	2
Snow zones	0-40 inches annually	28
	40-60 inches annually	56
	60-100 inches annually	16
Number of observations = 542		

CHAPTER 5
ANALYSIS RESULTS

The preliminary analysis began by developing pavement marking degradation plots for each level in the analysis taxonomies shown in Figures 3 and 5. The graphical degradation plots appear in Appendices A through D for epoxy markings; MFC A, B, and C waterborne paints; MFC D and E waterborne paints based on the 2002 NTPEP paint formulation; and MFC D and E waterborne paints based on the 2005 NTPEP paint formulation, respectively. In general, the epoxy pavement marking degradation plots appear non-linear, while all waterborne paint plots appear to show a linear degradation pattern over time. The final recommended statistical models based on the decision-tree process shown in Figure 1 are presented in this chapter of the report.

EPOXY PAVEMENT MARKINGS

The results described in this section of the memorandum relate to the analysis taxonomy shown in Figure 3. The analysis results are presented first for the OLS regression models and then for the panel data models.

Ordinary Least Squares Linear Regression

Because the pavement marking degradation plots shown in Appendix A show that the relationship between pavement marking retroreflectivity and time is non-linear, several transformations and non-linear regression specifications were tried to fit the epoxy pavement marking data. However, many of these specifications (e.g., inverse polynomial regression, exponential regression, power model) produced service life estimates that did not closely represent the data. As such, separate OLS linear regression models were first specified at the lowest level of disaggregation in the taxonomy for white edgelines, white skip lines, and yellow edgelines. Separate OLS linear regression models were also specified for pavement markings applied on concrete and asphalt pavement surfaces. In the white edgeline and white skip line pavement marking retroreflectivity models, the homoskedasticity assumption was violated and the normality assumption was not met. To correct for these violations, a logarithmic transformation was applied and robust estimators were used. In the yellow pavement marking model, the normality assumption was not met, but the homoskedasticity assumption was met. The logarithmic transformation was again used, but the standard errors were not corrected based on the presence of heteroskedasticity in the disturbances. Results from the pavement marking type OLS regression models are shown in Tables 8 through 10. Included in each table are the parameter estimates for statistically significant variables ($\alpha \leq 0.10$), coefficient of determination (R^2), and the sample size used to estimate the models. The variance inflation factors suggested that no multicollinearity was present in the model specifications. The Durbin-Watson statistic was between 0.80 and 1.00 in all three OLS regression models, indicating that positive autocorrelation was present in the model specifications. Autocorrelation results in an inefficient OLS estimator; however, the estimator remains unbiased and consistent (Gujarati, 2003). Because the purpose of the present study is to forecast when retroreflectivity levels reach a minimum threshold level, inefficient standard errors will not change the forecast time to reach a threshold level of retroreflectivity. Furthermore, some pavement markings were measured once, while others were measured up to five times over the data collection period. As a result, the lagging structure used to correct for autocorrelation would require different lag periods for each cross-sectional unit, which can make a substantial difference in the parameter estimates obtained from correction methods that consider only a single lag structure (e.g., Prais-Winsten regression or Cochrane-Orcutt procedure). Autocorrelation was therefore not corrected in the models shown in Tables 8 through 10. The coefficient of determination is a measure of variability in a data set explained by the linear regression model. It ranges from 0 to 1.0 with 1.0 indicating that the observed data perfectly fit the regression line. In Tables 8 through 10, the variability in the retroreflectivity data explained by the model ranged from 24 to 31 percent, indicating that the model does not fit the retroreflectivity data very well.

Table 8. White Edgeline Linear Regression Model for Epoxy Pavement Markings.

Variable	**Parameter Estimate**	**Standard Error**	**t-statistic**
Constant	5.449	0.049	110.78
Time (days)	-0.0005	0.00006	-8.52
ADT (in 1,000's)	-0.0030	0.0015	-1.96

Number of observations = 156
Breusch-Pagan/Cook-Weisburg $\chi^2(1)$ = 9.70 (p-value = 0.002)
Durbin-Watson = 0.80
R_{adj}^2 = 0.30

Table 9. White Skip Line Linear Regression Model for Epoxy Pavement Markings.

Variable	**Parameter Estimate**	**Standard Error**	**t-statistic**
Constant	5.109	0.104	49.35
Time (days)	-0.0005	0.00009	-6.01
Snowzone A and B[a]	0.225	0.102	2.21
Concrete[b]	0.176	0.086	2.05

Number of observations = 113
Breusch-Pagan/Cook-Weisburg $\chi^2(1)$ = 4.96 (p-value = 0.03)
Durbin-Watson = 1.00
R_{adj}^2 = 0.24

[a] Snow zone C is the baseline (60-100 inches). A positive parameter for the combined snow zone A and B indicator indicates that the expected pavement marking retroreflectivity is higher in these zones when compared to the Snow Zone C.
[b]Asphalt is the baseline. A positive parameter estimate for the concrete pavement type indicator indicates that the expected pavement marking retroreflectivity is higher on roadway sections with concrete when compared to pavement markings applied to asphalt.

Table 10. Yellow line Regression Model for Epoxy Pavement Markings.

Variable	Parameter Estimate	Standard Error	t-statistic
Constant	5.134	0.049	112.82
Time (days)	-0.0006	0.00007	-7.77
Concrete[a]	0.207	0.054	3.33

Number of observations = 155
Breusch-Pagan/Cook-Weisburg $\chi^2(1)$ = 0.14 (p-value = 0.713)
Durbin-Watson = 0.80
R_{adj}^2 = 0.31

[a] Asphalt is the baseline. A positive parameter estimate for the concrete pavement type indicator indicates that the expected pavement marking retroreflectivity is higher on roadway sections with concrete when compared to pavement markings applied to asphalt.

The age variable in all models shown in Tables 8 through 10 was negatively correlated with pavement marking retroreflectivity, indicating that as the age increases, the retroreflectivity decreases. The ADT variable was found to be insignificant in all of the models except the white edgeline model at the $\alpha = 0.10$ level. The negative parameter estimate for ADT in the white edgeline model indicates that as the traffic volume increases, the pavement marking retroreflectivity decreases. The concrete indicator was statistically significant in the white skip line and yellow edgeline models, but not in the white edgeline model. A positive parameter estimate for the concrete indicator suggests that the expected pavement marking retroreflectivity levels for epoxy markings are higher on concrete roadways when compared to markings applied on asphalt roadways. The snow zone indicator for roadways that have 0 to 60 inches of annual snowfall accumulation was statistically significant in the white skip line model, but was not statistically significant in the white or yellow edgeline marking models. The positive sign of the parameter estimate indicated that the expected pavement marking retroreflectivity was higher on roadways in these snowfall regions when compared to roadways with annual snowfall accumulations of 60 to 100 inches. The parameter estimates in the models shown in Tables 8 through 10 all have signs that are consistent with engineering intuition.

The Chow test was used to determine if the time variable and intercepts were consistent between the models shown in Tables 8 through 10 (separate models were estimated with only a constant and a time variable and, for brevity, are not provided here). When comparing the white edgeline to white skip line models, the Chow test for the time variable and intercept was not statistically significant (F[1, 418] = 0.04, p-value = 0.83 for the time variable; F[1, 418] = 1.26, p-value = 0.26 for intercept), indicating that the initial values of retroreflectivity and degradation rates were not different in the white edgeline and skip line models and therefore could be combined into a white pavement marking model. When comparing the white edgeline to yellow edgeline models, the Chow test for the time variable was not statistically significant (F[1, 418] = 0.06; p-value = 0.80); however, the intercepts were different (F[1, 418] = 12.00; p-value < 0.001). This indicates that the initial value of retroreflectivity for white and yellow pavement markings differs, but that the degradation rate is not different for the two pavement marking colors. As such, subsequent analyses of pavement marking retroreflectivity for epoxy markings include a separate indicator variable for the yellow markings.

Separate OLS regression models were estimated for pavement markings applied on concrete and asphalt roadway surfaces. The results of these models are shown in Tables 11 and 12.

In the concrete and asphalt models shown in Tables 11 and 12, the age of the marking (time) is negatively correlated with the pavement marking retroreflectivity. This suggests that as the pavement markings age, the retroreflectivity decreases. The white pavement marking indicator was positive in both models, indicating that retroreflectivity levels are higher for white pavement markings than for yellow pavement markings.

Table 11. Linear Regression Model for Epoxy Pavement Markings on Concrete Roadways.

Variable	**Parameter Estimate**	**Standard Error**	**t-statistic**
Constant	5.338	0.061	87.35
Time (days)	-0.0006	0.0001	-4.45
White Pavement Marking[a]	0.129	0.061	2.13

Number of observations = 114
Breusch-Pagan/Cook-Weisburg $\chi^2(1)$ = 6.88 (p-value = 0.01)
Durbin-Watson = 0.75
R_{adj}^2 = 0.22

[a] The baseline is a yellow pavement marking. A positive coefficient indicates that the retroreflectivity for a white pavement marking is higher than the retroreflectivity for a yellow pavement marking.

Table 12. Linear Regression Model for Epoxy Pavement Markings on Asphalt Roadways.

Variable	**Parameter Estimate**	**Standard Error**	**t-statistic**
Constant	5.123	0.041	125.94
Time (days)	-0.0005	0.00004	-12.41
White Pavement Marking[a]	0.229	0.043	5.38

Number of observations = 310
Breusch-Pagan/Cook-Weisburg $\chi^2(1)$ = 6.27 (p-value = 0.01)
Durbin-Watson = 1.19
R_{adj}^2 = 0.31

[a] The baseline is a yellow pavement marking. A positive coefficient indicates that the retroreflectivity for a white pavement marking is higher than the retroreflectivity for a yellow pavement marking.

The Chow test was used to determine if the time variable and intercepts were consistent between the concrete and asphalt models shown in Tables 11 and 12. When comparing the time variable in the models, the null hypothesis was not rejected (F[1, 420] = 0.01; p-value = 0.93), indicating that the retroreflectivity degradation rates were not different. When comparing the intercepts, the null hypothesis was rejected (F[1, 420] = 4.70; p-value = 0.03), indicating that the initial values of retroreflectivity for pavement markings applied on asphalt and concrete pavements differ. These findings suggest that the pavement surface type should be included as an indicator variable in the pavement marking degradation models, but separate models for markings applied on different pavement surface types are not necessary based on the present sample.

