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SEMI-PARAMETRIC MODELING OF PAVEMENT MARKING VISIBILITY DEGRADATION

A Thesis in

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by

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ABSTRACT

The core objective of this research is to provide a methodology for obtaining guidance based on empirical evidences on pavement marking replacement times. This dissertation investigates the degradation process of pavement marking visibility over time in the United States using semi-parametric family of duration models. Specifically, a methodological framework to analyze typical pavement making visibility inspection data was formulated. The National Transportation Product Evaluation Program datasets pertaining to water based paints from a total of nine testing locations in the states of Alabama, Pennsylvania, Mississippi, Minnesota, Texas, and Wisconsin were used for the purpose of this investigation. From a methodological standpoint this research suggests that mid-point imputation is reasonable to approximate interval level failure data. Furthermore, the elapsed time model seemed to exploit the empirical pattern of event dependence among multiple marking samples on an experimental deck better than the gap-time model. This suggests that event dependence exists and degradation of the pavement marking visibility is more simultaneous than sequential.

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Chapter 1

Introduction

Motivation for this research

Quality management pioneers, such as Deming, Juran, Crosby, Feigenbaum and Ishika have emphasized various quality management principles [**1**]. After undergoing many conceptualizations of quality principles, the Balridge criteria for excellent quality performance provided by the National Institute of Standards and Technology (NIST) resulted in seven categories in which the core values and quality concepts are embodied [**1**, **2**]. They are: leadership, strategic planning, customer and market focus, measurement analysis-knowledge management, workforce focus, process management, and business results. Though quality-based approaches and methodologies are well embraced by the private sector, quality management continues to progress in the public sector, particularly in transportation agencies [**1**, **3**-**7**]. The transportation sector has implemented a continuous improvement strategy, where the philosophy is that there is always room for organizational improvement [**1**]. In addition, key strategic priorities are set for different dimensions of quality, such as learning and growth, business processes, customer service and financial progression. As the transportation sector is moving towards a quality approach in various facets of administration, design, construction, and maintenance, this research attempts to contribute to that movement through a data-driven focus on quality approaches in infrastructure maintenance and asset management of highway facilities.

This research falls under the measurement-analysis-knowledge management category and fact-based decisions, which address one of the seven Balridge-NIST criteria. Specifically, the research contributes to the development of a data-driven information system for cost-effective and efficient decision-making processes in roadway pavement marking management.

Roadway Pavement Markings in the United States—A Status Quo

The Manual on Uniform Traffic Control Devices (MUTCD) for Streets and Highways [**8**], developed under the auspices of the Federal Highway Administration (FHWA), provides guidance on the use of pavement markings in the United States. It states that roadway delineation through pavement markings is one of the important ways to provide positive driver guidance, particularly for nighttime driving. This assumes the provision of a consistent and reliable standard for pavement marking visibility. Visibility is measured by retroreflectivity which is the material property that redirects light back in the direction of its source. More precisely, according to current pavement marking visibility standards, retroreflectivity is defined as the amount of light traveling in the direction of the source when viewed from 30 meters at an entrance angle of 88.76° and an observation angle of 1.05° [**9**] (Figure **1-1**). In an effort to provide consistent visibility, the U.S. Congress has mandated that the FHWA establish minimum levels for pavement marking retroreflectivity [**10**]. While research efforts are being pursed to address this issue, state transportation agencies are incurring millions of dollars of expenses installing and maintaining road markings. In 1993, the annual expenditure for maintaining pavement marking programs for nearly 795,000 miles of U.S. roadways was estimated to be approximately $ 353 million [**16**]. In 2000, the annual expenditure in 50 states in the United States and 13 Canadian provinces and territories was estimated to be about $1.5 billion for maintaining a total of 3.8 million centerline miles of roadway [**11**].

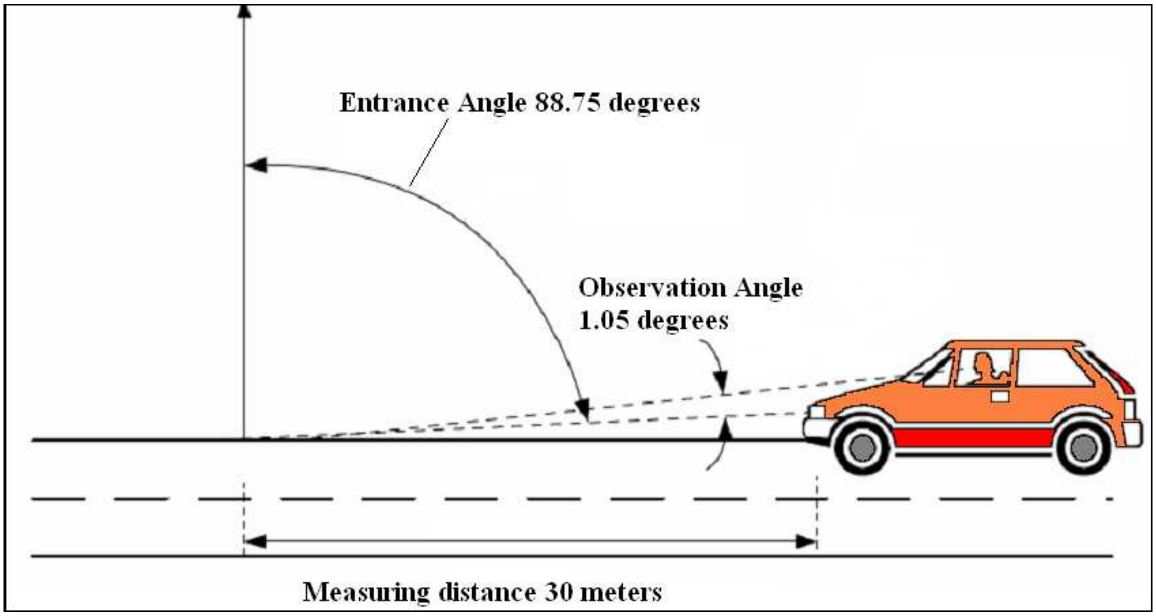


Figure **1-1**: Current standard parameters for measuring pavement marking visibility [**9**]

Currently, there are many types of pavement marking materials used for roadway delineation by various highway agencies across the United States, ranging from $0.05 to $ 4 per linear foot [**11**, **12, 14, 16**]. A literature review and survey of various state practices across the United States suggests that pavement marking practices is inconsistent [**100**]. It is, however, evident that some state agencies have made an effort to develop a structured pavement marking management process (Figure **1-2**) [**100**].

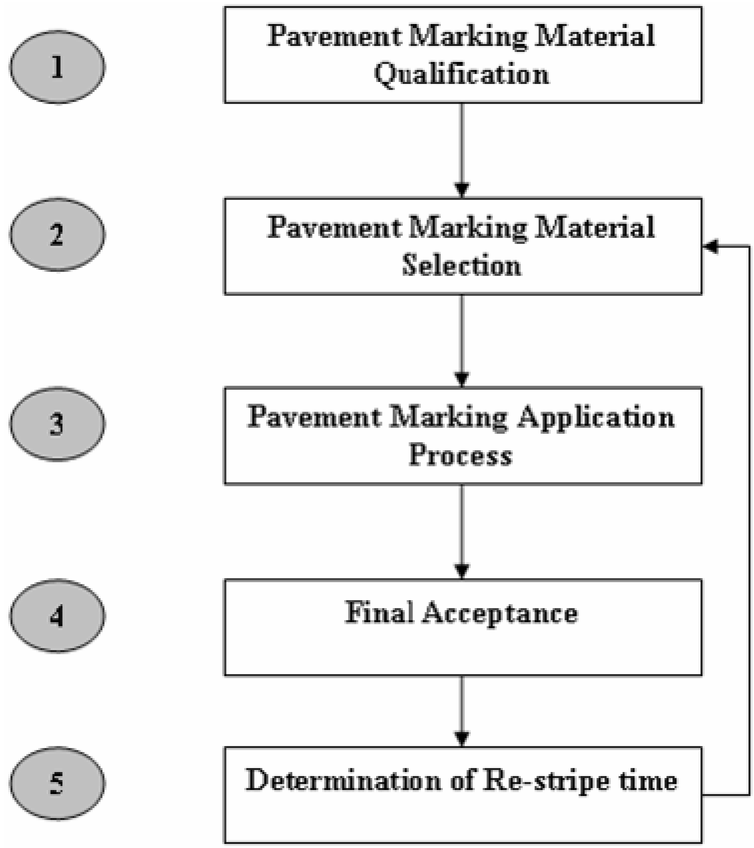


Figure **1-2**: General Pavement Marking Practice in the United States.

Typically, commercially available products are tested using standard material laboratory tests, and a qualified product list is developed (step 1 in Figure **1-2**). Next, markings are selected from the products available in the qualified product list for installation purposes (step 2 in Figure **1-2**). Then, the selected product is installed on the roadway by private contractors or state agency maintenance forces according to the specifications provided by the agency (step 3 in Figure **1-2**). Subsequently, the installation is examined for quality purposes and specification correctness by state agencies during the installation and quality assurance period (step 4 in Figure **1-2**). Steps 1-4 are repeated at every occasion when the pavement marking is re-striped. However, the justification when the re-striping should be done is not clear in the current practice (step 5 in Figure **1-2**). The central focus of this research is to develop a framework so that guidance on re-stripe time based on empirical evidences could be provided.

The replacement schedule for pavement markings is often a function of traffic, climatic conditions, remaining useful life of the pavement, available funds, blanket replacement, subjective visual inspection, subjective durability ratings, or manufacturers' durability recommendations. Some states do use quantitative measures such as benefit-cost ratios, traffic accidents, and/or visibility in their decision making process for pavement marking maintenance [**27 , 101**]. Appendix presents a sample of pavement marking selection matrices that are currently used by various state agencies. Although some maintenance strategies are identified, the maintenance practice adopted by state agencies is not integrated and consistent and often consists of heuristics [**13**, **27**]. An integrated and consistent decision making process could provide cost-effective improvement in pavement marking management. To strike a balance between available resources, system performance, cost, and the promotion of consistent practice, a management system that can integrate all of the aforementioned information is required. While efforts are currently underway to create such a management system [**13**], this research is essential to build a management system.

Since the main component of an effective pavement marking management system is service life prediction, it is imperative that accurate models of pavement marking degradation be developed. Further, such models should be portable across states from the standpoint of simplicity in data collection, model updating, and implementation. Combined, the two characteristics of this research approach enhance the development of a “belief” system among state agencies that quantitative methods such as the one proposed herein, may be beneficial both in the short and long term.

The core idea of this research is to focus on making decisions to replace pavement markings based on the likely end of their useful lives. This motivation steers to address the following two main factors:

1. not replacing the marking long after the expiration of the useful life, and
2. not replacing the markings when there is remaining useful life.

Since pavement markings are associated with lane guidance for drivers, the first scenario could create traffic safety concerns because of exposing drivers to roadway environments where pavement markings are no longer visible. The second scenario might result in inefficient use of transportation agency resources, unnecessary exposure of the work crew in the traffic environment, and undue increases in traffic delay due to constraints imposed on normal traffic flow for installation purposes. Either way, the replacement decision of the pavement marking not based on likely end of its useful life would incur unnecessary expenses and might result in inefficient management for the agencies.

Several researchers have attempted to understand and model the degradation of pavement marking visibility over time [**15-31**] (see Table **1-1**). Many have studied the degradation of actual longitudinal lines; however, relatively few have used the National Transportation Product Evaluation Program (NTPEP) data. No explicit criticism of the data is available. On the contrary, the data provide for geographically diverse site locations, pavement types, material types, and varying geo-climatic zones. Furthermore, due to the recent changes in the visibility measurement standards [**9**], the results of some previous studies are no longer reliable because past retroreflectivity measurements were not recorded to the standard specifications of the current retroreflectometers.

From a methodological standpoint, nearly all previous pavement marking degradation evaluations have used the ordinary least squares (OLS) regression model (Table **1-1**) to estimate the time when the marking would reach a given threshold retroreflectivity or visibility value [**15-25**, **27**, **28**]. Some have used trend analysis [**29**, **30**]. Various studies have considered the effects of traffic, marking material type, initial retroreflectivity value, and line configuration (centerline, edgeline, skipline) as a part of the model. Zhang and Wu [**26**] explained the need for adopting more rigorous modeling techniques and illustrated the use of time series models to understand the service life of pavement markings. Chapter 2 presents details on these studies.

Overall, many studies have addressed the objective of modeling pavement marking visibility degradation. However, their results vary widely. This could be attributed to a multitude of reasons including updates in visibility measuring instrument standards, evolution of marking material chemistry, inconsistent state practices, limited consideration of explanatory variables in the modeling, modeling methodology used, and time and space effects.

Table **1-1**: Previous studies in pavement marking service life modeling

Author	State	Retroreflectometer		Degradation		Modeling method	
		30-meter (current standard)	Others	Actual longitudinal line	NTPEP** style	OLS*	Others
Lu 1995	Alaska		X	X		X	
Andrady 1997	Alabama and Pennsylvania		X		X	X	
Scheuer et al., 1997	Michigan		X	X		X	
Perrin Jr et al., 1997	Utah		X	X		X	
Lee et al., 1999	Michigan		X	X		X	
Migletz et al., 2000	FHWA study (19 US states)	X		X		X	
Abboud and Bowman 2001	Alabama		X	X		X	
Lindly et al., 2003	Alabama	X		X		X	
Sarasua et al., 2003	South Carolina	X		X		X	
Kopf 2004	Washington	X		X		X	
Zhang and Wu 2004	Mississippi	X			X		Time series models
Liu 2006	Utah	X		X		X	
Bahar et al., 2006	California	X			X	X	
Lagergren et al., 2006	Washington	X		X			Trend analysis
Long et al., 2006	Michigan	X		X			Trend analysis
Vasudevan and Kaseko 2006	Nevada	X			X***		Spearmans's rank correlation
* Ordinary Least Squares							
** National Transportation Product Evaluation Program data							
*** Local Experimental test adopting NTPEP style							

Research Inquiry

Based on the aforementioned gaps identified in the current pavement marking management research, there is a need to better understand the degradation process of pavement markings. This research proposes to understand the degradation of pavement markings using duration models and to motivate pavement marking maintenance decisions on the basis of quantitative reasoning. As such, this research aims to contribute to the existing state of the knowledge in pavement marking management by providing:

1. an empirical basis for making pavement marking maintenance decisions such as inspection and replacement timing, as opposed to subjective judgments and fixed cycle replacement and other heuristic approaches,

2. a methodology for comparing durability performance of different pavement marking materials,
3. a method to utilize typical pavement marking visibility data collected by state transportation agencies,
4. an exposition of duration models using pavement marking visibility inspection data, and
5. a motivation to use duration models, which have been under utilized in the field of transportation engineering, where infrastructure degradation, failure, and rehabilitation are emerging as significant issues in the overall infrastructure asset management area.

Chapter 2

Literature Review

Introduction

The Manual on Uniform Control Devices (MUTCD) for Streets and Highways presents guidance on the use of pavement markings on U.S. highways [**8**]. However, there is currently no guidance on the minimum visibility threshold to be maintained for longitudinal pavement markings. Nevertheless, it is recognized that roadway delineation through pavement markings is one of the important ways for providing positive driver guidance [**8**]. Presently, there are many types of pavement markings that are used for roadway delineation by various highway agencies across the U.S. The material chemistry of pavement marking materials has undergone a remarkable development since its conception, and is improving as we proceed in advancing the efficiency and the safety of our transportation systems. Because of this evolution, it is not unusual to see diversity in practice and usage of different pavement marking materials across states. The main objective of this literature review is to synthesize previous studies that focused on determining the service life and cost effectiveness of pavement markings in the U.S.

Cost of Pavement Markings

As noted previously, pavement marking installation and maintenance efforts produces more than a billion dollars in monetary expenses annually [**11**]. There are many marking materials available for the same purpose of providing longitudinal delineation on roadways. Among various available pavement marking materials, water borne paints, thermoplastics, epoxies and tapes are used most commonly [**11**]. In general, pavement markings are classified in-terms of durable and non-durable materials. Though the classification of marking materials is not formalized, paints are classified as non-durable markings while others that last more than a year or two are called durable materials (e.g. methyl meta acrylate, tapes, thermoplastics). Markings can also be categorized into four different styles based on their application techniques. They are: flat, inlaid, profiled, and patterned markings installed by melt, excursion or spray procedures (see Table **2-1)**. Not all styles and application techniques are used with all materials. Nevertheless, a variety of marking materials and application options are currently available for providing pavement markings for different costs. Therefore, the overall cost associated with different pavement marking materials are very likely to fluctuate depending on the preferred materials and the chosen application techniques by transportation agencies. Moreover, the evolution of material chemistry of the markings and their resultant product performance further compounds cost inconsistency. This is because the recommended product installation procedures, usage, and performance might be different based on the nature of the material used. Consequently, the cost per linear foot of marking installation, and material cost could vary accordingly. Furthermore, the uncertainty involved in determining the service life of the markings produces difficulties in assessing life-cycle costs. Therefore, finding a cost effective pavement marking material can be challenging.

Table **2-1**: Typical Type of Pavement Markings

1. Traffic paints
    a. Water based
    b. Solvent based (e.g. alkyds, hydrocarbons, chlorinated-polyolefin etc…)
2. Thermoplastics (preformed, melt, sprayed and extruded)
    a. Flat
    b. Profiled
    c. Inlaid
3. Tapes (preformed, and melt excursion)
    a. Flat
    b. Profiled
    c. Inlaid
    d. Patterned
4. Multi-component field reacted materials (i.e. it involves chemical mixing/reaction at the site before application)
    a. Epoxy
    b. Polyester
    c. Methyl-meta acrylate
    d. Modified Urethane
    e. Polyurea
5. Cold Plastics (sprayed and extruded)
    a. Flat
    b. Profiled
    c. Patterned
6. Raised pavement markers
    a. Ceramic buttons (non-retroreflective)
    b. Raised pavement markers (retroreflective)
    c. Snowplowable raised pavement markers (retroreflective)
    d. Recessed raised pavement markers (both b and c can be used)
    e. Temporary raised pavement markers
7. Glass beads (Type I, II and III. This is rated based on the bead gradation/size I (small) → III (large))
    a. Drop-on
    b. Premixed
8. White cementasious material
9. Others

According to Cuelho et al [**103**], pavement marking costs are determined by the cost of materials, equipment, time required for installation, the volume of markings, and whether or not the markings are installed by a private firm or public agency. In general, the overall cost effectiveness of a pavement marking material is associated with the material cost, installation and mobilization cost, maintenance cost, road user cost, and life cycle cost.

Material, installation and mobilization costs are usually merged and expressed in dollars per linear foot ($/Lft). Road user cost is a measure of delay incurred (in vehicle-hours) as a result of pavement marking installation. Converting vehicle-hours into appropriate cost figures will provide an estimate of road user cost. Nevertheless, obtaining accurate estimates of road user cost is difficult. Maintenance cost includes discrete costs associated with pavement marking maintenance similar to patch work in the case of pavement maintenance. Usually, a small contract job where the cost is spread over limited miles involves more expenses than marking longer sections of roadway. This is because small contracts are likely to have substantial amounts of equipment and crew idle time [**12**].

Table **2-2** presents the descriptive statistics on the cost information of some common pavement markings that are currently used for longitudinal delineation purposes in the U.S. [**100**]. From the cost details gathered, it appears that the average cost for installing one foot of solvent borne paint is the cheapest (US$ 0.05) followed by water borne paints (US$ 0.06) (see Table **2-2**). However, solvent borne paints are seldom considered because of Environmental Protection Agency (EPA) stipulations on toxic materials of the solvent used [**16**]. Inlayed methyl-meta acrylate (MMA) is the costliest material among the others with an average cost of US$ 4.00 per linear foot of installation.

This high cost could be attributed to the installation process. For inlayed installations, the pavement is required to be recessed before the application of the marking materials. In general, the installation procedures for inlayed and profiled markings are quite involved and consequently a higher installation cost is incurred compared to other installation methods. White cementasious material (WCM), profiled tapes, and cold plastic markings are other expensive materials with an average cost of US$ 3.51, 2.23, and 2.21 per foot of installation, respectively.

Table **2-2**: Summary of Pavement Marking Material Cost U.S.$ per Linear Foot[1]

Materials	**Min**	**Max**	**Median**	**Mean**	**Sample Size**
Solvent based paints	0.02	0.15	0.05	0.05	11
Water based 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-MMA	0.25	1.53	0.85	0.86	6
Profiled-MMA	1.12	1.75	1.44	1.44	2
Flat-tape	0.12	2.65	1.65	1.67	14
Cold plastic	2.12	2.12	2.12	2.12	1
Profiled-Tape	1.50	3.10	2.10	2.23	3
White cementasious material (WCM)	3.51	3.51	3.51	3.51	1
Inlayed-MMA	4.00	4.00	4.00	4.00	1

1 The cost values provided in this table is a summary of cost information presented in detail in reference [**100**]. The report year ranges from 1997 to 2002. The cost values should be interpreted with caution.

Determinants of Pavement Marking Service Life

According to the FHWA Roadway Delineation 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*" [**14**]. Based on this definition, the components that are involved in identifying the useful lifetime are marking material presence, color, and visibility. Theoretically, anything that affects these three components (color, visibility and material presence) could directly influence the useful lifetime of the pavement marking material. Visibility (or retroreflectivity) is considered as a primary component in assessing the useful life of pavement markings in this research. Thus, the useful lifetime[1] of pavement markings in this research is defined as the time until the visibility level of the marking falls below a threshold value.

Various studies [**34-43**] have suggested a threshold level for pavement marking visibility based on driver judgment, preference, and cost and longevity of the markings. The suggested values fall between 70-180 mcd/m^2/lux. Some state agencies adopt thresholds values of 100, 120, 125, and 150 [**44**, **100**, **101**] to justify replacement of pavement markings. However, most of the studies used retroreflectometers that are not up to the current standard for pavement marking visibility measurements in determining the threshold value. A more recent study conducted by Debaillon et al recommended minimum levels of pavement marking visibility based on results from a model known as

[1] Service life and useful lifetime has the same definition and are used interchangeably in this document.

Target Visibility Predictor (TARVIP) **[112]**. The TARVIP provides estimates of minimum visibility values based on Computer Aided Pavement Making visibility Evaluator (CARVE) originally developed by Schnell and Zwahlen **[113]. Table 2-3** presents the recommended visibility levels for pavement marking with and without raised retroreflective pavement markers.

Table **2-3**: Recommended minimum pavement marking visibility levels **[112]**

Pavement Marking specification	Without raised retroreflective pavement markers (RRPM)			with RRPM
	≤ 50 mph	55-65 mph	≥ 70 mph	
With Edgeline (Both White and Yellow)	40	60	90	40
Yellow centerline only	90	250	570	50

Weather and climatic conditions dictate the mobility of the traffic stream, and also affect the useful life of pavement markings [**22**, **44**, **45**]. Cottrell [**45**] assessed the impact of snow-removal activities on the durability of paint, thermoplastics, and waffle tapes. The study recommended the use of inlaid markings ascertaining the importance of the thickness of the marking material. This is because thicker markings are susceptible to more abrasion by snowplow blades.

Traffic volume and composition are considered important variables to assess the useful life of pavement markings [**14**, **19**]. This is because higher traffic volumes can increase the rate of pavement marking degradation by increased vehicle-tire abrasion if vehicles pass over the markings. 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 [**44**].

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 as a surrogate measure 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 [**22**, **23, 46**]. 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 essentially contributes to the retroreflectivity level of a pavement marking. Thus, quantifying glass bead retention capability of marking types over time could provide a better understanding of the service life of pavement markings [**47**]. Glass beads used for the purpose of pavement marking retroreflectivity can be classified based on bead application and manufacturing properties [**44**]. Application properties include quantity of beads and 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 can influence embedment depth and hence the measured retroreflectivity [**44**]. Moisture proof and adhesive coatings are the two bead coatings that currently used. However, the extent to which these beads would affect the visibility is not known.

As detailed above, many factors can influence the useful lifetime or the service life of pavement markings after installation on the roadway. In addition to the challenge of developing empirical prediction of service life of pavement markings, inclusion of all the aforementioned variables in the model requires an enormous data collection effort over time and space.

Previous Research on Pavement Marking Service Life Modeling

Most research efforts to model pavement marking service life have been to establish pavement marking service life as a function of its retroreflectivity. Table **2-4** at the end of this chapter presents the highlights of various studies that attempted to model pavement marking service life.   Lu [**15**] conducted a study to evaluate pavement making materials that are typically used in states with heavy snowfall and snow plowing activities, including Alaska, Oregon, Washington and Idaho. Durable pavement marking materials are commonly used to provide roadway delineation in snow-belt regions. The types of pavement marking materials included in the study were thermoplastics, preformed tapes, traffic paints (unknown whether it is water or solvent based paints), and MMA. The study included a four-year assessment to judge the performance of the pavement marking material based on retroreflectivity measures using a 12 meter geometry retroreflectometer. The retroreflectivity performance evaluation of traffic markings used an exponential decay functional form to model the degradation of retroreflectivity (see Figure **2-1**). The objective evaluation concluded the following:

- Service life of all marking analyzed ranged between 4 and 12 months with traffic paints on the lower end of the estimated service life range.
- MMA is more suitable for Alaskan climatic conditions as it can be installed in the field at a temperature as low as –1 °C (30 °F) while others require more moderate temperatures. Therefore, MMA when compared to others studied was concluded as a suitable pavement marking material in cold regions.

The Alaska Department of Transportation and Public Facilities placed two test decks on a four lane divided asphalt paved highway using the guidelines prescribed in ASTM D-713 to evaluate the longevity of several durable pavement marking materials [**33**]. Preformed thermoplastics, preformed tapes, MMA, and traffic paint (unknown solvent) as a control were included in the testing. The test stripes were 4-inch transverse lines running across the traveled way. Retroreflectivity measurements were observed by using a LTL 2000 retroreflectometer (30 meter geometry) positioned parallel to the stripe including wheel path and non-wheel path locations. Though no modeling was done, the study established empirical recommendations and concluded that the MMA, thermoplastics and preformed pavement-markings are superior to paints in terms of durability. Paints were recommended on concrete pavements in rural and urban areas when the annual average daily traffic (AADT) is less than 2000, and mostly MMA markings were recommended beyond AADT levels 2000. For asphalt and other pavements that require frequent patching work, paints were recommended for all traffic levels.

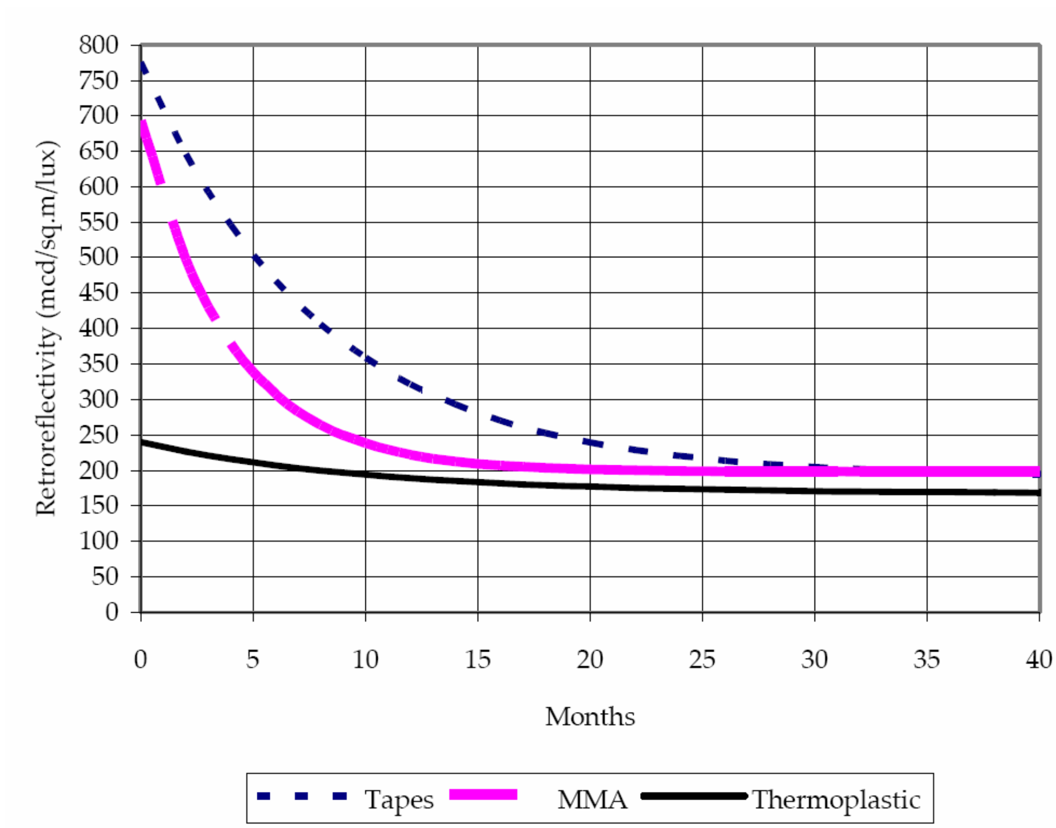


Figure **2-1**: Pavement marking visibility degradation curves (redrawn using model equations developed by Lu [15]

Andrady [**16**] analyzed retroreflectivity data measured using a 12 meter geometry retroreflectometer from the Southeastern and Northeastern Association of State Highway and Transportation Officials Regional Testing Program. An empirical equation between retroreflectivity and log of months fit the data well ($R^2 > 0.82$) (see Table **2-4** for model equation). However, the study showed that the deterioration of transverse stripes at test deck locations in Alabama and Pennsylvania was accelerated and may not necessarily represent the actual deterioration of the longitudinal markings.

Perrin et al., [**18**] evaluated the performance of solvent-based paint, epoxy, and preformed tape on Portland cement concrete (PCC) and asphalt concrete (AC) freeways and arterials in Salt Lake, UT. Except for preformed tape on PCC the results compared favorably to those obtained by Dale [**32**]. Data regarding marking types, location and date of application, initial and observed retroreflectivity, pavement type, highway lane geometry, and AADT levels were collected and corroborated to form an equation to determine the useful lifetime of the pavement marking material (see Table **2-3** for model equation). The study generally concluded that:

- epoxy paints had an improved useful life of between 18 percent and 45 percent over paint on PCC pavement types.
- paints and epoxy produced similar useful life ranges on AC pavements,
- preformed tape on AC pavement had a maximum useful life ranging from six to ten years, which is about 150 to 350 percent longer useful life on AC pavement than both paint and epoxy for a given AADT,
- in terms of material type longevity on pavement types, epoxy lasts 100 to 120 percent longer on PCC than on AC pavements; paints last about 40 to 80 percent longer on PCC than on AC, and,

- Though the goodness-of-fit measure was low, the study supports that a hyperbolic relationship between AADT and the useful life is a better representation than a linear fit.

Scheuer et al., [**17**] developed retroreflectivity degradation curves over time by evaluating the performance of longitudinal lines in Michigan (see Table **2-4** for model equation). However, their study indicated no statistically significant relationship between retroreflectivity levels, and the independent variables (material and pavement types) considered. Snow plowing and sanding were suspected to have adverse effects on the decay of retroreflectivity.