Panel Data Analysis

A fixed and random effects panel data model was estimated for the epoxy pavement markings applied on MFC A, B, and C roadways. Indicators for white pavement markings and a concrete pavement surface were included in the specification. The Hausman test favored the fixed effects panel data model ($\chi^2(1) = 40.26$; p-value < 0.001), so it is reported in Table 13. In the model, the concrete pavement indicator could not be included in the specification because it is collinear with the panel identifier. As such, the model only contains two explanatory variables.

The age of the pavement marking was statistically significant and negatively associated with pavement marking retroreflectivity. As such, as time increases, the pavement marking retroreflectivity decreases. The indicator for a white pavement marking was positive, indicating that white pavement markings have a higher pavement marking retroreflectivity than yellow pavement markings. Approximately 58 percent of the variability in the model is explained by the cross-sectional unit.

Table 13. Epoxy Pavement Marking Model.

Variable	**Parameter Estimate**	**Standard Error**	**t-statistic**
Constant	5.401	0.036	151.81
Time (days)	-0.001	0.0001	-16.75
White Pavement Marking[a]	0.207	0.027	7.53

Number of observations = 424
$R_{adj}^2 = 0.27$
$\sigma_\mu = 0.32$
$\sigma_\varepsilon = 0.27$
$\rho = 0.58$

[a] The baseline is a yellow pavement marking. A positive coefficient indicates that the retroreflectivity for a white pavement marking is higher than the retroreflectivity for a yellow pavement marking.

Discussion

Using the parameter estimates from the model presented in Table 13, the average time it takes for epoxy pavement markings applied on MFC A, B, and C roadways to reach a specified threshold value was computed. Two threshold values of 100 and 75 mcd/m^2/lux were used, and these estimates are shown in Table 14.

Table 14. Mean Pavement Marking Service Life Estimates
for Epoxy Pavement Markings (in days).

Threshold R_L = 100 mcd/m²/lux			Threshold R_L = 75 mcd/m²/lux		
White Edgeline	White Skip Line	Yellow Edgeline	White Edgeline	White Skip Line	Yellow Edgeline
973	973	773	1253	1253	1052

From Table 14, it is clear that white pavement markings have longer expected service lives when compared to yellow pavement markings. The mean service life of white pavement markings is 973 days when the minimum retroreflectivity value is 100 mcd/m²/lux. When the retroreflectivity threshold level is decreased to 75 mcd/m²/lux, the expected service life estimate of white pavement markings is 1,253 days. The expected service life of yellow pavement markings is 773 and 1,052 days for a minimum pavement marking retroreflectivity threshold level of 100 mcd/m²/lux and 75 mcd/m²/lux, respectively.

WATERBORNE PAINTS APPLIED ON MFC A, B, AND C ROADWAYS

The results described in this section of the memorandum relate to the analysis taxonomy shown in Figure 3. The analysis results are presented first for the OLS regression models and then for the panel data models.

Ordinary Least Squares Regression Models

Results from the pavement marking type OLS linear regression models are shown in Tables 15 through 17. Included in each table are the parameter estimates for statistically significant variables ($\alpha \leq 0.10$), coefficient of determination (R^2), and the sample size used to estimate the models. In all models, the homoskedasticity assumption was not violated and the normality assumption was met. Additionally, the variance inflation factors suggested that no multicollinearity was present in the model specifications. The Durbin-Watson statistic was between 0.82 and 0.89, indicating that positive autocorrelation was present in the model specifications. Autocorrelation results in an inefficient OLS estimator; however, the estimator remains unbiased and consistent (Gujarati, 2003). For reasons explained in the epoxy pavement marking analysis described in the previous section, autocorrelation was not addressed in the OLS linear regression models. The coefficient of determination is a measure of variability in a data set explained by the linear regression model. It ranges from 0 to 1.0 with 1.0 indicating that the observed data perfectly fit the regression line. In the models shown in Tables 15 through 17, the model explained between 42 and 46 percent of the variability in the pavement marking retroreflectivity data.

Table 15. White Edgeline Linear Regression Model.

Variable	Parameter Estimate	Standard Error	t-statistic
Constant	277.49	8.17	33.98
Time (days)	-0.38	0.03	-11.84
Directional Average Daily Traffic (in 1,000's)	-5.11	1.44	-3.54

Number of observations = 225
Breusch-Pagan/Cook-Weisburg $\chi^2(1) = 0.97$ (p-value = 0.33)
Durbin-Watson = 0.82
$R_{adj}^2 = 0.420$

Table 16. White Skip Line Linear Regression Model.

Variable	Parameter Estimate	Standard Error	t-statistic
Constant	277.07	10.60	26.15
Time (days)	-0.37	0.04	-9.05
Directional Average Daily Traffic (in 1,000's)	-3.34	0.89	-3.76

Number of observations = 123
Breusch-Pagan/Cook-Weisburg $\chi^2(1) = 0.01$ (p-value = 0.90)
Durbin-Watson = 0.89
$R_{adj}^2 = 0.458$

Table 17. Yellow Pavement Marking Linear Regression Model.

Variable	Parameter Estimate	Standard Error	t-statistic
Constant	196.25	6.50	30.21
Time (days)	-0.26	0.02	-11.74
Directional Average Daily Traffic (in 1,000's)	-3.58	1.16	-3.10
Concrete[a]	23.25	6.70	3.47

Number of observations = 231
Breusch-Pagan/Cook-Weisburg $\chi^2(1) = 0.53$ (p-value = 0.47)
Durbin-Watson = 0.87
$R_{adj}^2 = 0.454$

[a] Asphalt is the baseline. A positive parameter estimate for the concrete pavement type indicator indicates that the expected pavement marking retroreflectivity is higher on roadway sections with concrete when compared to pavement markings applied to asphalt.

A Chow test was conducted to determine if the time regression parameter differed among the models (separate models with only the intercept and time were estimated, but for brevity, are not shown here). When comparing the white edgeline and white skip line time parameters, the null hypothesis was not rejected ($\chi^2[1] = 0.16$, p-value = 0.69), so it was concluded that the degradation rate of these markings was the same based on the present sample. Similarly, the intercepts for the white edgeline and white skip line markings were evaluated using the Chow test. The null hypothesis was not rejected ($\chi^2[1] = 0.04$; p-value = 0.84). As such, all final models specified for waterborne paints on MFC A, B, and C roadways were completed by combining the white edgeline and skip line markings.

The null hypothesis was rejected when comparing the time variable for white edgelines to yellow edgeline markings ($\chi^2[1] = 9.62$; p-value = 0.002), suggesting that the degradation rate for yellow and white pavement markings is different for waterborne paints applied on MFC A, B, and C roadways. As such, separate models for white and yellow pavement markings were estimated.

The results of the white pavement marking OLS linear regression model are shown in Table 18. As expected, both the time and directional average daily traffic variables are negatively associated with the expected pavement marking retroreflectivity. It should be noted that the snow zone region indicators were not statistically significant in the white pavement marking models, suggesting that waterborne paint pavement marking retroreflectivity does not differ across snow zone regions on MFC A, B, and C roadways. Likewise, the indicator for a concrete pavement surface was not statistically significant in the waterborne paint models for MFC A, B, and C roadways.

Table 18. OLS Regression Model White Pavement Markings on MFC A, B, and C Roadways.

Variable	Parameter Estimate	Standard Error	t-statistic
Constant	274.25	6.20	44.22
Time (days)	-0.38	0.02	-15.03
DirADT (ADT/1,000)	-3.43	0.70	-4.94
Number of observations = 348			
Breusch-Pagan/Cook-Weisburg $\chi^2(1) = 0.94$ (p-value = 0.33)			
Durbin-Watson = 0.97			
$R_{adj}^2 = 0.433$			

Results from the pavement surface type OLS linear regression models are shown in Tables 19 and 20. Included in each table are the parameter estimates for statistically significant variables ($\alpha \leq 0.10$), coefficient of determination (R^2), and the sample size used to estimate the models. In the concrete model, the homoskedasticity assumption was not violated and the normality assumption was met. However, the homoskedasticity assumption was not met in the asphalt model, so robust standard errors were used to correct for the assumption violation. The variance inflation factors suggested that no multicollinearity was present in the model specifications. The Durbin-Watson statistic was between 1.27 and 1.29 in the models, indicating that positive autocorrelation was present in the model specifications. For reasons explained in the epoxy pavement marking analysis described in the previous section, autocorrelation was not addressed in the OLS linear regression models. The coefficient of determination is a measure of variability in a data set explained by the linear regression model. It ranges from 0 to 1.0, with 1.0 indicating that the observed data perfectly fit the regression line. In the models shown in Tables 19 and 20, the model explained between 40 and 55 percent of the variability in the pavement marking retroreflectivity data.

Table 19. Concrete Pavement Surface Linear Regression Model.

Variable	Parameter Estimate	Standard Error	t-statistic
Constant	253.57	12.64	20.07
Time (days)	-0.28	0.04	-7.58
Directional Average Daily Traffic (in 1,000's)	-5.29	1.75	-3.02
White Pavement Marking[a]	44.83	9.84	4.56
Snow Zone 40-100[b]	-38.29	9.81	-3.90

Number of observations = 166
Breusch-Pagan/Cook-Weisburg $\chi^2(1) = 0.01$ (p-value = 0.95)
Durbin-Watson = 1.29
$R_{adj}^2 = 0.40$

[a] The baseline is a yellow pavement marking. The positive parameter estimate indicates that white pavement markings have a higher expected pavement marking retroreflectivity than yellow pavement markings.

[b] The baseline is a snow zone with 0 to 40 inches of annual snowfall accumulation. The negative parameter estimate indicates that a pavement marking applied in a snow zone with an annual snowfall accumulation of 40 to 100 inches will have a lower pavement marking retroreflectivity than a pavement marking applied in a snow zone region with 0 to 40 inches of annual snowfall accumulation.

Table 20. Asphalt Pavement Surface Model.

Variable	Parameter Estimate	Standard Error	t-statistic
Constant	193.55	6.13	31.57
Time (days)	-0.33	0.02	-16.68
Directional Average Daily Traffic (in 1,000's)	-2.21	0.54	-4.11
White Pavement Marking[a]	51.60	4.95	10.43
Snow Zone 40-100[b]	21.78	5.28	4.13

Number of observations = 413
Breusch-Pagan/Cook-Weisburg $\chi^2(1) = 5.92$ (p-value = 0.02)
Durbin-Watson = 1.27
$R_{adj}^2 = 0.55$

[a] The baseline is a yellow pavement marking. The positive parameter estimate indicates that white pavement markings have a higher expected pavement marking retroreflectivity than yellow pavement markings.