Lee et al., [**19**] conducted a four-year evaluation of longitudinal pavement markings at 50 sites in Michigan that were comprised of Interstates and state truck routes. The objective of the study was intended to develop guidelines for the most cost-effective pavement marking material, and to investigate the relationship between retroreflectivity and nighttime crashes. The AADT ranged from 1400 to 45000 vehicle per day, percentage commercial vehicles ranged from 1 to 14 percent of the daily traffic; speed limits were between 35 and 70 mph; and, the annual average snowfall ranged from 50 to more than 100 inches. The evaluation included the following four types of pavement marking materials: water borne paints, polyester paints, thermoplastic materials, and performed tapes. Retroreflectivity measures obtained from a Mirolux 15 meter geometry retroreflectometer and a subjective durability rating were used as the performance measures to judge the effectiveness among the various material types included in the study. The analysis indicated that the retroreflectivity and traffic variables (AADT, speed limit, and commercial traffic percentage) were not correlated. Though the comparisons were not statistically significant, the study concluded that water-based paints are most cost-effective because they retain good retroreflectivity, have reasonable durability (80%), have a longer average time to failure and are less costly (0.05 US$/foot). The study also concluded that the percentage loss in retroreflectivity per day was 0.14% for all materials studied. Linear regression models were developed to depict the retroreflectivity degradation over time (see Table **2-3** for model equation). The study, however, highlighted that snowplowing and deicing activity appears to be a major contributing factor for retroreflectivity decay similar to Scheuer et al.,[**17**]. Figure **2-2** represents the retroreflectivity degradation models for water borne paints developed by Lee et al., [**19**], Perrin et al., [**18**], and Scheuer et al.,[**17**]. The x-axis represents the age (in months) and the left hand side y-axis represents retroreflectivity values for Lee, et al and Scheuer, et al study, and the right-hand side y-axis is for the Perrin, et al. study. If 100 mcd/sq.m/lux were assumed as a minimum threshold for re-stripe then the service life of water borne paints from the models (Lee, et al and Scheuer, et al) would range from 12-15 months. For Perrin, et al., the exponential decay model becomes asymptotic at approximately 112 mcd/sq.m/lux. Figure **2-3** presents the exponential degradation curves for tapes using the model equations developed by Perrin, et al. and Lu.

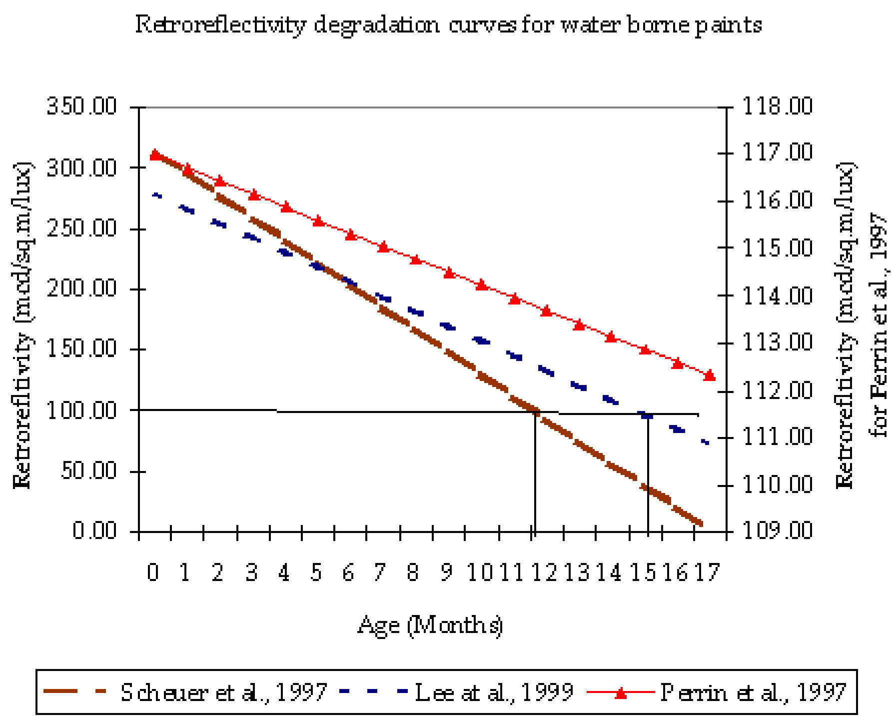


Figure **2-2**: Retroreflectivity degradation models for water based paints (drawn using model equations developed by the authors)

The FHWA conducted a research study to quantify the service life of all weather pavement markings in terms of cumulative traffic passages [**20**, **21**]. The evaluation included 85 study sites in 19 states that had longitudinal pavement marking lines including edgelines, centerlines and skiplines. The pavement marking materials used in the study were epoxy, MMA, flat and profiled polyester, flat and profiled thermoplastics, profiled performed tape, conventional paints, water-based paints and pavement markers including standard and snow-plowable raised retroreflective pavement markers (RPMs). The factors that were considered in the evaluation were type of pavement marking material, traffic volume, color, roadway type, and exposure to ambient weather conditions and snowplow operations. Measurement of retroreflectivity was observed at six-month intervals over a period of four years with a Laserlux 30m mobile retroreflectometer. The evaluation developed more than 100 regression models for determining the expected service life of pavement markings as a function of cumulative traffic passages (CTP) for each site. From the individual models expected service life in CTP was calculated and averaged for all sites with similar characteristics. From the expected service life in CTP (as an average of all the sites SL_{CTP}) an expected service life expressed in elapsed months since the marking installation to the minimum threshold retroreflectivity value was calculated (see Table **2-4** for model equation). The study exhibited large variations across sites from different states, emphasizing the variability in pavement marking performance across space.

Abboud and Bowman [**22**] established cost- and longevity-based criteria for scheduling re-stripe time in the state of Alabama. The criteria contained primarily the application cost, service life and the user cost relative to crashes during the striping lifetime. The pavement marking materials considered in the study were thermoplastics and water based paints. Part of the study focused on corroborated retroreflectivity values (measured using 15 meter geometry retroreflectometer) to traffic exposure, and developed logarithmic models for retroreflectivity degradation as a function of vehicle exposure (see Table **2-3** for model equation). Figure **2-4** presents the relationship between estimated useful lifetime of pavement markings to reach 150 mcd/sq.m/lux with increased traffic exposure.

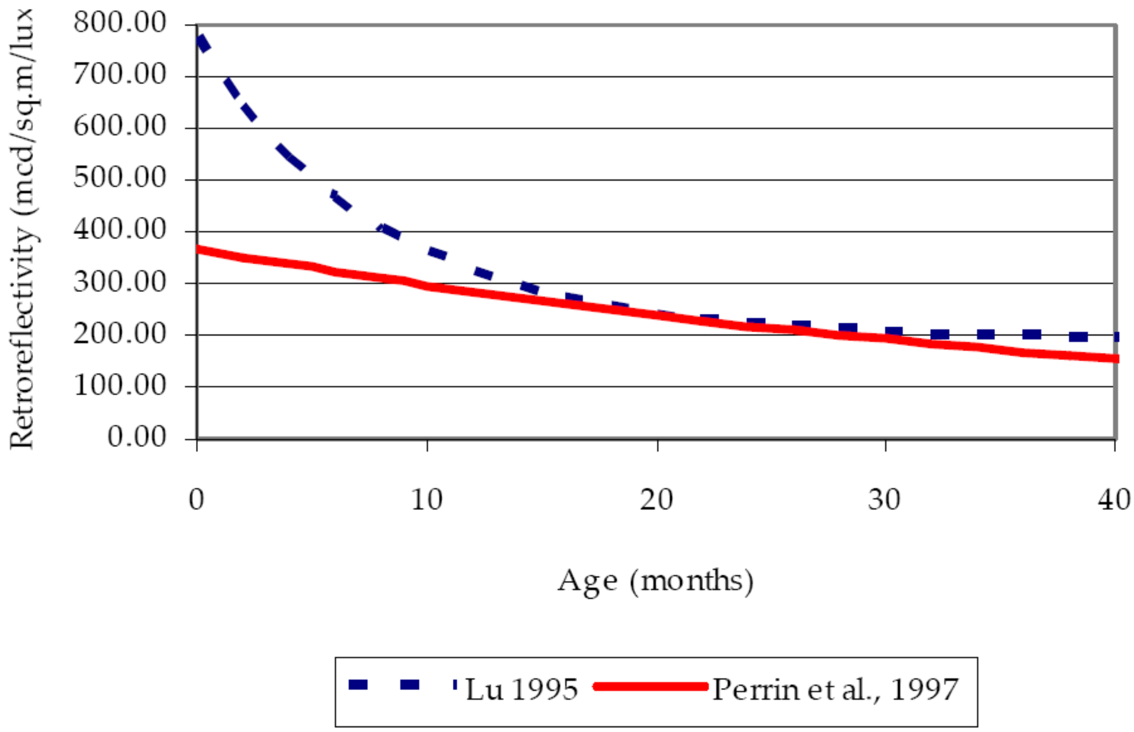


Figure **2-3**: Retroreflectivity degradation models for tapes (drawn using model equations developed by the respective authors)

Lindly and Wijesundera [**23**] evaluated thermoplastics and profiled thermoplastics on Alabama highways [**20**, **21**]. As a part of the evaluation, service life modeling based on retroreflectivity was considered. Retroreflectivity data (using 30 meter geometry retroreflectometer) were gathered from different sites within the state of Alabama with similar pavement markings at approximately six-month intervals over a period of one year. Subsequently, a decay model representing an aggregate degradation for that pavement marking type was developed (see Table **2-4**).

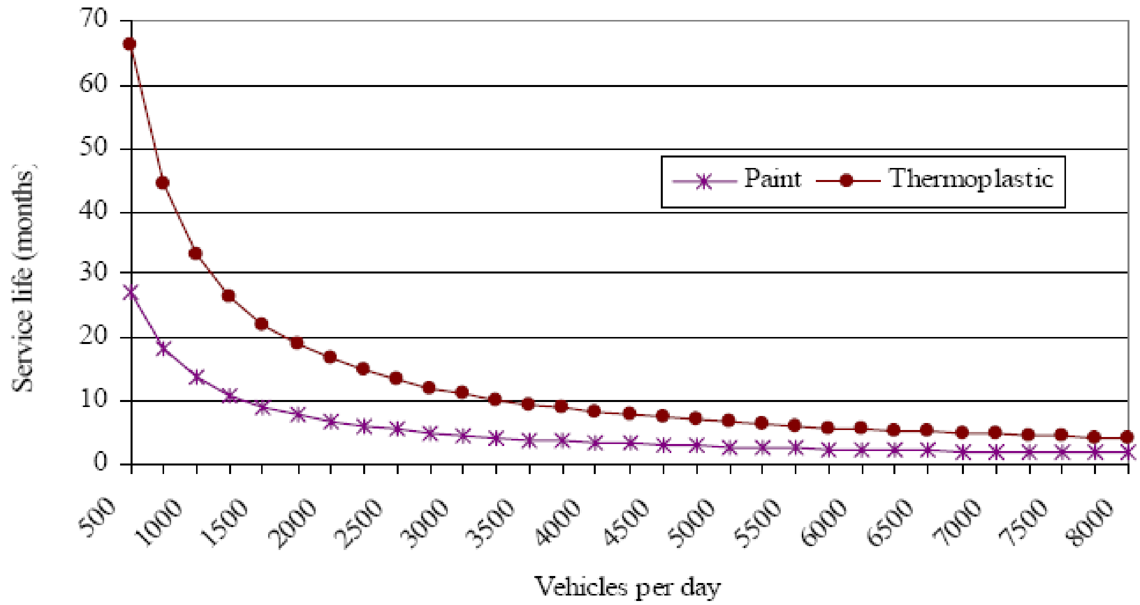


Figure **2-4**: Service life estimates of pavement markings for 150 mcd/sq.m/lux [**22**]

The independent variable (cumulative traffic passage) considered was similar to the FHWA study [**20**, **21**]; however, the modeling approach and the scope were different. FHWA developed site specific models and arrived at an aggregate estimate of the service life, while the Alabama study [**23**] developed an aggregate model based on data across all sites in the state. This implicitly assumes homogenous degradation across space. The scope of the FHWA study was across 19 different states with a variety of pavement marking materials and types of roadways and delineation treatments, while the Alabama study focused on edge lines where the ADT did not exceed 20,000 vehicles per day. Nevertheless, both the models estimated similar service life estimates for profiled thermoplastics markings.

Sarasua et al., [**24**] developed a methodology to estimate the lifecycle of pavement markings located on Interstate highways in South Carolina. The research included epoxy, thermoplastics and tapes on asphalt and Portland cement concrete pavements for the evaluation and modeling. A total of 149 sites were studied for retroreflectivity degradation modeling. The study considered the use of difference and percentage difference from the initial value as the dependent variable in modeling. However, the study implicitly assumed that degradation was essentially homogenous across sites. Sarasua et al., [**24**] included both linear and non-linear modeling techniques based on typical patterns observed in the data set. The non-linear model was used to model the number of days required for the marking to reach a stage of steady (i.e. linear) degradation. This is because the pavement markings exhibited an initial increase in the retroreflectivity measure before waning. This phenomenon was explained by the delayed bead exposure after installation, causing the retroreflectivity to increase initially. The linear model was used for those sites that surpassed the initial waxing and waning trend. Time was selected as the final independent variable for the model after considering traffic volume, temperature, and humidity as independent variables (see Table **2-4** for model equations). 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 models developed was between 20 and 80 percent. Sarasua et al., [**24**] concluded the following:

- Pavement surface type, marking material, and maintenance activities are the most significant factors influencing 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 influential factor in retroreflectivity degradation.

Kopf [**25**] conducted an evaluation in the state of Washington to model service life and determine degradation curves for water borne and solvent paint markings. The study used linear regression to model the marking visibility degradation. However, it was indicated that high variability in the retroreflectivity measures at similar traffic and environmental sites rendered the study to be statistically inconclusive.

Bahar et al., [**27**] conducted a study to find an association between pavement marking visibility and traffic accidents. In the process, retroreflectivity degradation modeling was attempted to associate a retroreflectivity value to the time when the accident occurred. The study utilized the National Transportation Product Evaluation Program's (NTPEP) pavement marking degradation data from various states that measured visibility values using 30 meter geometry retroreflectometers. An inverse polynomial relationship was determined to be a reasonable fit for the marking visibility degradation data (see Table **2-4** for model equations). The parameters were estimated using a non-linear regression analysis.

Liu [**28**] studied the effects of traffic volume on longitudinal water based pavement marking visibility over time in Utah. The study used ordinary least squares regression to estimate the model. It was determined that paints would survive 8-17 months prior to completely wearing out. Lagergren et al [**29**] and Long et al.,[**30**] used trend or graphical analysis to assess pavement marking visibility degradations in Washington and Michigan respectively. Vasudevan and Kaseko [**31**] conducted a local experimentation similar to NTPEP installation style in Nevada to assess alternative test deck installation designs.

Lessons Learned

In summary, there are three important components related to the service life of pavement markings. They are: color, material presence, and visibility. Visibility is considered the most important measure to evaluate the performance of pavement markings. Retroreflectivity is the visibility measure measured using a 30 meter geometry retroreflectometer. It is understood that many factors can influence the degradation of visibility of pavement markings. While there is a general understanding about the key factors such as installation practice, traffic, weather, pavement and color influencing the service life of pavement markings, the combined effects and the degree of influence of each is still not clear. Several studies have attempted to establish a relationship between retroreflectivity and service life through ordinary least squares regression methods. However, the results of those studies appear to vary widely. It appears that the retroreflectivity of pavement marking materials degrade after an initial rise. A non-linear functional form could be used to model the initial rise, and a linear degradation model used thereafter to approximate the degradation of pavement marking visibility. The use of a non-linear functional form for the initial rise and a subsequent linear degradation needs further investigation. Recently, the retroreflectivity degradation of pavement marking was illustrated using auto regressive integrated moving average time series methods.