[b] The baseline is a snow zone with 0 to 40 inches of annual snowfall accumulation. The negative parameter estimate indicates that a pavement marking applied in a snow zone with an annual snowfall accumulation of 40 to 100 inches will have a lower pavement marking retroreflectivity than a pavement marking applied in a snow zone region with 0 to 40 inches of annual snowfall accumulation.

In the pavement marking model for concrete pavement surfaces shown in Table 19, the age of the marking and the average daily traffic were both negatively correlated with pavement marking retroreflectivity. The white pavement marking indicator was positive while the snow zone region indicator was negative. All of the parameters in the concrete pavement marking surface model were consistent with engineering intuition.

In the pavement marking model for asphalt pavement surfaces shown in Table 20, the age of the marking and the average daily traffic were both negatively correlated with pavement marking retroreflectivity, as expected. The white pavement marking indicator was positive, which is consistent with engineering intuition. However, the snow zone region indicator was positively correlated with the pavement marking retroreflectivity. This finding was unexpected and may be the result of application differences in the markings.

A Chow test was used to determine if the age and intercepts in the concrete and asphalt pavement marking models differ. The null hypothesis was not rejected ($F[1, 575] = 1.28$, p-value = 0.26 for age variable; $F[1, 575] = 1.38$, p-value = 0.24 for intercept), so the models described in the panel data analysis section below did not consider the pavement surface type.

Panel Data Analysis

Both fixed and random effects panel data models were estimated for white and yellow waterborne pavement markings applied on MFC A, B, and C roadways. In the case of white pavement markings, the Hausman test favored the random effects model ($\chi^2(2) = 0.17$; p-value = 0.92). The results of the random effects model for white pavement markings are shown in Table 21. The time and directional average daily traffic were both negatively correlated with the expected pavement marking retroreflectivity. The snow zone and pavement surface indicators were not statistically significant in the white pavement marking model. Approximately 26 percent of the total variance (ρ) explained by the model is attributed to the cross-sectional unit effect (i.e., individual white pavement marking).

Table 21. White Pavement Markings Random Effects Panel Model.

Variable	**Parameter Estimate**	**Standard Error**	**t-statistic**
Constant	264.07	7.76	34.03
Time (days)	-0.35	0.02	-15.49
DirADT (ADT/1,000)	-2.71	0.94	-2.89

Number of observations = 348
$R_{adj}^2 = 0.435$
$\sigma_\mu = 29.68$
$\sigma_\varepsilon = 49.66$
$\rho = 0.26$

The Hausman test for the yellow pavement marking panel model favored the random effects model ($\chi^2(1) = 0.17$; p-value = 0.92) – the results are shown in Table 22. The time and directional average daily traffic were both negatively correlated with the expected yellow pavement marking retroreflectivity. The concrete surface type indicator suggests that the mean pavement marking retroreflectivity for yellow pavement markings is approximately 24 mcd/m^2/lux higher than the retroreflectivity for yellow pavement markings applied on asphalt roadways. Approximately 20 percent of the variability in the model is explained by the cross-sectional unit (i.e., individual yellow pavement marking).

Table 22. Yellow Pavement Marking Random Effects Panel Model.

Variable	**Parameter Estimate**	**Standard Error**	**t-statistic**
Constant	194.87	7.77	25.09
Time (days)	-0.25	0.02	-12.21
DirADT (ADT/1,000)	-3.70	1.45	-2.55
Concrete[a]	23.70	8.71	2.72

Number of observations = 231
R_{adj}^2 = 0.442
σ_μ = 19.19
σ_ε = 38.94
ρ = 0.20

[a] Asphalt is the baseline. A positive parameter estimate for the concrete pavement type indicator indicates that the expected pavement marking retroreflectivity is higher on roadway sections with concrete when compared to pavement markings applied to asphalt.

It should again be noted that to use the model specifications shown in Tables 21 and 22 for white and yellow pavement markings, the directional average daily traffic for the roadway segment must be known. If the roadway is a two-lane, undivided highway, the directional average daily traffic is simply one-half of the average daily traffic in both directions of travel. If the roadway is a four-lane, divided highway, the directional average daily traffic is one-half of the directional average daily traffic, or one-quarter of the average daily traffic in both directions of travel.

Discussion

Using the parameter estimates from the random effects panel data models presented in Tables 21 and 22, the average time it takes for white and yellow waterborne paint pavement markings along MFC A, B, and C roadways to reach a threshold value was computed. Two threshold values of 75mcd/m^2/lux and100 mcd/m^2/lux were considered to calculate the service life of pavement markings. The time estimates (in days) are shown in Table 23.

From the service life estimates shown in Table 23, it is clear that white pavement markings have longer service lives than yellow markings. The range of service life for white edgelines, based on a minimum retroreflectivity threshold of 100 mcd/m^2/lux, is 467 days for low-volume roadways to 372 days for high-volume roadways (based on the recommended panel data model). The range of service life estimates increases by approximately 70 days when the minimum retroreflectivity threshold is 75 mcd/m^2/lux. For white skip lines, the range of service life ranges from 465 days for low-volume roadways to 258 for high-volume roadways when the retroreflectivity threshold is 100 mcd/m^2/lux. The service life estimates for white skip lines increases by approximately 70 days when the retroreflectivity threshold is 75 mcd/m^2/lux. For yellow edgeline pavement markings, the range in mean service life is 194 days for high-volume roadways to 376 days for low-volume roadways based on a minimum retroreflectivity threshold of 100 mcd/m^2/lux. The service life estimates increase by 100 days when the retroreflectivity threshold is 75 mcd/m^2/lux for yellow markings.

Table 23. Mean Pavement Marking Service Life Estimates for Waterborne White and Yellow Pavement Markings Applied on MFC A, B, and C Roadways (in days).

ADT[a] (veh/day)	Threshold R_L = 100 mcd/m^2/lux			Threshold R_L = 75 mcd/m^2/lux		
	White Edgeline	**White Skip Line**	**Yellow Edgeline[b]**	**White Edgeline**	**White Skip Line**	**Yellow Edgeline[b]**
1,000	467	465	376	538	536	476
5,000	459	449	361	531	521	461
10,000	449	430	342	521	501	442
20,000	430	391	305	501	462	405
30,000	411	353	268	482	424	368
50,000	372	258	194	443	347	294

[a] The retroreflectivity thresholds for ADT are based on the estimated average daily traffic passes by vehicles in travel lanes adjacent to the pavement marking type indicated. For example, threshold for a white edgeline and yellow edgeline is computed based on one-half of the directional ADT, or one-quarter of the ADT in both directions. The threshold for a white skip line is computed based on the directional ADT.

[b] The yellow edgeline pavement marking service life estimates are based on an asphalt pavement surface. To compute the service life for yellow edgelines on concrete pavement surfaces, add 85 days to the estimates shown in Table 23.

WATERBORNE PAINTS ON MFC D AND E ROADWAYS

This section is separated into two subsections. The first describes results obtained for waterborne paints applied on MFC D and E roadways based on the 2002 NTPEP paint formulation, while the second section describes results obtained for waterborne paints applied on MFC D and E roadways based on the 2005 NTPEP paint formulation.

Pavement Marking Retroreflectivity Models based on 2002 NTPEP Paint Formulation

Ordinary Least Squares Linear Regression Model

For the waterborne pavement markings applied on MFC D and E roadways, the analysis taxonomy in Figure 5 was used. The pavement marking degradation plots in Appendix C appear to follow a linearly decreasing pattern for retroreflectivity over time. As such, separate OLS linear regression models were first specified at the lowest level of disaggregation in the taxonomy for white and yellow pavement markings, and for markings applied on concrete and asphalt roadways. Results from the pavement marking and surface type OLS regression models are shown in Tables 24 through 27. Included in each table are the parameter estimates for statistically significant variables ($\alpha \leq 0.10$), coefficient of determination (R^2), and the sample size used to estimate the models. In all models, the homoskedasticity and normality assumptions were met. The Durbin-Watson statistic was between 1.11 and 1.27 in all OLS regression models, indicating that positive autocorrelation was present in the model specifications. As noted in the epoxy pavement marking analysis results, issues related to autocorrelation were not addressed in the models because the purpose of the modeling effort was to forecast the time to reach a minimum retroreflectivity threshold. The coefficient of determination is a measure of variability in a data set explained by the linear regression model. It ranges from 0 to 1.0, with 1.0 indicating that the observed data perfectly fit the regression line. In the models shown in Tables 24 through 27, the model explained between 19 and 52 percent of the variability in the retroreflectivity data.

Table 24. White Pavement Marking Linear Regression Model for MFC D and E Roadways Based on 2002 NTPEP Paint Formulation.

Variable	**Parameter Estimate**	**Standard Error**	**t-statistic**
Constant	225.89	6.48	34.85
Time (days)	-0.332	0.027	-12.20
Snow Zone 40-100[a]	29.21	6.94	4.21
Concrete[b]	29.99	11.28	2.66

Number of observations = 148
Breusch-Pagan/Cook-Weisburg $\chi^2(1) = 0.18$ (p-value = 0.67)
Durbin-Watson = 1.11
$R_{adj}^2 = 0.52$

[a] Snow zone A is the baseline (0-40 inches). A positive parameter for the combined snow zone B and C indicator (40-100 inches) indicates that the expected pavement marking retroreflectivity is higher in these zones when compared to the snow zone A.
[b]Asphalt is the baseline. A positive parameter estimate for the concrete pavement type indicator indicates that the expected pavement marking retroreflectivity is higher on roadway sections with concrete when compared to pavement markings applied to asphalt.

Table 25. Yellow Pavement Marking Linear Regression Model for MFC D and E Roadways Based on 2002 NTPEP Paint Formulation.

Variable	**Parameter Estimate**	**Standard Error**	**t-statistic**
Constant	183.39	3.30	55.64
Time (days)	-0.236	0.012	-19.30
Snow Zone 40-100[a]	-20.44	3.13	-6.52
Concrete[b]	19.68	7.08	2.78
ADT (in 1,000’s)	4.82	0.65	7.42

Number of observations = 511
Breusch-Pagan/Cook-Weisburg $\chi^2(1) = 0.07$ (p-value = 0.79)
Durbin-Watson = 1.27
$R_{adj}^2 = 0.49$

[a] Snow zone A is the baseline (0-40 inches). A positive parameter for the combined snow zone B and C indicator (40-100 inches) indicates that the expected pavement marking retroreflectivity is higher in these zones when compared to the snow zone A.
[b]Asphalt is the baseline. A positive parameter estimate for the concrete pavement type indicator indicates that the expected pavement marking retroreflectivity is higher on roadway sections with concrete when compared to pavement markings applied to asphalt.