Currently, many state agencies adopt a minimum visibility threshold value ranging from 100-150 mcd/sq.m/lux. A recent study suggests that a value between 40 and 90 mcd/sq.m/lux for white markings and a value between 40 and 570 mcd/sq.m/lux for yellow markings as the recommended minimum values. While research studies are being conducted for establishing minimum levels of pavement marking visibility, many agencies have developed selection matrices to justify re-stripe times as presented in Appendix. Due to the lack of a proper degradation model for pavement markings, the selection matrices currently adopted by different states agencies are general, inconsistent, and are heuristic in nature. Given the state of knowledge, it is understandable why pavement marking management practices across states is inconsistent. However, it is believed that a uniform management process will be developed in the future as more progressive research that promotes quantitative judgments is conducted. Overall, there exists a need to understand the degradation of pavement marking visibility and to develop accurate service life estimates of pavement markings, which is the major focus of this research. This study used duration modeling techniques to understand the service life of pavement markings. The following chapter presents details on the methodology adopted for conducting this research.

Table **2-4**: Previous Service life modeling efforts

Study	State	Modeling Technique	Field Condition	Pavement marking service life model / general form of the model	Independent variable effects considered in the modeling attempt	Length of study, number of sites and retroreflec tometer
Lu (1995) [15]	Alaska	Regression with exponential functional form	Actual longitudinal lines ranging from 500-1000 feet in length.	$R_{tapes} = 191.4 + 584.3e^{(-0.125*Time)}: R^2 = 0.878$ $R_{MMA} = 198.3 + 494.8e^{(-0.252*Time)}: R^2 = n/a$ $R_{thermoplasics} = 167.5 + 72.3e^{(-0.100*Time)}: R^2 = 0.203$ *Where,* $R_{marking\ materials}$ = *retroreflectivity (mcd/sq.m/lux)* *Time = Age in months*	Time; MMA, thermoplastics, tapes; Interstate; Edgelines.	3 years; N/A; Mirolux-12
Andrady (1997) (NCHRP study) [16]	Alabama and Pennsylvania	Regression with logarithmic functional form	Alabama and Pennsylvania Test deck: Transverse lines	$T_{100} = 10\,(R_0 - 100)/b$ $R^2 > 0.82$ *Where,* R_0 = *Estimate of the initial retroreflectivity value* b = *gradient of the semi-log plot of retroreflectivity* T_{100} = *Duration in months for retroreflectivity to reach a value of 100 units*	Time; Tapes, polyester, paints, thermoplastics, MMA, preformed thermoplastics, epoxy and solvent paints; Color; Traffic volume; Weather conditions.	NTPEP Test deck procedures; Mirolux-12 and Erickson
Scheuer et al., (1997) [17]	Michigan	Linear regression	Actual longitudinal lines	$Y = 265.59 - 0.3824X: R^2 = 0.1877$ *Where,* Y = *retroreflectivity of paints (mcd/sq.m/lux)* X = *Age in days*	Polyester, paints, thermoplastics; Time, Traffic volume; Edgelines, lanelines and centerlines; Color	1-year; N/A; Mirolux-12

Table **2-5**: Previous Service life modeling efforts (continued…)

Perrin Jr et al., (1997) [**18**]	Utah	Regression with exponential functional form	Actual longitudinal lines	$R_{epoxy} = 130e^{(-0.0098*A)}; R^2 = 0.027$ $R_{paints} = 117e^{(-0.0024*A)}; R^2 = 0.005$ $R_{tapes} = 366e^{(-0.0215*A)}; R^2 = 0.5796$ *Where,* $R_{marking\ material}$ = *retroreflectivity (mcd/sq.m/lux)* A = *Age in months* $U = \left(I - M / C * V\right)$ U = *useful life (months)* C = *Calculated deterioration rate [(mcd/sq.m/lx)/month]/(AADT/lane)* M = *Minimum acceptable retroreflectivity (mcd/sq.m/lx)* V = *AADT/Lane* I = *Initial retroreflectivity (mcd/sq.m/lx)*	Epoxy, paints, tapes; Time; Traffic volume; Freeways, arterials, PCC and AC	Laserlux Mobile with substandard geometry
Lee et al, (1999) [**19**]	Michigan	Linear regression	Actual longitudinal lines	$Y = 279.42 - 0.4035X : R^2 = 0.17$ *where* Y = *retroreflectivity of paints (mcd/sq.m/lux)* X = *Age in days*	Polyester, paints, thermoplastics, tapes, Snowfall, Time, Interstate, truck route	3-years and 4-months; 50 sites; Mirolux-12
Migletz et al., 2000 (FHWA study) [**20**]	19 different states in the US	Regression with linear, exponential and power functional forms were considered	Actual longitudinal lines	$SL_{months} = \dfrac{SL_{CTP}}{\left[\dfrac{CTP_{Final}}{Date_{final} - Date_{install}}\right] * \left[\dfrac{36525\ days}{12\ months}\right]}$ *where,* SL_{months} = *Service life in elapsed months* SL_{CTP} = *Service life in CTP (millions of vehicles)* CTP_{Final} = *Cummulative Traffic Passage (millions of vehicles) at final field measurement date* $Date_{Final}$ = *Date of final field measurement* $Date_{Install}$ = *Installation date of pavement marking*	Epoxy, methyl methacrylate, flat and profiled polyester, flat and profiled thermoplastics, profiled performed tape, conventional paints, water-based paints and pavement markers Time, traffic volume, Functional classification of roads, delineation treatment (Edge line, lane lines, color), weather.	4-years; 85 sites; Laserlux mobile

Table **2-6**: Previous Service life modeling efforts (continued…)

Bowman and Abboud (2001) [**22**]	Alabama	Regression with logarithmic functional form	Actual longitudinal lines	$R_{paints} = 26.27 - 19.457 ln(VE) : R^2 = 0.3139$ $R_{thermoplastics} = 639.66 - 70.806 ln(VE) : R^2 =$ *where* $R_{marking\ material}$ = *retroreflectivity (mcd/sq.m/* VE = *Vehicle exposure in thousands of vehicles* = *ADT per lane * age of markings * 30.4/1000* $Service\ life = \frac{K}{ADT_{per\ lane}}$ *where,* *K is calculated based on the degradation model for specific marking material and a minimum threshold for retroreflectivity.*	Paints, thermoplastic, traffic volume, edge lines, white color	15 meter handheld
Lindly and Wijesundera 2003 [**23**]	Alabama	Regression with linear and exponential functional forms	Actual longitudinal lines	$R_{Thermoplastic} = 310 - 311 * CTP_{per\ edgeline} : R^2 = 0.66$ $R_{Thermoplastics} = 329 * e^{-0.16 * CTP_{per\ edgeline}} : R^2 = 0.67$ $R_{Profiled\ Thermoplastic} = 239 - 289 * CTP_{per\ edgeline}$ $: R^2 = 0.53$ $R_{Profiled\ Thermoplastic} = 244 * e^{-0.16 * CTP_{per\ edgeline}}$ $: R^2 = 0.55$ *where* $R_{marking\ material}$ = *retroreflectivity (mcd/sq.m/lux)* $CTP_{per\ edgeline}$ = *Cummulative Traffic Passage* $= \frac{ADT * Age\ of\ marking\ in\ days}{1000000 * Number\ of\ lines}$	Thermoplastic and profiled thermoplastics, traffic volume, time, edgeline, number of lanes, urban and rural areas, presence of street lightings/RPMs, speed limits.	1-year; 40 sites; Lasurlux

Table **2-7**: Previous Service life modeling efforts (continued…)

Sarasua, Clarke, and Davis (2003) [24]	South Carolina	Step wise linear regression, and non-linear regression	Actual longitudinal lines	*Retroreflectivity difference* $= Q + K^{*}(Days)$ *Retroreflectivity percentage difference* $= Q + K^{*}(Days)$ *Retroreflectivity difference* $= Q + K_1^{*}(Days) + K_2^{*}(Days)^2$ *Retroreflectivity percentage difference* $= Q + K_1^{*}(Days) + K_2^{*}(Days)^2$ *Where,* Q, K_1, K_2 *are parameters* *Days = Number of days*	Asphalt and Portland cement concrete pavement types; epoxy, thermoplastics, and tapes; White and Yellow color; Interstate routes; traffic volume, temperature, humidity.	28-month; 149 sites; LTL 2000
Kopf J (2004) [25]	Washington	Regression with linear, exponential and logarithmic functional forms	Actual longitudinal lines	Models were stated to be inconclusive	Water borne and solvent paints; traffic volume; environmental condition	1-year; 80 sites; Laser lux
Zhang and Wu (2004) [26]	Mississippi	Smoothing Spline and Time series	Mississippi Test deck: Transverse lines	A six-month forecasting power was concluded.	Tapes, paints, preformed thermoplastics and thermoplastics; asphalt and concrete pavements; Traffic volume; weather	LTL 2000
Bahar et al (2006) [27]	NCHRP Study	Non-linear regression-Inverse polynomial functional form	NTPEP test decks Alabama, California, Minnesota, Pennsylvania, Mississippi, Texas, Utah, and Wisconsin	$R = \frac{1}{\beta_0 + \beta_1 * Age + \beta_2 * Age^2}$ Where, R – Retroreflectivity Age – Time (months) when the retroreflectivity measurement was made.	Water and solvent based paints, thermoplastics, and epoxy	LTL 2000

Chapter 3

Research Plan

Introduction

The primary objective of this research is to better understand the degradation process of pavement marking visibility over time using duration models, and present a methodology to provide data driven maintenance decisions. In addressing the objective of this research, a three phase methodology is proposed.

1) Database development,
2) Service life modeling, and
3) Life cycle cost analysis

The following sections describe the details involved in the first two phases of this research. Phase 3 involved an economic analysis using the net present value method that is explained along with the analysis results in Chapter 4.

Phase 1: Database Development

As described in Chapter 2, many factors can affect the duration of the useful life of pavement markings which in this study is defined in terms of retroreflectivity. The present study will be constrained within the scope of available data from the National Transportation Product Evaluation Program (NTPEP), administered by the American Association of State Highways and Officials (AASHTO). The NTPEP program is designed to conduct performance evaluations of transportation products. Pavement markings are one of the products tested across various geo-climatic regions as designated by the program. The marking materials include waterbased paints, thermoplastics, epoxies, preformed tapes, Polyurea, methyl-meta acrylate (MMA), cold plastics, poly cement, and polyester. The evaluations are conducted by using accelerated wear test guidelines provided by the ASTM D713 "Standard Practice for Conducting Road Service Tests on Fluid Traffic Marking Materials" [**50**]. As such, different marking materials from participating manufacturers are laid in a transverse pattern in a roadway travel lane (see Figure **3-1**) for testing [**48, 49**]. Specific site requirements for the purpose of NTPEP testing include the following:

- Flat grade,
- No curves or access points or intersections,
- Minimum AADT of 5000 vehicles,
- The road shall be fully exposed to the sun,
- The drainage should be uniform, and
- Test deck should have been opened to traffic for at least one year.

Figure **3-1**: NTPEP Testing setup

As a part of the field evaluation plan, visibility data measures are recorded periodically in a consistent fashion [**48**]. The visibility data are measured near the skipline area and in one of the wheel paths (see Figure **3-1**) by trained personnel using a 30-meter geometry retroreflectometer, which is the current standard for measuring pavement marking visibility. The current 30-m geometry retroreflectometer measures the visibility of the pavement marking according to the configuration details presented in Figure 1.1.

The inspection is planned to begin seven days after installation and at approximately 30 day intervals thereafter during the first year and at approximately 120 day intervals for subsequent years. Typically, the data are not collected if the visibility reading is below 100 mcd/m^2/lux or worn out. In addition, a portion of the sample used in the field test is used to perform laboratory examinations and testing. A common criticism of using the NTPEP data is that it does not necessarily represent longitudinal pavement markings applied to a roadway. It is to be noted however, that the inspection data are collected in a planned fashion making the data consistent for analysis and therefore allowing valuable insights on pavement marking degradation. Moreover, the data collected by the NTPEP are not analyzed by the program and no conclusions as to the effectiveness of the markings are made. It is left to the participating transportation agencies to make their own interpretations and conclusions.

Some of the data are available via the AASHTO-NTPEP DataMine website [**51**] in electronic form, while other NTPEP data must be obtained from hard copy reports. Figure **3-2** represents the plan of action for building the database. Electronic data will be usable directly while hardcopy reports were digitized into a spreadsheet form using ScanSoft OmniPage® optical character reader software. The digitized image was checked manually by visual inspection for any abnormal data entry. After quality assurance checking, the data were stored in Microsoft Excel.

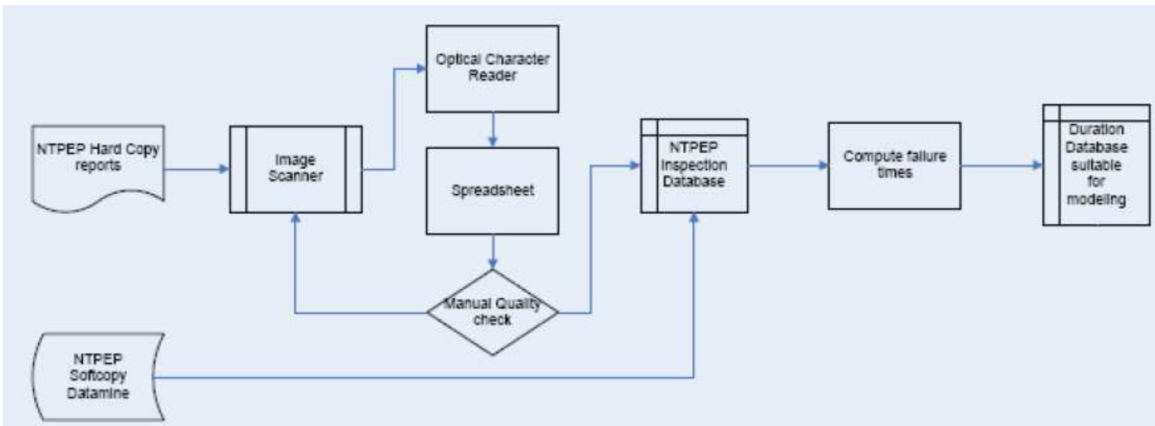


Figure **3-2**: Phase I: Data development

Subsequently, the failure times (defined in Phase II**)** will be computed and all necessary coding will be done for modeling purposes. For the purpose of this research, available historical NTPEP data from various states that satisfies the current ASTM standards on visibility measurement will be gathered and used for modeling. Visibility data obtained near the skipline area and the wheel path area (see Figure **3-1**) over time will be used as the quantitative measure to define useful life time of pavement markings. The wheel path area is expected to produce rapid degradation and may be considered as the lower bound for pavement marking degradation. In addition, various available installation measures including pavement type, color of the marking, thickness of the markings, glass bead types, glass bead coatings, amount of glass beads, no track time, road temperature, air temperature, wind speed, due point, barometer reading, and humidity at the time of marking application, lagged visibility readings, and other plausible influencing factors will be given consideration for inclusion in model development. Based on a preliminary investigation of data availability and sample size restrictions, this research proposes to analyze water-based paints from Alabama, Minnesota, Pennsylvania, Texas, Mississippi, and Wisconsin. Chapter 4 presents the descriptive statistics of the data collected in Phase 1.