Table 26. Linear Regression Model for Pavement Markings Applied on Concrete Pavement Surfaces of MFC D and E Roadways Based on 2002 NTPEP Paint Formulation.

Variable	Parameter Estimate	Standard Error	t-statistic
Constant	208.95	16.86	12.39
Time (days)	-0.217	0.066	-3.29

Number of observations = 42
Breusch-Pagan/Cook-Weisburg $\chi^2(1) = 0.06$ (p-value = 0.81)
Durbin-Watson = 1.09
$R_{adj}^2 = 0.19$

Table 27. Linear Regression Model for Pavement Markings Applied on Asphalt Pavement Surfaces of MFC D and E Roadways Based on 2002 NTPEP Paint Formulation.

Variable	Parameter Estimate	Standard Error	t-statistic
Constant	192.27	3.34	57.61
Time (days)	-0.272	0.013	-20.16
Snow Zone 60-100[a]	-10.94	4.95	-2.21
ADT (in 1,000's)	3.74	0.70	5.37

Number of observations = 617
Breusch-Pagan/Cook-Weisburg $\chi^2(1) = 0.10$ (p-value = 0.76)
Durbin-Watson = 1.25
$R_{adj}^2 = 0.43$

[a] Snow zone 0 to 60 inches is the baseline. A positive parameter estimate for the snow zone 60 to 100 inches indicator suggests that the expected pavement marking retroreflectivity is lower on roadway sections with 60 to 100 inches of annual snowfall accumulation when compared to roadways in snow zone with 0 to 60 inches of annual snowfall accumulation.

The time variable in all models was negatively correlated with pavement marking retroreflectivity, indicating that as the age of the marking increases, the retroreflectivity decreases. The ADT variable was found to be statistically significant in yellow and asphalt pavement surface models at the $\alpha = 0.10$ level. The ADT parameter was positive, suggesting that as the traffic volume increases, the expected pavement marking retroreflectivity increases. This finding is counterintuitive, but may be the result of superior pavement marking application processes on higher-volume roadways. The concrete indicator was statistically significant in the white and yellow pavement marking models. The positive parameter estimate for the concrete indicator suggests that the expected pavement marking retroreflectivity levels for waterborne pavement markings is higher on concrete roadways when compared to markings applied on asphalt roadways. A snow zone indicator was statistically significant in the white, yellow, and asphalt pavement marking models. A positive sign of the parameter estimate in the white pavement marking model indicated that the expected pavement marking retroreflectivity was higher on roadways with 40 to 100 inches of annual snowfall accumulation when compared to roadways with less annual snowfall accumulations. The negative sign in the yellow and asphalt models suggests that the expected pavement marking retroreflectivity is lower in the snow zone regions, with 40 to 100 and 60 to 100 inches, respectively, when compared to the baseline snow zone region. The snow zone indicator had a counterintuitive sign in the white pavement marking model and may be the result of differences in the application process of white pavement markings in higher snowfall accumulation zones.

The Chow test was used to determine if the time variable and intercepts were consistent between the white and yellow pavement marking models. The Chow test for the time and intercept variables were statistically significant ($\chi^2[1] = 3.85$; p-value = 0.05 for time; ($\chi^2[1] = 92.48$; p-value < 0.001 for intercept), indicating that the degradation rate and initial levels of pavement marking retroreflectivity for white and yellow pavement markings differ. When comparing the models for pavement markings applied on concrete and asphalt roadway surfaces, the Chow test did not reject the null hypothesis ($\chi^2[1] = 0.95$; p-value = 0.33 for time; ($\chi^2[1] = 0.28$; p-value = 0.59 for intercept). This indicates that the initial value of retroreflectivity and the degradation patterns for markings applied on concrete and asphalt roadway surfaces do not differ significantly in the present sample. Based on the Chow test findings, separate models for white and yellow pavement markings should be specified, but estimating separate models (or indicator variables) for separate pavement surfaces is not suitable based on the sample.

Panel Data Analysis

A fixed effects panel data model was estimated for the white pavement markings applied on MFC D and E roadways. An F-test that all cross-sectional unit effects are equal was not rejected ($F[39, 107] = 1.11$; p-value = 0.33), so the data were pooled and the OLS linear regression model for white pavement markings shown in Table 24 was used to estimate the service life of white pavement markings applied on MFC D and E roadways based on the 2002 NTPEP Pennsylvania test deck paint formulation. The same conclusion did not result for the yellow pavement marking model, so both fixed and random effects panel models were estimated. The Hausman test favored the random effects panel data model ($\chi^2(1) = 0.07$; p-value = 0.79), so it is reported in Table 28. In the model, the time variable is negatively correlated with pavement marking retroreflectivity. This indicates that as the pavement marking ages, the retroreflectivity decreases. Similarly, the snow zone indicator for regions with 40 to 100 inches of annual snowfall accumulation is negative, meaning that yellow pavement markings applied in these snow zone regions have lower levels of pavement marking retroreflectivity than yellow markings applied in snow zone regions with 0 to 40 inches of annual snowfall accumulation. The ADT variable is positively correlated with pavement marking retroreflectivity, indicating that as the traffic volume increases, the retroreflectivity increases.

Table 28. Random Effects Panel Data Model for Yellow Markings Applied on MFC D and E Roadways Based on the 2002 NTPEP Paint Formulation.

Variable	**Parameter Estimate**	**Standard Error**	**t-statistic**
Constant	181.85	5.31	34.23
Time (days)	-0.243	0.011	-21.84
Snow Zone 40-100[a]	-15.48	5.94	-2.61
ADT (in 1,000's)	4.83	1.26	3.83

Number of observations = 511
$R_{adj}^2 = 0.49$
$\sigma_\mu = 19.73$
$\sigma_\varepsilon = 29.05$
$\rho = 0.32$

[a] The baseline is the snow zone with 0 to 40 inches of annual snowfall accumulation. A negative coefficient indicates that the retroreflectivity for a yellow pavement marking applied on a roadway segment in a snow zone with 40 to 100 inches of annual snowfall accumulation is lower than a marking applied on a roadway segment in a snow zone with 0 to 40 inches of annual snowfall accumulation.

Discussion

Using the parameter estimates from the models presented in Tables 24 and 28, the average time it takes for waterborne paint pavement markings applied on MFC D and E roadways (based on 2002 NTPEP paint formulation) to reach a specified threshold value was computed. Two threshold values of 100 and 75 mcd/m^2/lux were used, and these estimates are shown in Table 29.

Table 29. Mean Pavement Marking Service Life Estimates for Waterborne Paint Pavement Markings Applied on MFC D and E Roadways Based on 2002 NTPEP Paint Formulation (in days).

ADT[a] (veh/day)	**Threshold R_L = 100 mcd/m^2/lux**		**Threshold R_L = 75 mcd/m^2/lux**	
	White Markings[b]	**Yellow Markings[c]**	**White Markings[b]**	**Yellow Markings[c]**
500	379	342	455	445
1,000		347		450
5,000		387		489
10,000		436		539

[a] For the yellow pavement marking models, the estimated service life was computed using one-half of the average annual daily traffic.

[b] The service life estimates for the white pavement markings were computed based on pavement markings applied on asphalt roadway surfaces in snow zones with an annual snowfall accumulation of 0 to 40 inches. If the markings are applied on concrete roadway surfaces, add 90 days to the service life estimates provided. If the markings are applied in regions with annual snowfall accumulations of 40 to 100 inches, add 88 days to the values shown above.

[c] The service life estimates for the yellow pavement markings were computed based on pavement markings applied in snow zones with an annual snowfall accumulation of 0 to 40 inches. If the markings are applied in regions with annual snowfall accumulations of 40 to 100 inches, subtract 64 days from the values shown above.

From Table 29, white pavement markings have longer service life estimates than yellow markings when the traffic volume is less than 1,000 vehicles per day. However, yellow pavement markings have higher estimated service lives than white markings when the traffic volumes reach and exceed 5,000 vehicles per day. This finding is counterintuitive, but is primarily the result of the higher degradation rate of white pavement markings on two-lane highways when compared to yellow pavement markings. A possible explanation for this finding may be the result of narrow travel lane or shoulder widths on low-volume, lower functional class roadways. Furthermore, the application location of the white edgeline pavement markings is not known, but could be on or near a construction joint that results in a rapid loss of pavement marking durability when compared to the centerline markings on two-lane roadways.

Pavement Marking Retroreflectivity Models based on 2005 NTPEP Paint Formulation

Ordinary Least Squares Linear Regression

For the waterborne pavement markings applied on MFC D and E roadways, the analysis taxonomy in Figure 5 was used, without the pavement surface type models. The pavement marking degradation plots in Appendix D appear to follow a linearly decreasing pattern for retroreflectivity over time. As such, separate OLS linear regression models were first specified at the lowest level of disaggregation in the taxonomy for white and yellow pavement markings. Results from the pavement marking type OLS regression models are shown in Tables 30 and 31. Included in each table are the parameter estimates for statistically significant variables ($\alpha \leq 0.10$), coefficient of determination (R^2), and the sample size used to estimate the models. In all models, the homoskedasticity and normality assumptions were met. The Durbin-Watson statistic was between 0.25 and 0.48 in the OLS regression models, indicating that positive autocorrelation was present in the model specifications. The issue with autocorrelation was not mitigated for the reasons noted in the epoxy pavement marking analysis results section. The coefficient of determination is a measure of variability in a data set explained by the linear regression model. It ranges from 0 to 1.0 with 1.0, indicating that the observed data perfectly fit the regression line. The models shown in Tables 30 and 31 explained approximately 70 percent of the variability in the pavement marking retroreflectivity data, indicating that the models are a good statistical fit.

Table 30. White Pavement Marking Linear Regression Model for MFC D and E Roadways Based on 2005 NTPEP Paint Formulation.

Variable	**Parameter Estimate**	**Standard Error**	**t-statistic**
Constant	276.53	6.84	40.44
Time (days)	-0.500	0.028	-17.63

Number of observations = 135
Breusch-Pagan/Cook-Weisburg $\chi^2(1) = 0.10$ (p-value = 0.76)
Durbin-Watson = 0.25
$R_{adj}^2 = 0.70$

[a] Snow zone A is the baseline (0-40 inches). A positive parameter for the combined snow zone B and C indicator (40-100 inches) indicates that the expected pavement marking retroreflectivity is higher in these zones when compared to the snow zone A.
[b]Asphalt is the baseline. A positive parameter estimate for the concrete pavement type indicator indicates that the expected pavement marking retroreflectivity is higher on roadway sections with concrete when compared to pavement markings applied to asphalt.