Phase II: Service Life Modeling

As in many fields that involve duration data, the idea is to develop an understanding of the factors that determine the time until a specific event occurs, in this case a formally defined "failure time" for the pavement markings based on a visibility threshold. Such an analysis dealing with duration data or time until failure is called duration modeling. An alternate term used to describe the same method is survival analysis. Though the concept of duration modeling has been prevalent for a long time in the fields of medicine, social and political sciences, industrial and manufacturing engineering, epidemiology, economics, marketing, and psychology, transportation engineering has begun to apply such methods only recently. Despite the opportunity to apply duration modeling in many aspects of transportation engineering [**55**, **56**], researchers have applied duration modeling techniques to some issues. Table **3-1** presents a survey of duration model applications in transportation engineering [**57-99**]. Many of the applications have been related to activity-based modeling (16-studies), traffic and truck safety (6- studies), automobile ownership (4-studies), traffic operations (3-studies), travel behavior (2-studies), incident management (2-studies) and transit (1 study). Recently, duration modeling has been used to model infrastructure deterioration (6 studies), mainly addressing structural pavement deterioration.

Table **3-1**: Application of duration models in Transportation Engineering field

Author	Application in Transportation Engineering	Duration modeling			Special considerations		
		Parametric	Cox Semi-Parametric	Non-parametric	Unobserved heterogeneity	State Dependence	Time varying covariates
Kim and Mannering 1992	**Activity duration**	X			X		
Hamed and Mannering 1993		X					
Mannering et al., 1994			X			X	
Ettema 1995 *		X					
Niemeier and Morita 1996			X				
Wang 1996		X					
Bhat 1996				X	X		
Bhat 1996 *				X			
Kitamura et al., 1997		X					
Misra and Bhat 1999				X	X		
Oh and Polak 2001		X			X		
Srinivasan and Guo 2003		X					
Bhat et al., 2004				X	X		
Bhat et al., 2005				X	X		
Timmermans 2006		X					
Miller 2006					X		
Mohammadian and Doherty 2006		X		X			
Prozzi and Madanat 2000	**Infrastructure deterioration**	X					
Mauch and Madanat 2001			X				
Prozzi and Madanat 2002		X					
DeLisle et al., 2003		X					
Andreas and Karlaftis 2005		X					
Ziad and Madanat 2006		X					
Jovanis and Chang 1989	**Traffic safety**		X				
Chang and Jovanis 1990			X				
Mannering 1991		X					
Yang et al., 1992			X				
Lin et al., 1993			X				
Mannering 1993		X					
Mannering and Winston 1991	**Automobile ownership**	X					
Gilbert 1992		X					
de Jong, G 1996		X			X		X
Yamamota et al., 1999 *		X					X
Hensher and Raimond 1992	**Traffic operations**	X			X		
Paselk and Mannering 1994		X					
Stathopoulos and Karlaftis 2002		X					
Jones et al., 1991	**Incident Management**	X					
Nam and Mannering 2000		X			X		
Mannering and Hamed 1990	**Travel behavior**	X					
Mannering et al., 1994		X			X		
Christopher 2005	**Transit**	X					
* Competing risk models							

Characteristics of Duration Data

Typically, in duration modeling applications, the subject or sample is followed over a period of time for the event of interest. If the event occurs within the time frame of the study, then the sample is considered failed and the corresponding time *(t)* is recorded. Such duration data are called uncensored or exact duration data (see Figure **3-3)**. If the event of interest has occurred before the beginning of the follow-up (-∞, b], the sample is then said to be left censored at *b*. If the event of interest did not occur [0, ∞), then the sample is said to be right-censored at the end of the study time or fallen out of the experiment for some reason after a period of follow-up. Finally, if the failure is known to have occurred during an interval [a, b], then the sample is said to be interval censored duration data.

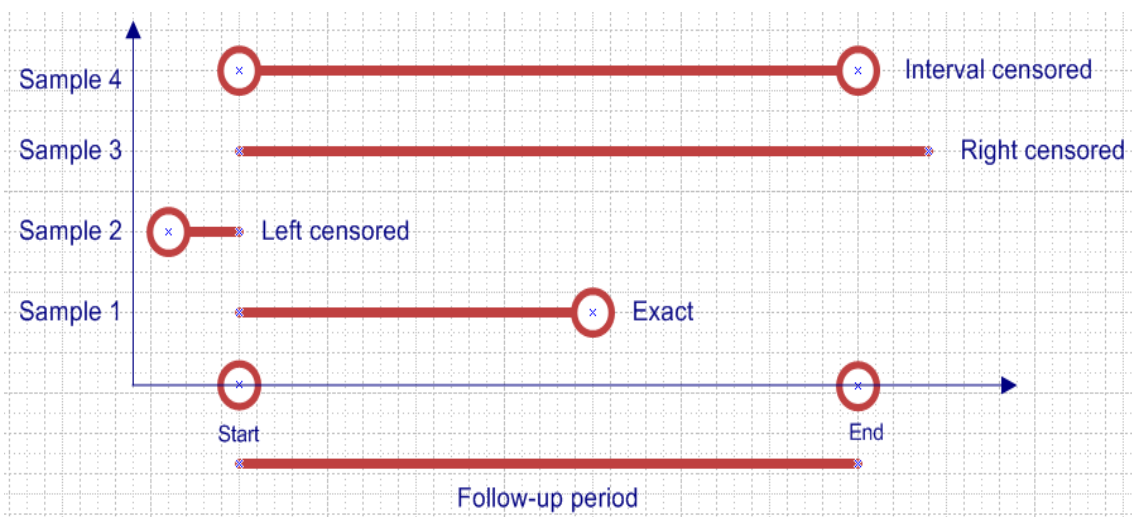


Figure **3-3**: Duration data types

Figure **3-4** presents the duration data types that were present in the NTPEP dataset. Pavement marking visibility values were measured on an interval basis. Therefore, we know the interval in which the material failed for the chosen threshold value. Such samples are called interval censored data or interval level data. Samples 4-6 in figure **3-4** represents interval level data, and samples 6 represents the one that has a skipped inspection. Furthermore, some materials did not fail till the end of the follow-up time thus causing right censoring (sample 3) in the dataset. Some markings (sample 1) had the chosen threshold visibility value on the day of the inspection. Such markings are considered as exact failed samples. Therefore, the dataset in hand is unequal spaced interval-level with exact and right-censored duration data. Left censored data (sample 2) are those that had a visibility reading lower than the threshold on the day of first inspection. Left censored data are usually not a concern in this application because state transportation agencies do adopt minimum visibility requirements for the markings that are well above the threshold value considered. Relevant statistical methods to address the censoring nature of the duration data are resorted for the modeling.

Another focus of this research is to make use of the well established methods to analyze exact duration data. For this purpose imputation methods will be used. Imputation methods essentially assume an exact failure time within the known failure interval. The plan is to test the sensitivity of the following imputation methods: quarter point, midpoint, three-quarter point and linear interpolation between the failed time intervals. A sensitivity analysis on using the imputation methods in a parametric context revealed midpoint imputation performs better than others proposed when compared to the interval nature of the data **[110].** Therefore, midpoint imputation was used to analyze exact failure time duration data.

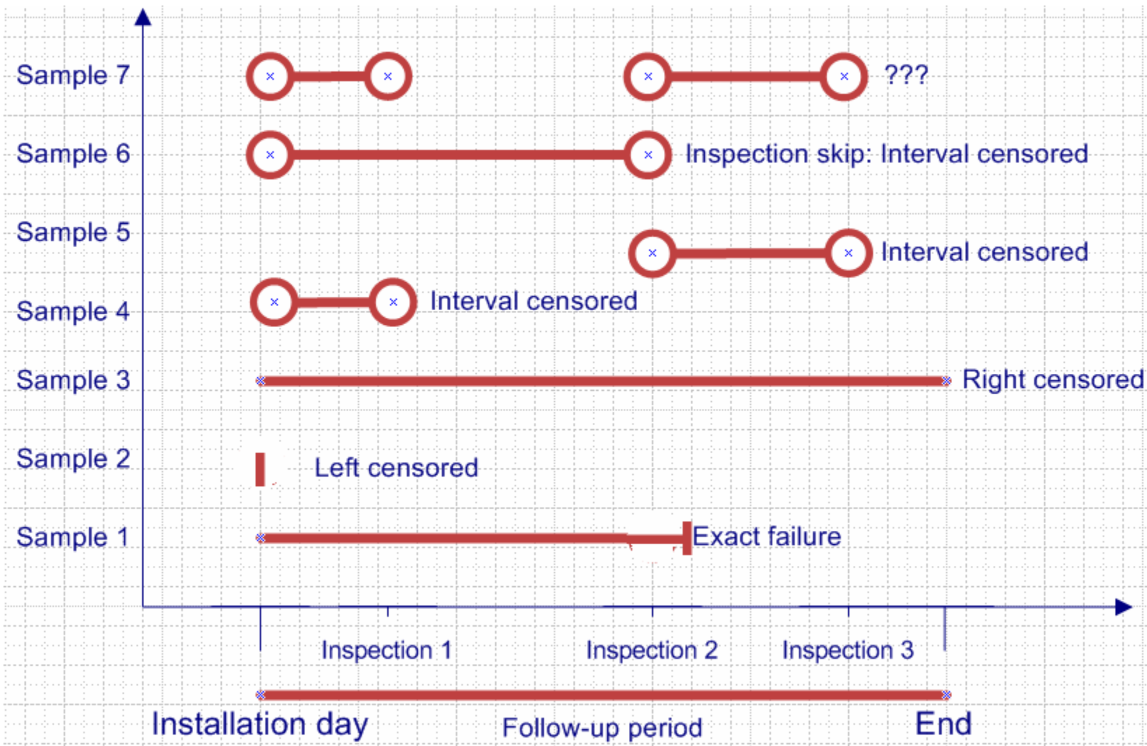


Figure **3-4**: Duration data types present in the database

Duration Modeling Framework

Pavement marking visibility degradation can be thought of a process that begins from an installation date and ends at the next re-stripe date. However, the re-stripe time in practice is justified not solely because of pavement marking failures. This can be due to pavement restoration, resurfacing, and rehabilitation and/or other possible reasons including heuristic reasons. The interest in this research is directed toward understanding the process of pavement marking visibility degradation within the service duration (i.e. from installation date to the end of study time or follow up or any intervention) so that better maintenance decisions could be made on the basis of pavement marking performance.

In addition, our interest is to know the effect of some covariates on the risk of experiencing a failure event within the study time. The event of interest in the current context is the time interval when the pavement marking is known to have fallen below a chosen threshold visibility level.

Pavement marking failure events can be expected to happen at discrete locations. In other words, within a particular geographic area multiple failure times are possible. This suggests that pavement marking failure events within regions may be correlated. Thus pavement marking failure events can be thought of as a "repeated events" problem. Duration modeling of repeated events contains three major issues:

1. Event dependency
2. Unobserved heterogeneity
3. Both event dependency and unobserved heterogeneity

The issue of event dependency arises because the failure events are considered to be correlated within a geographic region, and failing to take care of this issue would create inefficiency and bias in the estimated parameters **[108]**.

When modeling duration data, it is implicitly assumed that the distribution is homogeneous across observations. In other words, all variations in durations are assumed to be captured by the included covariates. In reality, expecting such homogeneity across observations amidst variation is likely unjustified. As noted previously, many factors contribute to the degradation of pavement marking visibility and some samples may be more or less prone to failure because of the intrinsic properties associated with the markings. Presence of unobserved heterogeneity in the model indicates specification error and can lead to erroneous inferences in the shape of the hazard function, parameter estimates, and standard error estimates [**55, 56**]. Therefore, the scope of this research considers pavement marking failure events as a state dependent repeated events process with effects of possible unobserved heterogeneity.

Typically duration modeling is accomplished using non-parametric, semi-parametric or parametric formulations. The non-parametric formulation assumes no underlying distributional assumption and works with the philosophy that *"the data speak for themselves"*. On the other hand, the semi-parametric formulation assumes less stringent distributional assumptions, while the parametric formulation assumes a specific distribution for the failure times. Past studies have considered all three formulations (parametric, non-parametric and semi-parametric) in different contexts of modeling duration data in the field of transportation engineering (see Table **3-1**). The choice to use a particular formulation is however, unclear. This could be mainly due to the non existence of a-priori information to support the applied setting. Since there is no a-priori information for pavement marking visibility degradation, it is difficult to say for certain which formulation would be the best. For the purposes of this research the Cox regression framework is chosen. The Cox framework is described below.

Cox Regression

The Cox regression estimates the hazard of the material to failure given it has survived until that time. The semi-parametric method developed by Sir David Cox [**54**] as an improvement to the non-parametric estimators in the sense that Cox regression can include the effects of explanatory variables to adjust the failure time characterizing functions. The Cox estimator considers the baseline hazard as a nuisance parameter and is left unspecified, although post-hoc baselines can be retrieved. In essence, the model serves as a tool to find out the relationship between the survival of the material from failure and its effects on the explanatory variables of interest. More formally, the Cox proportional hazards model estimates the hazard for a sample *i* at time *t,* as the product of two factors (see Eq. **3.1**):

1. A non-negative baseline hazard function $\lambda_0(t)$ that is left unspecified (i.e. no distributional assumptions involved) and is dependent on time *t*. This is called the baseline hazard function for a sample when the covariates are *zero*.
2. A linear function with a vector of *X* covariates and corresponding coefficients *β* that are exponentiated and is independent of time *t* that acts multiplicatively on the baseline hazard function.

$$h_i(t) = \lambda_0 * \exp(\beta' X) \qquad \textbf{3.1}$$

The above equation is the basic Cox formulation where every event is considered to be independent and no unobserved heterogeneity is included. In order to account for event dependency variance correction models are used while unobserved heterogeneity is taken care by using a random effects model. The variance correction models will correct the standard errors after parameter estimation using robust standard errors, while the random effects will include a stochastic variation attributed to the unobserved effects **[109]**.

Three modeling formulations developed in the class of variance correction models are considered in this research. Anderson and Gill (AG model) assumes that the risk of an event for a given sample is unaffected by the earlier events following non-homogenous Poisson arrival events. This is very similar to the basic Cox model. The difference however, is the correction for standard errors for the dependence assumption is done robustly. The Prentice, Williams and Peterson (PWP model) assumes that the sample is not at risk for a later event until all the prior events have already occurred. The PWP model is also called as conditional model where every event is conditioned on the previous events. The dependency issue in the PWP model is taken care of by allowing the baseline hazard to vary over the risk sequence *k* (see Eq. **3.2)**. Furthermore, the PWP model can be used for both gap time (GT) and elapsed time (ET).

$$h_i(t) = \lambda_{0k} * \exp(\beta' X) \qquad \textbf{3.2}$$

Now, if we consider unobserved heterogeneity in the specification, Eq 3.2 becomes Eq. **3.3**

$$h_i(t) = \lambda_{0k} * \exp\left(\beta' X + e_{ij}\right) \qquad \textbf{3.3}$$

The e_{ij} in Eq. **3.2** indicates unobserved heterogeneity of sample *i* shared within cluster *j*, which takes into account other unobserved factors that are not included as a part of the specification. In other words, this assumes that some samples are intrinsically more or less prone to failure and are characterized by gamma heterogeneity with mean one and some unknown variance.