Table 31. Yellow Pavement Marking Linear Regression Model for MFC D and E Roadways Based on 2005 NTPEP Paint Formulation.

Variable	**Parameter Estimate**	**Standard Error**	**t-statistic**
Constant	209.94	4.24	49.46
Time (days)	-0.347	0.012	-28.21
Snow Zone 60-100[a]	-22.92	5.56	-4.12
Snow Zone 40-60[a]	-13.05	4.31	-3.03
ADT (in 1,000's)	0.0023	0.0011	2.16

Number of observations = 407
Breusch-Pagan/Cook-Weisburg $\chi^2(1) = 0.45$ (p-value = 0.50)
Durbin-Watson = 0.48
$R_{adj}^2 = 0.71$

[a] Snow zone A is the baseline (0-40 inches). A negative parameter for the snow zone indicators in the table indicates that the pavement marking retroreflectivity is lower on roadway segments that receive annual snowfall accumulations of 40 to 60 or 60 to 100 inches per year when compared to the baseline.

The age variable in all models was negatively correlated with pavement marking retroreflectivity, indicating that as the age increases, the retroreflectivity decreases. The ADT variable was found to be statistically significant in the yellow pavement marking model, but not in the white pavement marking model. The ADT parameter was positive, suggesting that as the traffic volume increases, the expected pavement marking retroreflectivity increases. This finding is counterintuitive, but may be the result of superior pavement marking application processes on higher-volume roadways. The snow zone indicators in the yellow pavement marking model are statistically significant and have negative values. This indicates that yellow markings applied on roadways in snow zone regions with 40 to 60 or 60 to 100 inches of annual snowfall accumulation per year have lower pavement marking retroreflectivity levels than yellow pavement markings applied on roadways with annual snowfall accumulations of 0 to 40 inches per year.

The Chow test was used to determine if the time variable and intercepts were consistent between the white and yellow pavement marking models. The Chow tests for the time and intercept variables were statistically significant ($\chi^2[1] = 22.31$; p-value < 0.001 for time; ($\chi^2[1] = 93.55$; p-value < 0.001 for intercept), indicating that the degradation rate and initial levels of pavement marking retroreflectivity for white and yellow pavement markings differ. Based on the Chow test findings, separate models for white and yellow pavement markings were specified in the panel data models.

Panel Data Analysis

Both fixed and random effects panel models were estimated for white and yellow pavement markings. The Hausman test for the white pavement marking model favored the fixed effects model ($\chi^2(1) = 5.65$; p-value = 0.02), so it is reported in Table 32. The time variable has a negative value, indicating that as the pavement marking age increases, the retroreflectivity decreases.

Table 32. Fixed Effects Panel Data Model for White Markings Applied on MFC D and E Roadways Based on the 2005 NTPEP Paint Formulation.

Variable	**Parameter Estimate**	**Standard Error**	**t-statistic**
Constant	251.12	9.86	25.48
Time (days)	-0.372	0.046	-8.17

Number of observations = 135
$R_{adj}^2 = 0.70$
$\sigma_\mu = 38.97$
$\sigma_\varepsilon = 34.47$
$\rho = 0.56$

The Hausman test for the yellow pavement marking model favored the random effects model ($\chi^2(1) = 0.06$; p-value = 0.81), so it is reported in Table 33. The time variable is negative, indicating that as the pavement marking age increases, the retroreflectivity decreases.

Table 33. Random Effects Panel Data Model for Yellow Markings Applied on MFC D and E Roadways Based on the 2005 NTPEP Paint Formulation.

Variable	**Parameter Estimate**	**Standard Error**	**t-statistic**
Constant	201.09	4.25	47.35
Time (days)	-0.354	0.012	-29.02

Number of observations = 407
$R_{adj}^2 = 0.69$
$\sigma_\mu = 29.36$
$\sigma_\varepsilon = 24.39$
$\rho = 0.59$

Discussion

Using the parameter estimates from the models presented in Tables 32 and 33, the average time it takes for waterborne paint pavement markings applied on MFC D and E roadways (based on 2005 NTPEP paint formulation) to reach a specified threshold value was computed. Two threshold values of 100 and 75 mcd/m^2/lux were used, and these estimates are shown in Table 34.

Table 34. Mean Pavement Marking Service Life Estimates for Waterborne Paint Pavement Markings Applied on MFC D and E Roadways Based on 2005 NTPEP Paint Formulation (in days).

Threshold R_L = 100 mcd/m^2/lux		**Threshold R_L = 75 mcd/m^2/lux**	
White Markings	**Yellow Markings**	**White Markings**	**Yellow Markings**
406	286	473	356

From Table 34, it is clear that white pavement markings have longer service life estimates than yellow markings. It is worth noting that the 2005 and 2002 paint formulations were similar when comparing the pavement marking service life estimates in Tables 29 and 34. The yellow pavement marking service life estimates were higher for the 2002 paint formulation (see Table 29) when compared to the 2005 paint formulation (see Table 34).

CHAPTER 6
CONCLUSIONS

The conclusions from the research are organized based on the pavement marking type analysis results provided in Chapter 5. A general discussion concerning the modeling methods used is provided as are issues related to pavement marking management.

EPOXY PAVEMENT MARKINGS

Pavement marking retroreflectivity data collected by BC Traffic Engineering, Inc. were modeled with the objective of producing service life estimates of epoxy pavement markings applied on MFC A, B, and C roadways. The pavement marking degradation pattern did not appear linear based on the plots shown in Appendix A, so a logarithmic transformation of the dependent variable was used to model retroreflectivity. A fixed effects panel model was used to estimate the service life of pavement marking retroreflectivity. Based on a threshold level of 100 mcd/m^2/lux, the service life for white pavement markings was 973 days (2.7 years) while the service life for yellow pavement markings was 773 days (2.1 years). If a retroreflectivity threshold level of 75 mcd/m^2/lux is used, the service life for white pavement markings increases to 1,253 days (3.4 years) while the yellow pavement marking service life increases to 1,052 days (2.9 years). If the threshold retroreflectivity level of 100 mcd/m^2/lux is adopted by PennDOT to manage pavement markings across the Commonwealth, these findings suggest that white epoxy markings should be re-applied every 2.5 years and yellow pavement markings should be re-applied every 2 years. If a threshold of 75 mcd/m^2/lux is adopted, these findings suggest that white epoxy markings should be re-applied every 3 years and yellow pavement markings should be re-applied every 2.5 years. The implications of the service life estimates computed indicate that the (re)application of epoxy pavement markings should occur in the spring or fall painting seasons so that the 0.5 year cycles can be accommodated.

It is interesting to note that, based on the pavement marking retroreflectivity data provided by PennDOT, there were 10 white pavement markings in the sample with an initial retroreflectivity reading recorded during the first 21 days after application. Of these, 4 of the markings did not meet the minimum installation retroreflectivity requirements of 250 mcd/m^2/lux specified by PennDOT. The only yellow pavement marking with an initial retroreflectivity reading recorded during the first 21 days after application did meet the minimum retroreflectivity requirement of 200 mcd/m^2/lux specified by PennDOT.

WATERBORNE PAINTS APPLIED ON MFC A, B, AND C ROADWAYS

Pavement marking retroreflectivity data collected by BC Traffic Engineering, Inc. were modeled with the objective of producing service life estimates for waterborne paint pavement markings applied on MFC A, B, and C roadways. The pavement marking degradation pattern did appear linear based on the plots shown in Appendix B, so OLS linear regression and panel data models were used to predict pavement marking retroreflectivity without any data transformation. In these models, all but the autocorrelation assumption was met. Because of the various lagging structures that would be required to address this issue for each cross-sectional unit (i.e., pavement marking segment), the models specified did not correct for autocorrelation. This, however, does not have an effect on the pavement marking service life estimates. Separate random effects panel data models were used to estimate the mean pavement marking service life of white and yellow pavement markings. The results indicate that the pavement marking service life estimates range from 372 to 467 days (1 to 1.3 years), depending on the traffic volume, when a threshold retroreflectivity level of 100 mcd/m^2/lux for white pavement markings is used. When the retroreflectivity threshold is reduced to 75 mcd/m^2/lux, the service life estimates range from 443 to 538 days (1.2 to 1.5 years), depending on the average daily traffic volume. This suggests that PennDOT's current policy of re-striping white waterborne paint pavement markings on an annual basis be continued.

For yellow pavement markings, the results indicate that the service life estimates range from 194 to 376 days (0.5 to 1 year), depending on the traffic volume, when a threshold retroreflectivity level of 100 mcd/m^2/lux is used. When the retroreflectivity threshold is reduced to 75 mcd/m^2/lux, the service life estimates range from 294 to 476 days (0.8 to 1.3 years), depending on the average daily traffic volume. These estimates are based on pavement markings applied on asphalt pavement surfaces. If the markings are applied on concrete pavement surfaces, an additional 85 days (3 months) can be added to the service life estimates.

It is interesting to note that, based on the pavement marking retroreflectivity data provided by PennDOT, there were 22 white pavement markings in the sample with an initial retroreflectivity reading recorded during the first 21 days after application. Of these, 10 of the markings did not meet the minimum installation retroreflectivity requirements of 250 mcd/m^2/lux specified by PennDOT for waterborne paints. There were 13 yellow pavement markings in the sample with an initial retroreflectivity reading recorded during the first 21 days after application. Of these, 7 of the markings did not meet the minimum installation retroreflectivity requirements of 165 mcd/m^2/lux specified by PennDOT for waterborne paints.

WATERBORNE PAINTS APPLIED ON MFC D AND E ROADWAYS (2002 PAINT FORMULATION)

Pavement marking retroreflectivity data collected by PennDOT were modeled with the objective of producing service life estimates of waterborne paint pavement markings applied on MFC D and E roadways based on the 2002 NTPEP paint formulation. The pavement marking degradation pattern did appear linear based on the plots shown in Appendix C, so linear models were used to estimate the service life of white and yellow pavement markings. Based on the analysis results, a pooled OLS linear regression model was used to estimate the service life of white pavement markings, while a random effects panel data model was used to estimate the service life of yellow pavement markings. Based on a threshold level of 100 mcd/m^2/lux, the service life for white pavement markings was 379 days (1 year), assuming that the markings are applied on asphalt pavement in regions with low annual snowfall accumulation. Additional life can be obtained if the pavement markings are applied on concrete pavement markings (approximately 3 months) or in higher snowfall regions (approximately 3 months). The extended service life estimates for higher snowfall regions was counterintuitive, but may be the result of different pavement marking application and maintenance practices across PennDOT Engineering Districts. If a retroreflectivity threshold level of 75 mcd/m^2/lux is used, the service life for white pavement markings increases to 455 days (1.2 years), but additional life can be obtained if the markings are applied on concrete pavements or in regions with higher snowfall accumulations. Based on these results, it appears that PennDOT's policy to re-stripe MFC D and E roadways with white waterborne paints on an annual basis should be continued.

The service life for yellow pavement markings ranged from 342 to 436 days (0.9 to 1.2 years), depending on the average daily traffic using a minimum retroreflectivity threshold of 100 mcd/m^2/lux. The service life range increases to 445 to 539 days (1.2 to 1.5 years) if a threshold of 75 mcd/m^2/lux is adopted by PennDOT, depending on the traffic volume along the roadway segment. These results were obtained assuming that the yellow pavement markings are applied in areas with low annual snowfall accumulations. If applied in areas of higher snowfall accumulation, the service life is reduced by approximately 2 months. Based on these results, it appears that PennDOT's policy to re-stripe MFC D and E roadways with yellow waterborne paints on an annual basis be continued.

It is interesting to note that, based on the pavement marking retroreflectivity data provided by PennDOT, there was 1 white pavement marking in the sample with an initial retroreflectivity reading recorded during the first 21 days after application. It did not meet the minimum installation retroreflectivity requirements of 250 mcd/m^2/lux specified by PennDOT (243 mcd/m^2/lux was recorded). Both yellow pavement markings with an initial retroreflectivity reading recorded during the first 21 days after application did meet the minimum retroreflectivity requirement of 165 mcd/m^2/lux specified by PennDOT.

WATERBORNE PAINTS APPLIED ON MFC D AND E ROADWAYS (2005 PAINT FORMULATION)

Pavement marking retroreflectivity data collected by PennDOT were modeled with the objective of producing service life estimates of waterborne paint pavement markings applied on MFC D and E roadways based on the 2005 NTPEP paint formulation. The pavement marking degradation pattern did appear linear based on the plots shown in Appendix D, so linear models were used to estimate the service life of white and yellow pavement markings. Based on the analysis results, a fixed effects panel model was recommended to estimate the service life of white pavement markings, while a random effects panel model was recommended to estimate the service life of yellow pavement markings. Based on a threshold level of 100 mcd/m^2/lux, the service life for white pavement markings was 406 days (1.1 years) while the service life for yellow pavement markings was 286 days (0.8 years). Based on a threshold level of 75 mcd/m^2/lux, the service life for white pavement markings was 473 days (1.3 years) while the service life for yellow pavement markings was 365 days (1 year). Based on these results, it appears that PennDOT's policy to re-stripe MFC D and E roadways with waterborne paints on an annual basis should be continued. It should be noted that the 2005 paint formulation appears to provide similar pavement marking retroreflectivity levels when compared to the 2002 paint formulation for white markings; however, the 2002 paint formulation appears to provide higher pavement marking retroreflectivity levels than the 2005 paint formulation for yellow paints.

It is interesting to note that, based on the pavement marking retroreflectivity data provided by PennDOT, there were 6 white pavement markings in the sample with an initial retroreflectivity reading recorded during the first 21 days after application. Of these, 1 of the markings did not meet the minimum installation retroreflectivity requirements of 250 mcd/m^2/lux specified by PennDOT (230 mcd/m^2/lux). No pavement marking readings were recorded for yellow pavement markings during the first 21 days after application in the sample.

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APPENDIX A
PAVEMENT MARKING DEGRADATION PLOTS FOR EPOXY MARKINGS

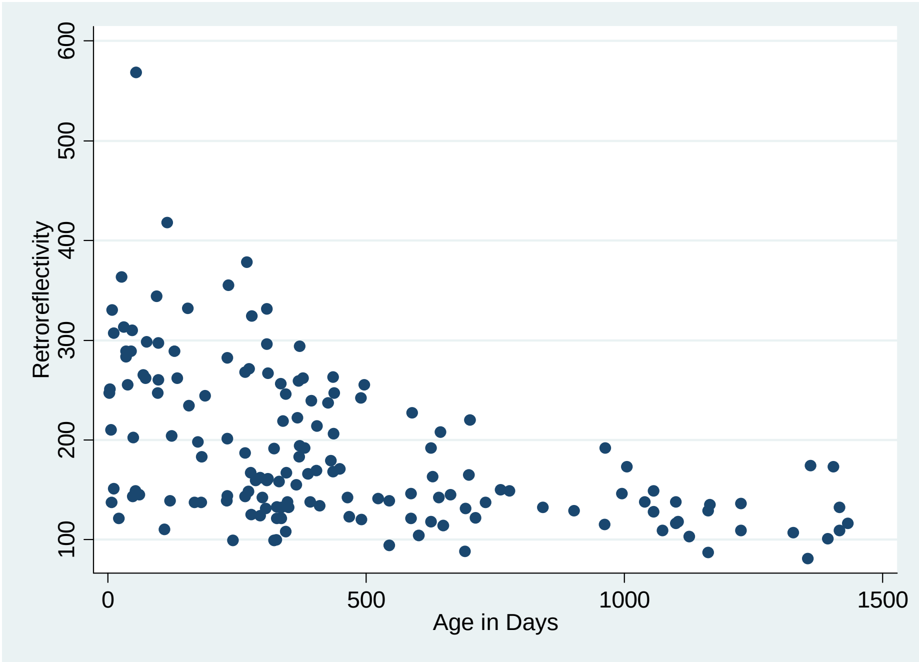

Figure A.1. White Edgeline Pavement Marking Retroreflectivity Degradation Plot.

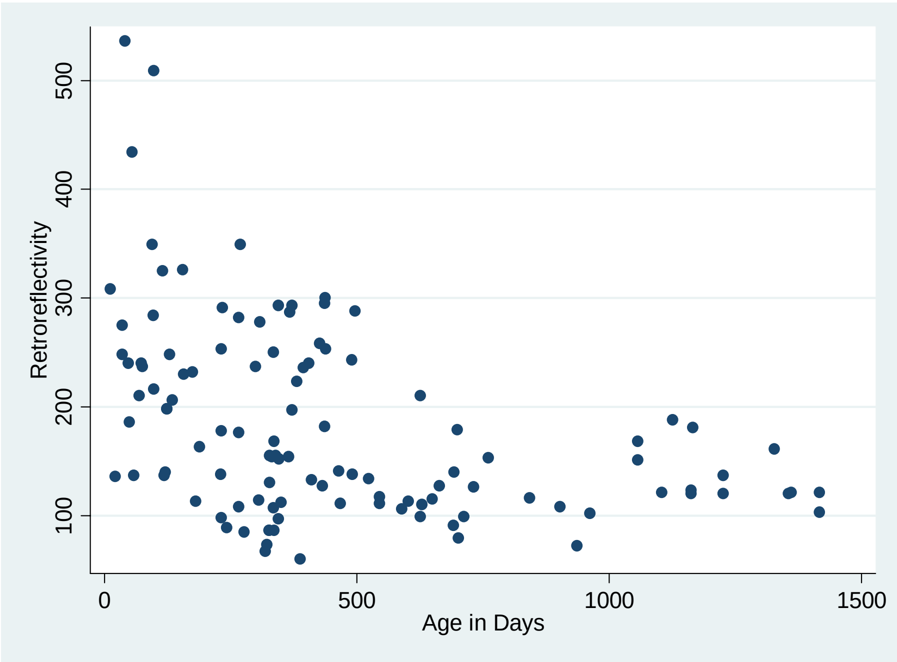

Figure A.2. White Skip Line Pavement Marking Retroreflectivity Degradation Plot.

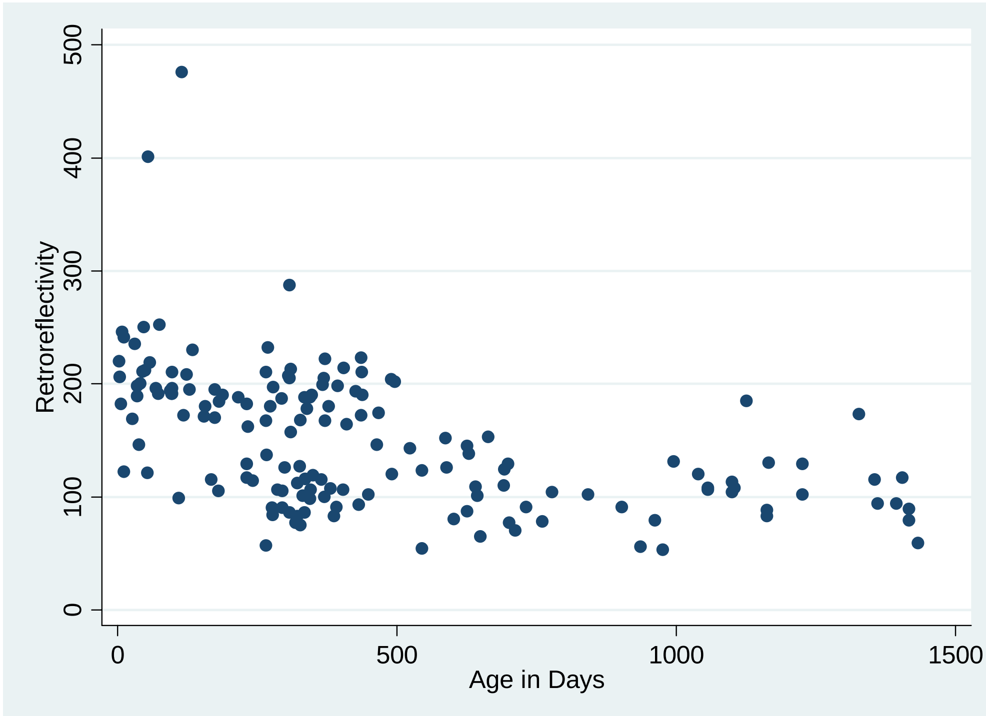

Figure A.3. Yellow Edgeline Pavement Marking Retroreflectivity Degradation Plot.