The Cox model uses the method of partial likelihoods to estimate the model parameters. First, the partial likelihood function is constructed and iterative methods (e.g., Newton Raphson) are used to solve for the parameters. The estimator for the coefficient variance is then the inverse of the negative Hessian of the log likelihood function. Generally, the likelihood function is the product of the likelihoods for all the samples while the partial likelihood is the product of the likelihoods for the sample present in the risk set at time *t.* A risk set is defined as the number of samples exposed to the risk of failure at any instant including those that are censored. Thus, if *K* is the number of failure events observed among *i* samples excluding the censored samples, we can write the partial likelihood *(PL)* as the product of all *K* likelihoods *(L)* (see Eq. **3.4)**

$$PL = \prod_{k=1}^{K} L_k \qquad \textbf{3.4}$$

Consider n independent pavement marking samples (i = 1, 2,….,n) used for service life testing. For each sample, the data consists of three parts: time of the failure event or censoring (t_i), censor status indicator variable (δ_i), and the vector of covariates (X). To obtain the partial likelihood function for a dataset of size n with k distinct failure events and n-k right censored data, the data is first ordered such that $t_1 < t_2 \ldots < t_k$. Let us suppose that failure times t_i are not tied. Then, the general expression for the partial likelihood for data with fixed covariates based on the Cox proportional hazards model is (see Eq. **3.5):**

$$PL = \prod_{i=1}^{n} \left[\frac{Exp(\beta x_i)}{\sum_{j \in R(t_j)} Y_{ij} Exp(\beta x_j)} \right]^{\delta_i} \qquad \textbf{3.5}$$

where, $Y_{ij} = 1$ if $t_j \geq t_i$ and $Y_{ij} = 0$ if $t_j < t_i$, and j is the time of failure event or censoring for the sample i. The indicator variable Y_{ij} is included in the expression to ensure that failed samples are removed from the risk set. When tied failure times are present, modifications in the PL are provided either by using Exact, Discrete, Breslow, or Efron methods. The logic of the Exact method supposes that tied failure times are continuous and it is merely the result of imprecise failure time measurements. It assumes that there is a true time ordering among the tied failure times. The discrete method assumes that the failure times are non-continuous and that the ties are true in reality. The Breslow and Efron methods were developed as numerical approximations after recognizing that the Exact and Discrete methods are cumbersome and involve significant computing time. The logic of the Breslow method assumes that the size of the risk set is the same regardless of which event among the tied occurred first. The Breslow method was used in this study.

Summary

The objective of this study is to apply suitable methods that are within the Cox regression framework to explain the empirical question being enquired. The methods explained above are in no means exhaustive and only provides a brief summary of the concept. Readers are referred to other references that have an elaborate explanation of the methods used in this study **[104-109]**.

It is believed that pavement marking degradation is likely to be correlated within the geographic region with effects of possible unobserved heterogeneity. The following chapters present the summary of the data used in this research followed by the analysis results and conclusions.

Chapter 4

Data Analysis and Results

General

The methodology presented in chapter 3, Phase 1 detailed the steps involved in the data development process. Visibility inspection data collected over time on each pavement marking transverse line or 'sample' on the wheelpath and the skipline area were gathered. Some of the data were available from the NTPEP datamine website while others were obtained from hard copy reports. The method on how data was acquired from the hard copy report was explained in Chapter 3 Phase 1. Another key feature of this research is to develop suitable data structures so that the analysis could be done. This chapter presents the descriptive statistics of the data gathered in Phase 1 and also presents the format of the data required to run the models. Furthermore, the modeling results are also presented.

Data Summary

Pavement marking retroreflectivity data pertaining to water based paints from a total of 9 test decks in 6 different states in the United States were gathered. The test decks were located in Alabama, Minnesota, Mississippi, Pennsylvania, Texas and Wisconsin. The time frame of the data gathered ranges from 1997 to 2005. Specific time frames for each site, their testing duration and other site specific details are presented in Table **4–1.** All the sites satisfied the minimum site conditions required by ASTM D-713. Visibility data for a total of 3,874 samples were assembled. This includes, 1,759 samples (45%) representing the skipline area, and 2,115 samples (55 %) representing the wheelpath area. The site located in Wisconsin did not collect skipline area data, and the site located in Texas collected data in the area in-between the wheel paths instead of the skipline area. Table **4–3** presents more details on the sample size for each site. A total of 18 manufacturers represented their products for testing in the test decks and were considered as part of the explanatory variables in the model building. Table **4-2** presents a summary of the sample sizes grouped by manufacturers across the nine sites.

Table 4–1: NTPEP Site summary

Geo-climatic zones	**Dataset ID**	**State**	**Testing duration**	**Highway facility**	**ADT**
Hot, humid, gulf state	AL97_99	Alabama	June 1997- June 1999	I-65	8,000-9,000
	MS99_01	Mississippi	June 1999 - July 2001	U.S. 78	15,000-20,000
	MS02_04	Mississippi	July 2002 - June 2004	U.S. 78	22,000-24,000
	TX98_00	Texas	Oct 1998 - Sep 2000	U.S. 287	11,600 - 13,100
Cold, humid, altitude	PA98_02	Pennsylvania	July 1998 - April 2002	I-80	10,000
	PA00_01	Pennsylvania	Aug 2000 - July 2001	I-80	12,000
	PA02_05	Pennsylvania	July 2002 - July 2005	I-80	13,500
Cold, dry, altitude	MN97_00	Minnesota	July 1997-July 2000	I-94	21,000
	WI99_01	Wisconsin	July 1999 - July 2001	U.S. 53	5,200-5,800

Subsequent to gathering the retroreflectivity inspection data over time for each sample, the left and right end points of the failure interval, and the respective censoring status, were identified for each sample with an assumed visibility threshold level[2] of 75 mcd/sq.m/lux. Figure **4-1** presents the censoring distribution in the data set. Majority of the samples failed within an interval (68%), while some failed exactly on the day of the inspection (2%). Right censored samples constituted about 29 %, while a small percent of the sample was left censored (0.15%).

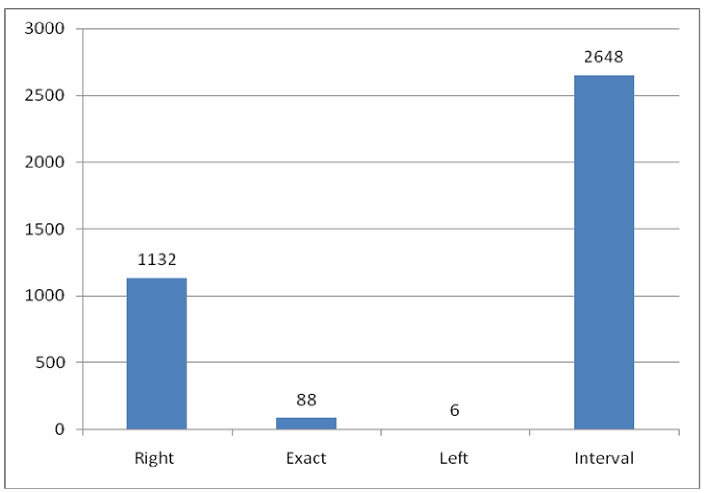


Figure **4-1**: Censoring distribution (failure threshold 75 mcd/sq.m/lux)

[2] Since there is no minimum visibility standard currently available, a threshold value of 75 mcd/sq.m/lux was assumed for this research. Certainly other threshold values can be used and this is identified as a future research exercise.

Table 4-2: Summary of sample size

Dataset ID	**Pavement types**	**Sample size**					
		White	Yellow	Total		Skipline area	Wheelpath area
AL97_99	Asphalt	34	42	76	151	151	151
	Concrete	34	41	75			
MS99_01	Asphalt	17	16	33	66	66	66
	Concrete	17	16	33			
MS02_04	Asphalt	28	24	52	104	104	104
	Concrete	28	24	52			
TX98_00*	Asphalt	23	14	37	74	0	74
	Concrete	23	14	37			
PA98_02	Asphalt	43	47	90	182	182	182
	Concrete	45	47	92			
PA00_01	Asphalt	127	116	243	485	485	485
	Concrete	127	115	242			
PA02_05	Asphalt	172	156	328	655	655	655
	Concrete	172	155	327			
MN97_00	Asphalt	31	27	58	116	116	116
	Concrete	31	27	58			
WI99_01*	Asphalt	86	56	142	282	0	282
	Concrete	84	56	140			
*** Only wheelpath area data**						1759	2115
						3874	

Table 4–3: Sample size summary grouped by manufacturers

	Asphalt		**Asphalt Total**	**Concrete**		**Concrete Total**	**Grand Total**
Manufacturer	**White**	**Yellow**		**White**	**Yellow**		
AexcelCoorporation	10	10	20	10	10	20	40
CataphoteInc	2	2	4	2	2	4	8
CenterlineIndustries	55	61	116	55	61	116	232
DouglasChemicalCo	18	18	36	18	18	36	72
DowChemicalCompany	22	22	44	22	22	44	88
EnnisPaintInc	288	314	602	288	310	598	1200
LaFargeRoadMarkingsInc	56	80	136	54	80	134	270
LinearDynamics	24	30	54	24	30	54	108
NCDOCCorrections	1	1	2	1	1	2	4
ReichholdChemicals	4	4	8	4	4	8	16
Rohm&HaasCompany	163	12	175	165	12	177	352
SafetyCoatings	6	12	18	6	12	18	36
SherwinWilliamsCompany	276	280	556	274	278	552	1108
Swarco	1	1	2	1	1	2	4
TechnicalCoatingsCorp	3	3	6	3	3	6	12
TMTPathwayLLC	32	32	64	32	32	64	128
UtilityDevelopmentCorp	8	NA	8	8	NA	8	16
VogelPaint&Wax	44	44	88	48	44	92	180
Grand Total	1013	926	1939	1015	920	1935	**3874**

Table **4-4** presents a snap shot of the data format. The first column is the sample identification while the second identifies the site with the year. It can be seen that there are two rows for each of the samples. In all the samples the first row is right censored, and the second row is either right censored or failed. Models 1 and 2 are estimated using the midpoint data but without the first row for all samples. Model 3 uses the gap time represented by ‘gapLeft75’ and ‘gapRight75’, while Models 4 and 5 uses the elapsed time represented by ‘elapsedLeft75’ and ‘elapsedRight75’ as the end points. The difference in gap time from elapsed time is that the interval gets reset for gap times after the end of the first interval. The ‘cenStatus75’ indicates whether or not the sample failed in the interval with ‘zero’ representing right censored data. The ‘riskSequence’ column denotes the stratification variable which is ordered by the right end of the failure interval within a site.

Table **4-4**: Snap shot of the data structure used in the modeling

Primary_key	siteYr	elapsedLeft75	elapsedRight75	midpt75	gapLeft75	gapRight75	censorStatus75	riskSequence75
3872	Alabama1997	0	6	3	0	6	0	1
3872	Alabama1997	6	37	21.5	0	31	1	1
3633	Alabama1997	0	11	5.5	0	11	0	2
3633	Alabama1997	11	42	26.5	0	31	1	2
3696	Alabama1997	0	11	5.5	0	11	0	3
3696	Alabama1997	11	42	26.5	0	31	1	3
.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.
3112	Minnesotta1997	0	2	1	0	2	0	1
3112	Minnesotta1997	2	32	17	0	30	1	1
3090	Minnesotta1997	0	2	1	0	2	0	2
3090	Minnesotta1997	2	32	17	0	30	1	2
3111	Minnesotta1997	0	2	1	0	2	0	3
3111	Minnesotta1997	2	32	17	0	30	1	3
3053	Minnesotta1997	0	2	1	0	2	0	4
.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.
2591	Mississippi1999	0	1	0.5	0	1	0	1
2591	Mississippi1999	1	30	15.5	0	29	1	1
2535	Mississippi1999	0	8	4	0	8	0	2
2535	Mississippi1999	8	37	22.5	0	29	1	2
2613	Mississippi1999	0	61	30.5	0	30	0	3
2613	Mississippi1999	30	61	45.5	0	31	1	3
.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.
652	Penn2002	0	1	0.5	0	1	0	1
652	Penn2002	1	62	31.5	0	61	1	1
653	Penn2002	0	1	0.5	0	1	0	2
653	Penn2002	1	62	31.5	0	61	1	2
980	Penn2002	0	1	0.5	0	1	0	3
980	Penn2002	1	62	31.5	0	61	1	3
.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.
3203	Texas1998	0	125	62.5	0	125	0	1
3203	Texas1998	125	184	154.5	0	59	1	1
3165	Texas1998	0	245	122.5	0	245	0	2
3165	Texas1998	245	306	275.5	0	61	1	2
3145	Texas1998	0	245	122.5	0	245	0	3
3145	Texas1998	245	306	275.5	0	61	1	3
.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.
2837	Wisconsin1999	0	11	26	0	11	0	1
2837	Wisconsin1999	11	41	26	0	30	1	1
2857	Wisconsin1999	0	17	32	0	17	0	2
2857	Wisconsin1999	17	47	32	0	30	1	2
2721	Wisconsin1999	0	17	32	0	17	0	3
2721	Wisconsin1999	17	47	32	0	30	1	3
.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.

Modeling Results

This section discusses the semi-parametric foundation for the analysis of degradation of pavement marking visibility over time. One may argue that a non-parametric approach may serve as a more appropriate foundation due to the fact that no distributional assumptions are made about the nature of the hazard function. The hazard function represents the instantaneous probability of a pavement marking degrading below a threshold given that it has not until that time. The non-parametric foundation is in fact part of the foundation of the thesis through exploratory research on the treatment of interval data on a visibility index **[110]**. While the non-parametric results from the exploratory research indicated the plausibility of interval mid-point imputations as reasonable approximations of interval measures, the approach cannot explicitly account for the impact of pavement configuration (and potentially manufacturer) characteristics on the nature of degradation of pavement marking visibility. It is the goal of this chapter to explore the nature of the above-mentioned characteristics and the manner in which they can be incorporated into the hazard function formulation. Specifically, this research attempts to model the pavement marking service life as a hazard function taking into account possible effects of pavement marking color, the type of pavement, location of visibility reading (wheelpath vs skipline area), possible effects due to manufacturer differences, site effects, unobserved heterogeneity, and state dependency issue within the Cox regression framework. The failure time is defined as the time when the pavement markings reached a retroreflectivity value of 75 mcd/sq/lux. As left censored samples were negligible and for the reasons stated earlier they were removed from the sample.

All the models developed are based on a total of 3,868 NTPEP test samples over 9 different test sites in the U.S.

Figure **4-2** presents the flow diagram of the modeling work conducted in this study. The first objective was to identify an appropriate imputation method. A sensitivity analysis was conducted to identify whether midpoint, ¼ point, ¾ point, or a linearly interpolated point in the failed interval was comparable with the interval level estimates in a parametric duration context **[110]**. The results indicated that midpoint imputation closely approximates the interval level estimates. Based on this sensitivity analysis midpoint imputation was considered to run models that incorporate exact failures.