APPENDIX B

PAVEMENT MARKING DEGRADATION PLOTS FOR WATERBORNE PAINTS APPLIED ON MFC A, B, and C ROADWAYS

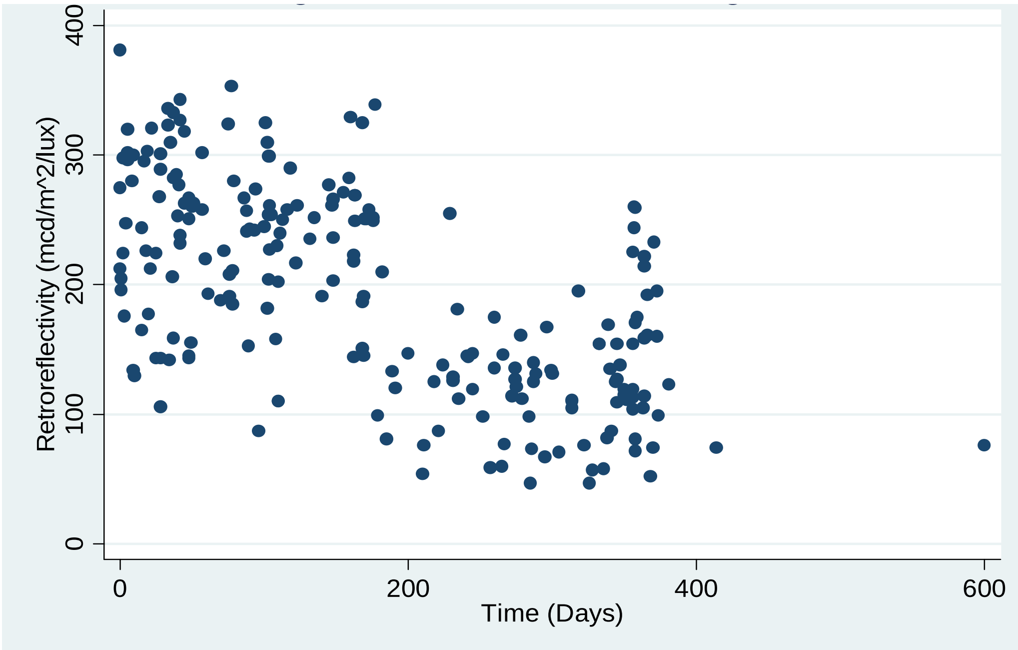

Figure B.1. Pavement Marking Degradation Plot for White Edgelines.

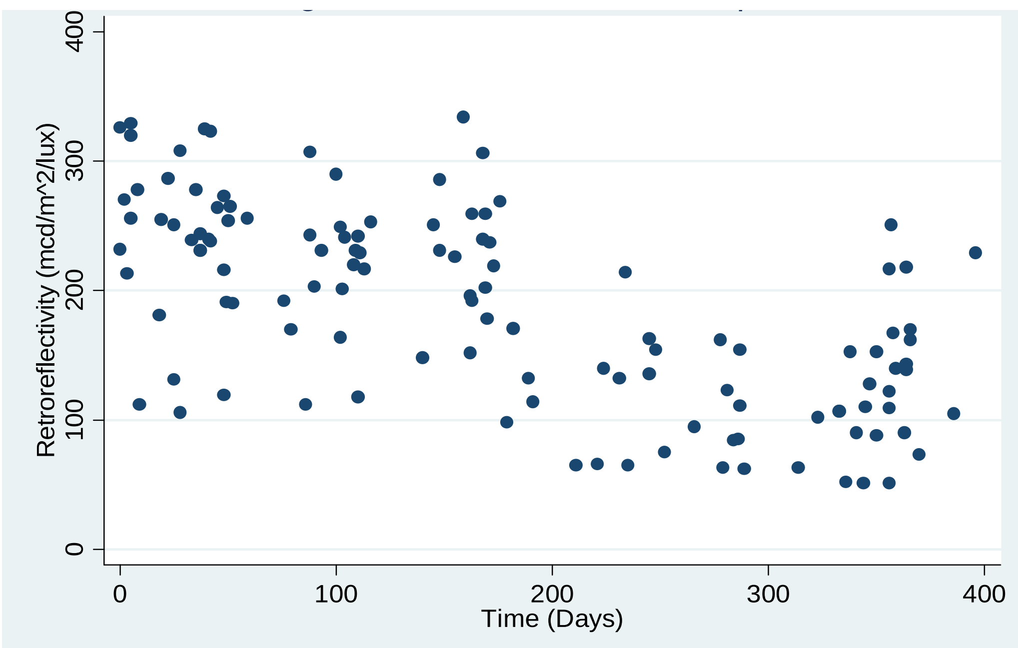

Figure B.2. Pavement Marking Degradation Plot for White Skip Lines.

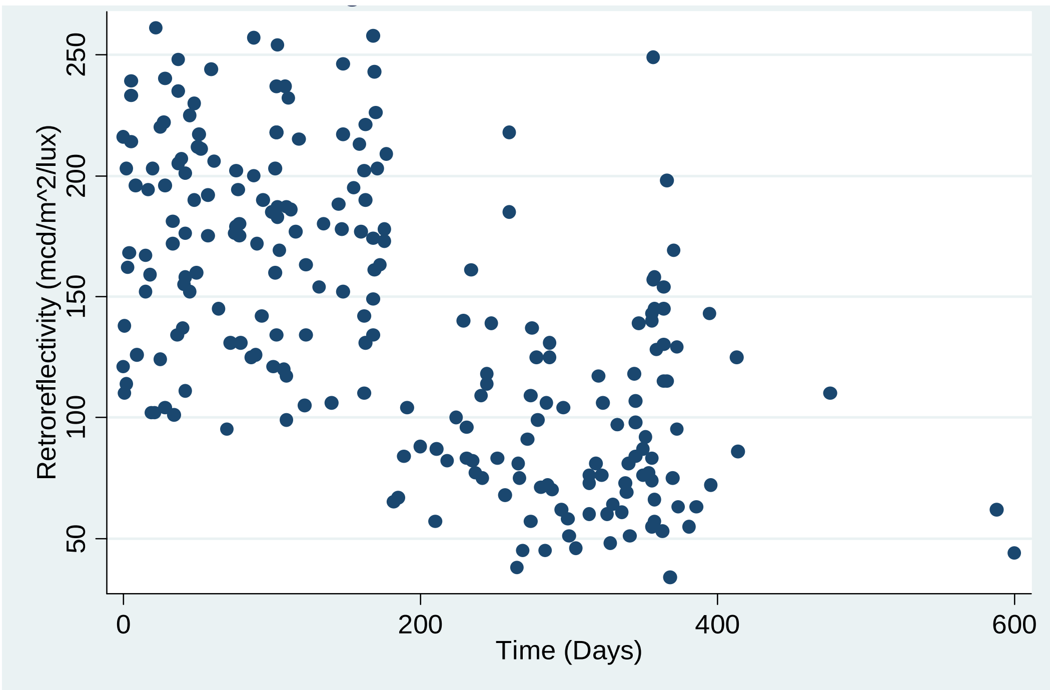

Figure B.3. Pavement Marking Degradation Plot for Yellow Markings.

APPENDIX C

PAVEMENT MARKING DEGRADATION PLOTS FOR WATERBORNE PAINTS APPLIED ON MFC D and E ROADWAYS

(based on 2002 NTPEP paint formulation)

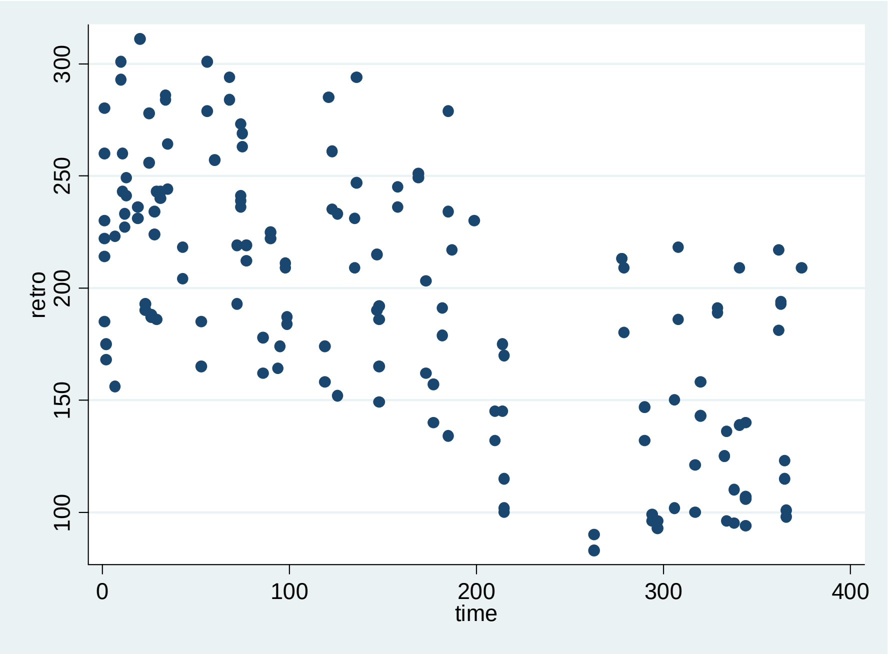

Figure C.1. White Pavement Marking Degradation Plot.

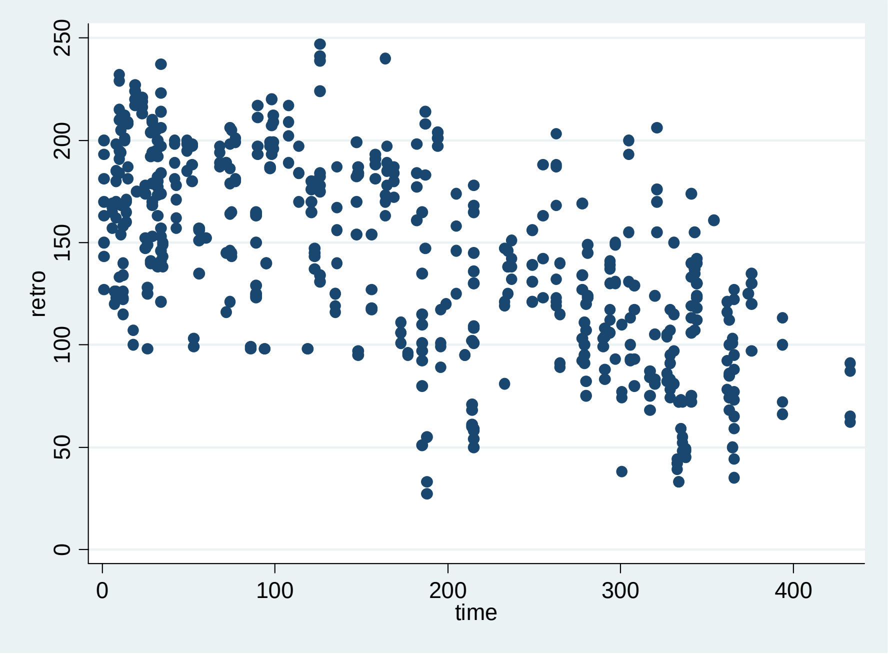

Figure C.2. Yellow Pavement Marking Degradation Plot.

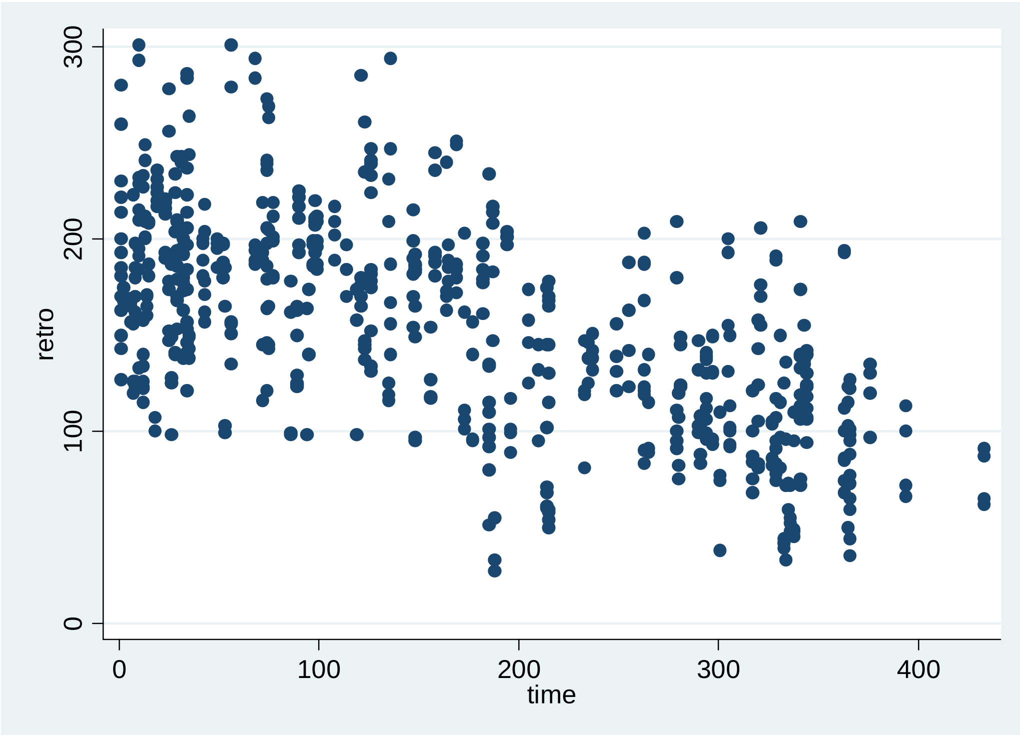

Figure C.3. Asphalt Pavement Marking Degradation Plot.

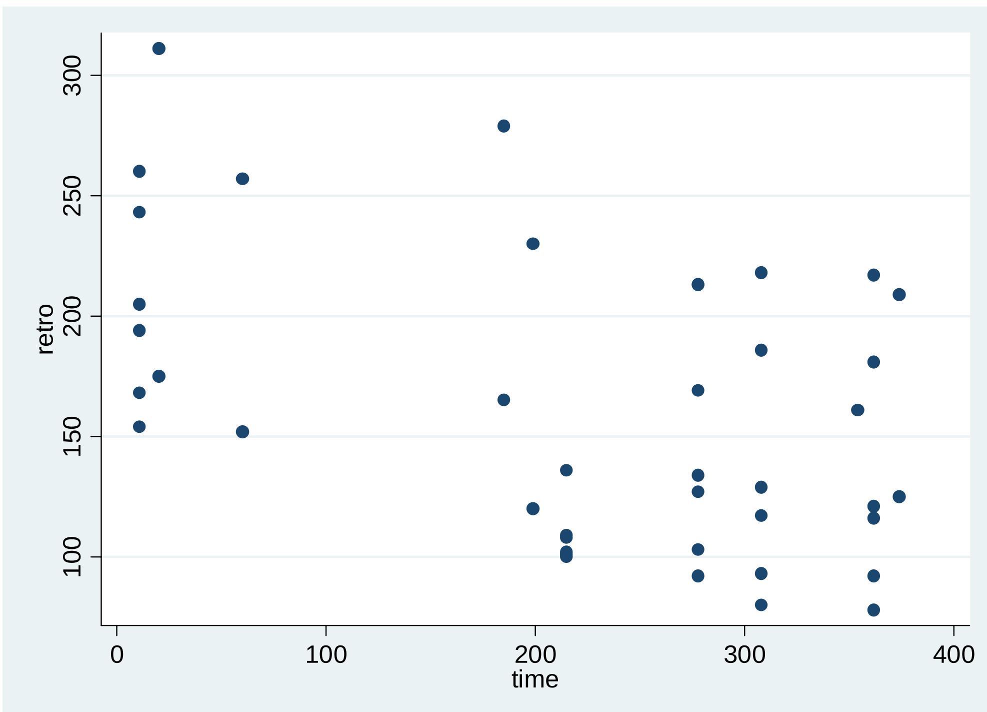

Figure C.4. Concrete Pavement Marking Degradation Plot.

APPENDIX D
PAVEMENT MARKING DEGRADATION PLOTS FOR WATERBORNE PAINTS APPLIED ON MFC D and E ROADWAYS
(based on 2005 NTPEP paint formulation)

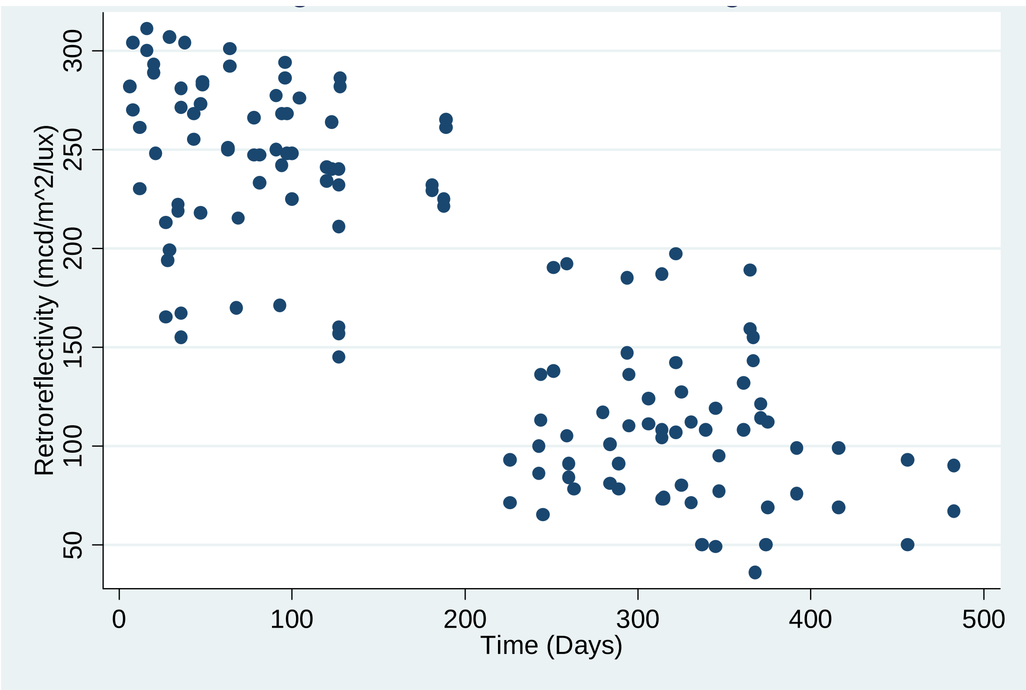

Figure D.1. White Pavement Marking Degradation Plot.

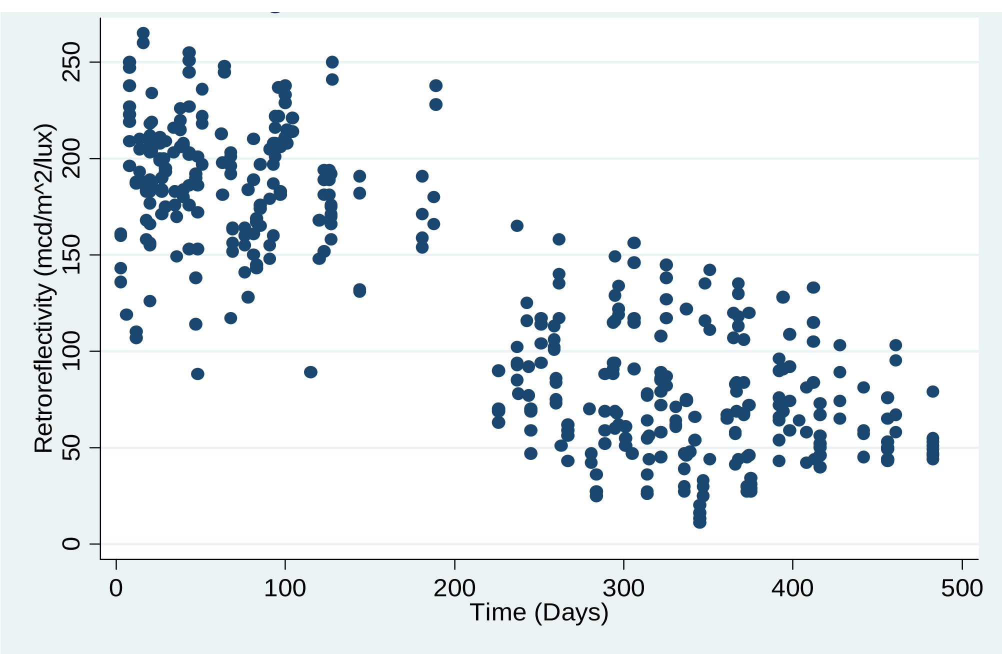

Figure D.2. Yellow Pavement Marking Degradation Plot.