Subsequently, the classic Cox regression framework assuming the midpoint imputation for the failure times with gamma heterogeneity was developed. A number of specifications were tried and a final specification that allowed unobserved heterogeneity parameter *theta* to be insignificant was used in all the models. As discussed earlier, the heterogeneity effect presumed apriori in the model structure is reasonable. This mainly arises from the fact that unobserved effects due to variations in manufacturer installation practices, weather effects, pavement location effects and associated interactions with the environment may be at play. A typical assumption for the nature of heterogeneity is gamma heterogeneity. The inverse Gaussian form is an alternative approach, but is suspect to convergence problems and associated estimability problems. The upshot of a Cox-based approach is that it is semi-parametric and involves no assumptions about the

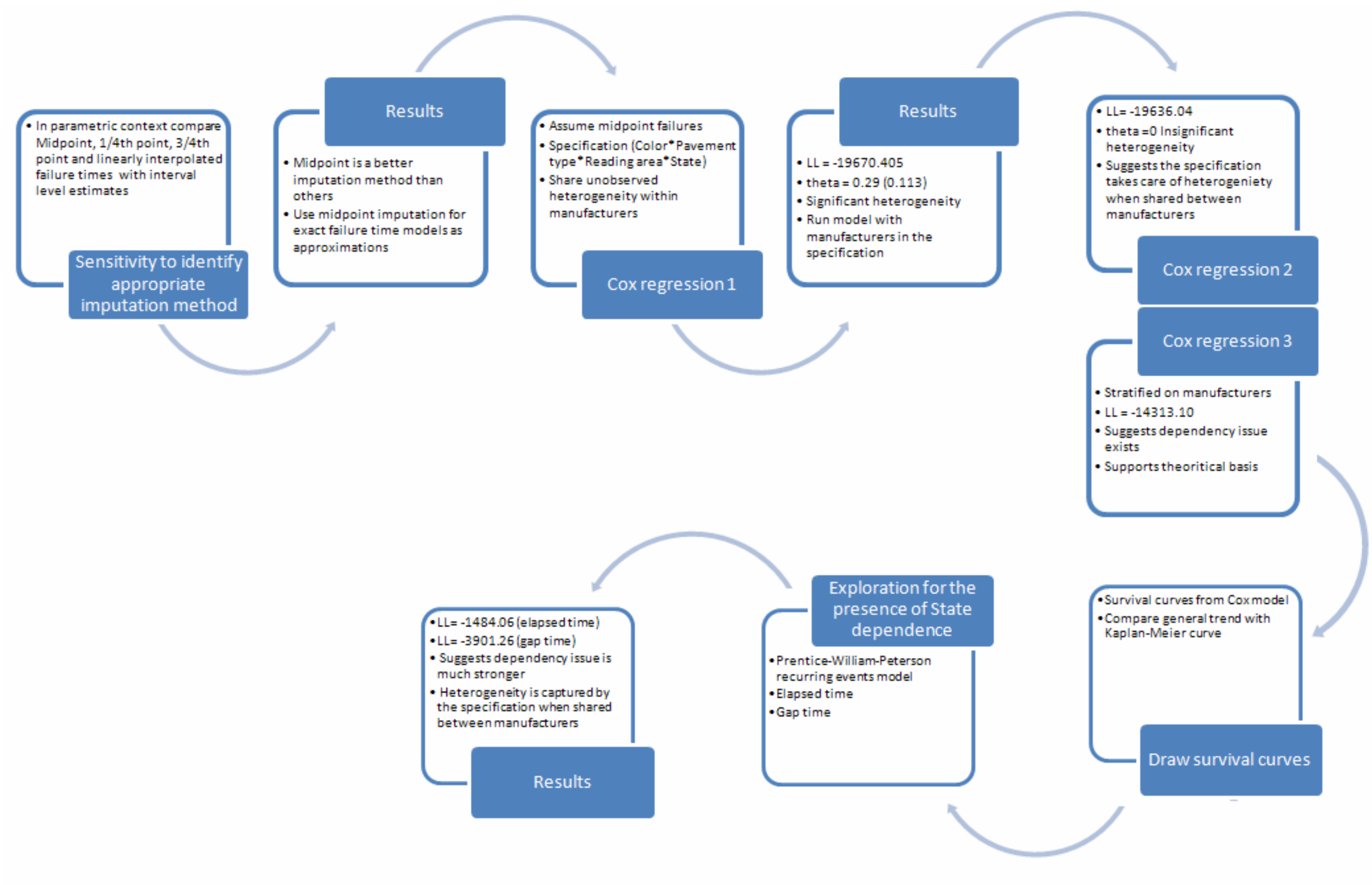


Figure **4-2**: Modeling flow diagram

nature of the baseline hazard. Furthermore, the Cox approach is reasonably robust to distributional variations.

To be sure that the heterogeneity effect was fully captured in the Cox framework, a fully interactive model was specified in order to incorporate as explicitly as possible through observed covariates. Any residual effect would be accounted for by the gamma heterogeneity term. If the gamma heterogeneity term was found to be insignificant, then one may conclude that the fully interactive model is reasonably robust to unobserved effects arising in pavement marking degradation contexts. Thus the final specification included the effects of manufacturers and four-way interactions between color (white, yellow), pavement type (asphalt, concrete), measurement location (skipline, wheelpath), and test states (Alabama, Pennsylvania, Mississipi, Minnesota, Texas, and Wisconsin). All these variables were coded as dummy indicators. There were a total of eighteen manufacturers (coded as dummies) and forty four-way interaction variables. In theory, a total of forty-eight interactions are possible; however, no data was available for seven interactions due to unavailable visibility measurements. The four-way interactions were labeled in a consistent sequence of letters starting with the color of marking, followed by pavement type, followed by measurement location on pavement and followed by state. For example, the label for the interaction variable *"WCSPA"* represents a white marking on a concrete pavement in the skipline area in Pennsylvania. The manufacturer variable *"Vogel"* and the interaction variable *"WCWMS (white marking on concrete pavement in the wheelpath area in Mississippi)"* were considered as baselines to avoid the dummy variable trap problem in estimation. Interactions with zero observations were *WASWI*, *WCSWI*, *YASWI*, *YCSWI*, *WASTX*, *WCSTX*, *YASTX*, and *YCSTX*. Finally, in order to account for possible dependence among events, Cox models were stratified using gap-time and elapsed-time structures as shown in Table **4-4**. In sum, Table **4-4** represents the logical sequence of modeling efforts to accommodate both heterogeneity and dependence effects. The uniqueness of this sequence is it circumvents the usual inseperaability between heterogeneity and dependence by utilizing a fully-interactive specification as a surrogate for heterogeneity. This may be an artifact of the pavement marking dataset; nevertheless it proves to be advantageous in our ability to treat heterogeneity and dependence sequentially. By accounting for a fully-interactive structure as a substitute for distributional heterogeneity, dependence is modeled exclusively through a Cox procedure stratified at the site level.

Table **4-5** presents the parameter estimates of the Cox-model with unobserved heterogeneity along with parameter standard errors and confidence intervals. The unobserved heterogeneity parameter *theta* clustered over the manufacturers was insignificant (p-value of 0.5) suggesting that the four-way interactive specification captures heterogeneity at the manufacturer level. In addition, among the fifty-eight variables used, thirty-seven variables were found to be significant at the ninety-five percent confidence level. The sign of the estimated parameter for each independent variable indicates the direction of the contribution to the overall hazard function. A positive sign increases the hazard and decreases the survival, while a negative sign decreases the hazard and increases the survival of the pavement marking. Figure **4-3** presents the baseline survival function along with the non-parametric Kaplan Meier estimate. Depending on the variable of interest, survival curves can be constructed. In effect the baseline survival (or hazard) will be increased or decreased proportionally which is the basic assumption of the Cox structure. One may argue that statistically insignificant effects if omitted may contribute to increased heterogeneity; however, it is premature to assume that the observed variables that were insignificant would continue to be insignificant if more observations were available. The model structure as such should be viewed as a broad-spectrum specification that accounts for all possible four-way interactions. In this light, it should be mentioned that the seven four-way interactions with zero observations may indeed turn out to be potentially significant if observations became available from extended testing.

Figure **4-4** presents survival plots for white markings on asphalt pavements across various states. It suggests that the degradation of white markings on asphalt is faster in Pennsylvania than compared to Texas while all the other states are in-between them. Figure **4-5** presents a similar plot across various states for yellow markings on asphalt pavement. In this case yellow markings in Alabama test deck degraded faster than all the other considered, with Texas having a slower degradation when compared to others. Figure **4-6** presents survival curves for white markings on asphalt and concrete for wheelpath and skipline areas in the state of Pennsylvania. It suggests that degradation in the wheelpath area is rapid compared to the skipline area (an expected result); and white markings on asphalt pavements degrade faster compared to white markings on concrete pavements in Pennsylvania. The solid line in all the plots is the median survival where the probability of the marking to fail is 50 %. Table **4-6** presents the median survival times in days from the classic Cox model. In general, it was observed that yellow markings degraded faster than white markings; markings laid over asphalt pavement appear to degrade marginally faster than concrete, and wheelpath areas degrade faster than skipline areas.

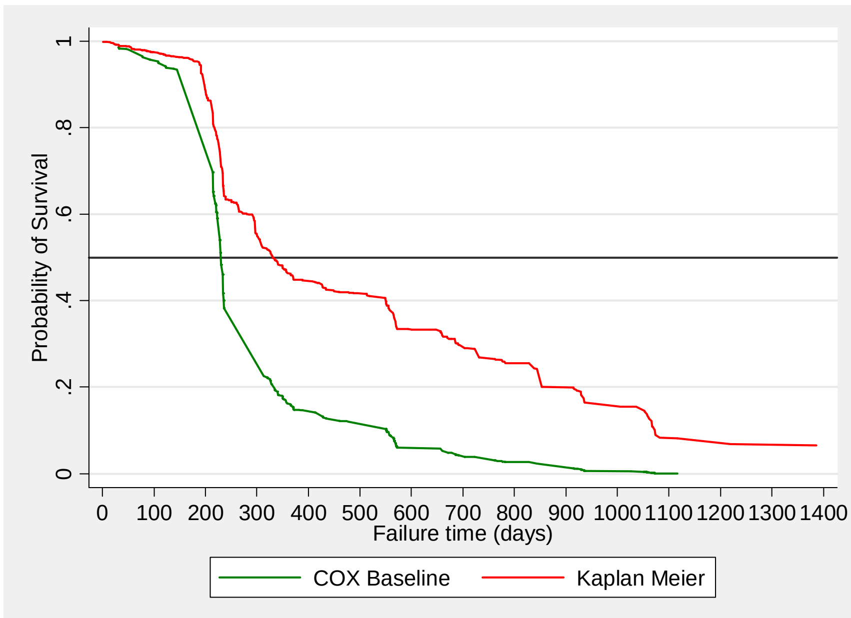


Figure **4-3**: Baseline survival curve

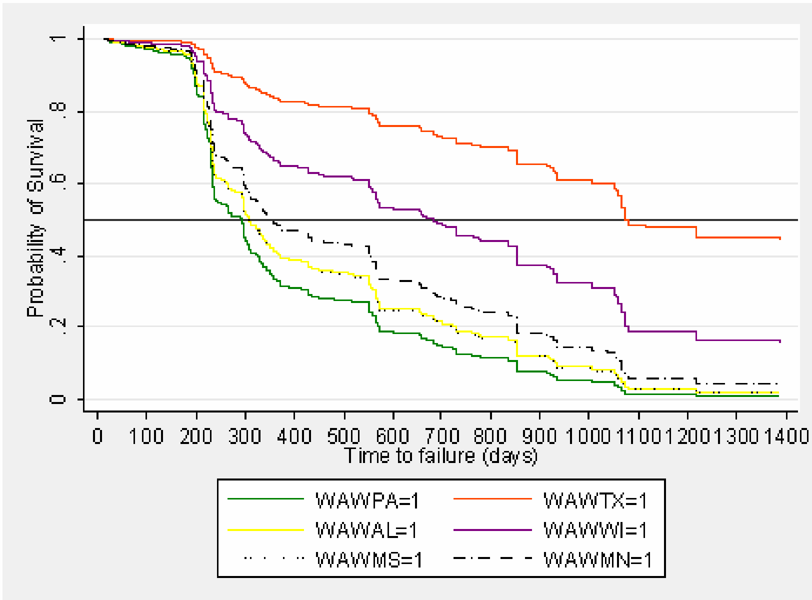


Figure **4-4**: Estimated survival plots for white asphalt wheelpath area across various states

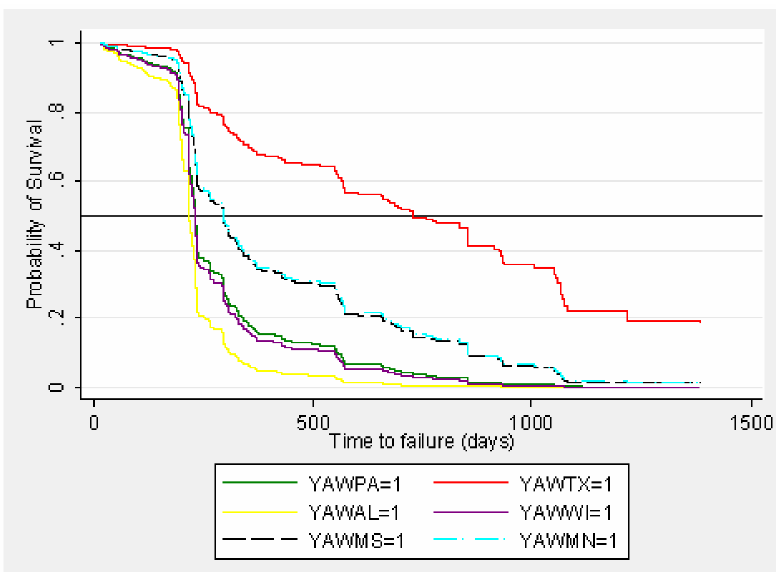


Figure **4-5**: Estimated survival plots for yellow asphalt wheelpath area across various states

Table **4-5**: Classic Cox with gamma unobserved heterogeneity

Midpt75 CoxPHf LL=-19636.044 (Manufacturer level gamma unobserved heterogenity)							
	coef	exp(coef)	se(coef)	z	p	LCI	UCI
Aexcel	-1.443	0.236	**0.245**	**-5.890**	**0.000**	**-1.923**	**-0.963**
Catapho	0.588	1.801	0.423	1.390	0.164	-0.241	1.418
Centerline	**-1.039**	**0.354**	**0.116**	**-8.920**	**0.000**	**-1.268**	**-0.811**
Douglas	**-1.410**	**0.244**	**0.171**	**-8.260**	**0.000**	**-1.745**	**-1.076**
Dow	**-0.492**	**0.611**	**0.147**	**-3.360**	**0.001**	**-0.779**	**-0.205**
Ennis	**-0.947**	**0.388**	**0.085**	**-11.190**	**0.000**	**-1.113**	**-0.781**
LaFarge	**-0.230**	**0.795**	**0.111**	**-2.070**	**0.038**	**-0.448**	**-0.012**
Linear	**-1.268**	**0.282**	**0.146**	**-8.670**	**0.000**	**-1.554**	**-0.981**
NCDOCC	-0.557	0.573	0.755	-0.740	0.460	-2.037	0.923
Reichhold	-0.282	0.754	0.299	-0.940	0.346	-0.868	0.305
RohmH	-0.530	0.589	**0.106**	**-5.000**	**0.000**	**-0.738**	**-0.322**
SafetyC	-2.531	0.080	**0.398**	**-6.370**	**0.000**	**-3.310**	**-1.752**
SherwinW	-0.965	0.381	**0.088**	**-11.000**	**0.000**	**-1.137**	**-0.793**
Swarco	-0.335	0.715	0.757	-0.440	0.658	-1.818	1.148
TMTPathway	-0.918	0.399	**0.136**	**-6.750**	**0.000**	**-1.185**	**-0.652**
TechCoating	-1.429	0.239	**0.463**	**-3.090**	**0.002**	**-2.336**	**-0.523**
UtilityDevp	-0.199	0.820	0.263	-0.760	0.450	-0.713	0.316
WAWAL	0.172	1.187	0.282	0.610	0.542	-0.380	0.724
WAWPA	**0.416**	**1.516**	**0.183**	**2.270**	**0.023**	**0.057**	**0.775**
WAWWI	**-0.615**	**0.541**	**0.217**	**-2.830**	**0.005**	**-1.041**	**-0.189**
WAWMN	-0.049	0.952	0.277	-0.180	0.860	-0.592	0.494
WAWTX	**-1.441**	**0.237**	**0.453**	**-3.180**	**0.001**	**-2.329**	**-0.554**
WAWMS	0.184	1.202	0.233	0.790	0.430	-0.273	0.640
WASAL	**-0.778**	**0.460**	**0.350**	**-2.220**	**0.026**	**-1.464**	**-0.091**
WASPA	**-0.702**	**0.496**	**0.187**	**-3.740**	**0.000**	**-1.070**	**-0.335**
WASMN	**-1.378**	**0.252**	**0.396**	**-3.480**	**0.001**	**-2.154**	**-0.602**
WASMS	**-1.537**	**0.215**	**0.346**	**-4.440**	**0.000**	**-2.215**	**-0.859**
YASAL	0.502	1.653	0.259	1.940	0.053	-0.006	1.010
YASPA	0.066	1.069	0.184	0.360	0.719	-0.295	0.428
YASMN	**-0.749**	**0.473**	**0.353**	**-2.120**	**0.034**	**-1.442**	**-0.057**
YASMS	**-0.621**	**0.537**	**0.266**	**-2.340**	**0.019**	**-1.142**	**-0.101**
YAWAL	**1.368**	**3.929**	**0.245**	**5.590**	**0.000**	**0.889**	**1.848**
YAWPA	**0.940**	**2.560**	**0.183**	**5.140**	**0.000**	**0.582**	**1.299**
YAWWI	**0.950**	**2.586**	**0.222**	**4.280**	**0.000**	**0.515**	**1.385**
YAWMN	0.287	1.332	0.290	0.990	0.322	-0.281	0.855
YAWTX	-0.706	0.494	0.461	-1.530	0.125	-1.608	0.197
YAWMS	0.309	1.362	0.238	1.300	0.194	-0.157	0.775
WCSAL	**-0.835**	**0.434**	**0.378**	**-2.210**	**0.027**	**-1.575**	**-0.094**
WCSPA	**-0.843**	**0.430**	**0.190**	**-4.450**	**0.000**	**-1.215**	**-0.472**
WCSMN	**-1.271**	**0.280**	**0.378**	**-3.360**	**0.001**	**-2.012**	**-0.531**
WCSMS	**-1.569**	**0.208**	**0.346**	**-4.540**	**0.000**	**-2.247**	**-0.891**
YCSAL	-0.087	0.917	0.301	-0.290	0.772	-0.677	0.503
YCSPA	-0.095	0.909	0.186	-0.510	0.607	-0.459	0.269
YCSMN	**-0.724**	**0.485**	**0.344**	**-2.100**	**0.035**	**-1.398**	**-0.050**
YCSMS	**-1.073**	**0.342**	**0.309**	**-3.470**	**0.001**	**-1.678**	**-0.467**
YCWAL	**0.786**	**2.195**	**0.255**	**3.090**	**0.002**	**0.287**	**1.286**
YCWPA	**0.497**	**1.644**	**0.183**	**2.720**	**0.006**	**0.139**	**0.855**
YCWWI	**1.143**	**3.137**	**0.224**	**5.100**	**0.000**	**0.704**	**1.583**
YCWMN	**0.786**	**2.194**	**0.266**	**2.950**	**0.003**	**0.264**	**1.308**
YCWTX	**-1.095**	**0.334**	**0.552**	**-1.980**	**0.047**	**-2.177**	**-0.014**
YCWMS	**0.617**	**1.853**	**0.236**	**2.610**	**0.009**	**0.154**	**1.079**
WCWAL	-0.019	0.981	0.307	-0.060	0.951	-0.620	0.582
WCWPA	0.062	1.064	0.184	0.340	0.735	-0.298	0.422
WCWWI	-0.276	0.759	0.210	-1.310	0.190	-0.688	0.137
WCWMN	0.018	1.019	0.281	0.070	0.948	-0.532	0.569
WCWTX	-1.495	0.224	**0.452**	**-3.310**	**0.001**	**-2.381**	**-0.610**
theta	0.000		0.000		0.500		

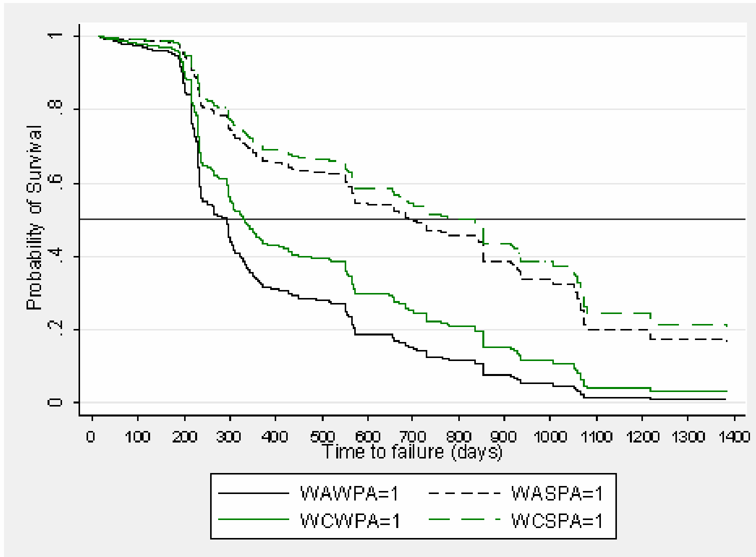


Figure **4-6**: Estimated survival plots for white markings on asphalt and concrete in the state of Pennsylvania

Table **4-6**: Estimated median survival times of pavement markings (days)

Pavement type	Marking Color	Reading location	Alabama	Minnesotta	Mississippi	Pennsylvania	Wisconsin	Texas	Mean	
Asphalt	White	Skipline area	838	1072	1117	702			932	717
		Wheelpath area	304	355	305	294	685	1073	502	
	Yellow	Skipline area	261	777	686	330			514	423
		Wheelpath area	215	297	297	230	229	732	333	
Concrete	White	Skipline area	844	1061	1219	828			988	762
		Wheelpath area	350	338		331	549	1117	537	
	Yellow	Skipline area	365	732	936	366			600	483
		Wheelpath area	233	233	235	265	225	1006	366	

The above results suggest the impact of a fully interactive specification on the shift in the baseline hazard. It should be noted that figures 4-4, 4-5 and 4-6 represent proportional hazard based survival plots when accounting for heterogeneity alone. The issue of dependency in events still remains. Dependency in events is fundamentally a recurrence phenomenon where an individual site can experience recurrent failures over time. Since multiple marking samples over various configurations are tested site-by-site over various states, the problem of dependency may remain even though the actual marking samples are supposedly independent. One can hypothesize that this dependency may arise due to the fact that the markings are at a localized pavement sample with finite physical dimensions to it, i.e., as a deck. As a result, contributing factors common to a deck may generate an underlying dependency among event occurrence. The importance of event occurrence lies in the fact that this is a phenomenon separable from heterogeneity effects. Heterogeneity effects within a sample deck based on sample-specific stratification may capture some dependency, but not to the extent to which an explicit framework accounting for time-related dependency effects is factored into the baseline hazard function. This is in essence the function of a gap-time, or elapsed-time Cox model, as proposed by Prentice, Williams and Peterson **[111]**. The PWP model adjusts the baseline hazard function within a deck to represent event dependence. In a classic Cox framework, the baseline hazard is not adjusted to account for event dependence. Tables **4-7** and **4-8** present model estimates from PWP gap time and elapsed time models respectively. The gap-time model represents a likelihood at convergence of -3,901.26, while an elapsed time structure represents a convergence likelihood of 1,484.06. The significant improvement in elapsed time likelihood suggests that marking degradation occurs in a form where dependence exists across risk sequences. In a gap-time structure, time between events is measured continuously within a risk sequence, while in an elapsed time model, the measurement is continuous across risk sequences. The key questions arise based on this observation are: a) what is the survival curve shift due to the impact of dependence, and b) what is the realistic implication of dependence in terms of marking degradation. Clearly, in a realistic driving environment, marking samples are not likely to be juxtaposed as in the NTPEP testing deck, but it is reasonable to expect some longitudinal dependence along a paint stripe in the direction of travel. Answering this question will provide light on a strategic sampling method. More investigation on actual longitudinal lines should be pursued.

Table **4-7**: Prentice Willimans and Peterson (PWP) gap time model

PWP Gap Time Model LL=-3901.26								
	Coef	exp(coef)	se(coef)	se-robust	z	p	LCI	UCI
Aexcel	-0.701	0.496	0.275	0.069	-10.155	0.000	-0.836	-0.565
Catapho	0.876	2.401	0.468	0.140	6.276	0.000	0.602	1.149
Centerline	-0.366	0.693	0.143	0.134	-2.731	0.006	-0.629	-0.103
Douglas	-0.640	0.527	0.198	0.184	-3.484	0.000	-1.001	-0.280
Dow	-0.080	0.923	0.172	0.186	-0.430	0.670	-0.444	0.284
Ennis	-0.123	0.884	0.118	0.100	-1.229	0.220	-0.319	0.073
LaFarge	0.072	1.075	0.147	0.205	0.354	0.720	-0.328	0.473
Linear	-0.464	0.629	0.171	0.169	-2.751	0.006	-0.795	-0.134
NCDOCC	0.806	2.239	0.798	0.112	7.210	0.000	0.587	1.025
Reichhold	-0.010	0.990	0.333	0.139	-0.073	0.940	-0.283	0.263
RohmH	-0.002	0.998	0.143	0.107	-0.017	0.990	-0.211	0.207
SafetyC	-1.344	0.261	0.427	0.248	-5.420	0.000	-1.829	-0.858
SherwinW	-0.262	0.769	0.122	0.142	-1.844	0.065	-0.541	0.017
Swarco	0.273	1.314	0.799	0.073	3.759	0.000	0.131	0.415
TMTPathway	-0.403	0.668	0.196	0.124	-3.240	0.001	-0.647	-0.159
TechCoating	-0.177	0.838	0.501	0.594	-0.298	0.770	-1.341	0.987
UtilityDevp	-0.249	0.779	0.405	0.126	-1.985	0.047	-0.495	-0.003
Vogel	Baseline							
WAWAL	0.249	1.283	0.321	0.134	1.859	0.063	-0.014	0.511
WAWPA	0.335	1.398	0.213	0.127	2.648	0.008	0.087	0.583
WAWWI	-0.100	0.905	0.249	0.199	-0.503	0.610	-0.490	0.290
WAWMN	0.091	1.095	0.305	0.038	2.420	0.016	0.017	0.164
WAWTX	-1.371	0.254	0.466	0.105	-13.016	0.000	-1.577	-1.164
WAWMS	0.138	1.147	0.255	0.074	1.866	0.062	-0.007	0.282
WASAL	-0.416	0.660	0.384	0.180	-2.315	0.021	-0.768	-0.064
WASPA	0.014	1.014	0.228	0.119	0.115	0.910	-0.219	0.246
WASMN	-0.898	0.407	0.422	0.138	-6.508	0.000	-1.168	-0.627
WASMS	-0.891	0.410	0.366	0.189	-4.719	0.000	-1.260	-0.521
YASAL	0.277	1.320	0.282	0.097	2.873	0.004	0.088	0.467
YASPA	0.306	1.358	0.218	0.088	3.483	0.001	0.134	0.478
YASMN	-0.454	0.635	0.379	0.098	-4.661	0.000	-0.646	-0.263
YASMS	-0.058	0.944	0.289	0.289	-0.199	0.840	-0.624	0.509
YAWAL	0.526	1.693	0.269	0.175	3.006	0.003	0.183	0.869
YAWPA	0.536	1.708	0.207	0.130	4.111	0.000	0.280	0.791
YAWWI	0.643	1.902	0.252	0.297	2.164	0.030	0.060	1.225
YAWMN	0.140	1.150	0.305	0.103	1.361	0.170	-0.062	0.341
YAWTX	-1.006	0.366	0.492	0.084	-12.040	0.000	-1.170	-0.842
YAWMS	0.133	1.142	0.264	0.107	1.237	0.220	-0.078	0.343
WCSAL	-0.614	0.541	0.409	0.146	-4.215	0.000	-0.899	-0.328
WCSPA	-0.252	0.777	0.232	0.246	-1.025	0.310	-0.734	0.230
WCSMN	-0.780	0.459	0.406	0.086	-9.113	0.000	-0.947	-0.612
WCSMS	-1.002	0.367	0.362	0.171	-5.861	0.000	-1.336	-0.667
YCSAL	-0.099	0.906	0.329	0.153	-0.650	0.520	-0.398	0.200
YCSPA	0.098	1.103	0.221	0.127	0.774	0.440	-0.150	0.347
YCSMN	-0.378	0.685	0.369	0.089	-4.260	0.000	-0.552	-0.204
YCSMS	-0.559	0.572	0.328	0.076	-7.372	0.000	-0.708	-0.411
YCWAL	0.391	1.478	0.283	0.115	3.405	0.001	0.166	0.616
YCWPA	0.303	1.354	0.210	0.115	2.627	0.009	0.077	0.529
YCWWI	0.731	2.076	0.253	0.350	2.089	0.037	0.045	1.416
YCWMN	0.276	1.318	0.287	0.109	2.540	0.011	0.063	0.489
YCWTX	-1.308	0.270	0.563	0.117	-11.173	0.000	-1.538	-1.079
YCWMS	0.235	1.265	0.261	0.053	4.439	0.000	0.131	0.338
WCWAL	-0.073	0.930	0.337	0.109	-0.666	0.510	-0.287	0.142
WCWPA	0.219	1.245	0.215	0.135	1.630	0.100	-0.044	0.483
WCWWI	0.099	1.104	0.238	0.100	0.989	0.320	-0.097	0.295
WCWMN	0.132	1.141	0.308	0.083	1.585	0.110	-0.031	0.295
WCWTX	-1.281	0.278	0.462	0.101	-12.697	0.000	-1.479	-1.084
WCWMS	Baseline							

Table **4-8**: Prentice Williams and Peterson (PWP) elapsed time model

PWP Elapsed Time Model LL=-1484.06								
	Coef	exp(coef)	se(coef)	se-robust	z	p	LCI	UCI
Aexcel	**-2.232**	**0.107**	**0.351**	**0.390**	**-5.722**	**0.000**	**-2.996**	**-1.468**
Catapho	**0.734**	**2.084**	**0.542**	**0.287**	**2.561**	**0.010**	**0.171**	**1.297**
Centerline	**-1.278**	**0.279**	**0.187**	**0.393**	**-3.249**	**0.001**	**-2.048**	**-0.508**
Douglas	**-2.061**	**0.127**	**0.260**	**0.468**	**-4.404**	**0.000**	**-2.978**	**-1.144**
Dow	-0.583	0.558	0.215	0.429	-1.358	0.170	-1.424	0.258
Ennis	-0.284	0.753	0.156	0.196	-1.446	0.150	-0.668	0.100
LaFarge	0.975	2.652	0.207	0.687	1.419	0.160	-0.372	2.322
Linear	**-1.344**	**0.261**	**0.218**	**0.462**	**-2.911**	**0.004**	**-2.250**	**-0.438**
NCDOCC	**-3.647**	**0.026**	**10.603**	**0.901**	**-4.050**	**0.000**	**-5.413**	**-1.881**
Reichhold	-0.115	0.892	0.409	0.461	-0.249	0.800	-1.019	0.789
RohmH	0.157	1.170	0.187	0.315	0.499	0.620	-0.460	0.774
SafetyC	**-2.412**	**0.090**	**0.498**	**0.402**	**-6.004**	**0.000**	**-3.200**	**-1.624**
SherwinW	-0.342	0.711	0.159	0.445	-0.768	0.440	-1.214	0.530
Swarco	**-3.251**	**0.039**	**8.927**	**1.061**	**-3.065**	**0.002**	**-5.331**	**-1.171**
TMTPathway	0.170	1.185	0.272	0.558	0.304	0.760	-0.924	1.264
TechCoating	-1.476	0.229	0.703	0.784	-1.883	0.060	-3.013	0.061
UtilityDevp	-0.424	0.655	0.580	0.269	-1.577	0.110	-0.951	0.103
Vogel				**Baseline**				
WAWAL	1.694	5.444	0.415	0.947	1.790	0.073	-0.162	3.550
WAWPA	**2.122**	**8.347**	**0.286**	**0.953**	**2.226**	**0.026**	**0.254**	**3.990**
WAWWI	0.217	1.243	0.357	0.865	0.251	0.800	-1.478	1.912
WAWMN	1.449	4.259	0.379	0.939	1.543	0.120	-0.391	3.289
WAWTX	**-2.927**	**0.054**	**0.861**	**0.638**	**-4.588**	**0.000**	**-4.177**	**-1.677**
WAWMS	0.560	1.750	0.342	0.347	1.615	0.110	-0.120	1.240
WASAL	1.088	2.967	0.509	0.944	1.152	0.250	-0.762	2.938
WASPA	1.098	2.999	0.314	0.964	1.139	0.250	-0.791	2.987
WASMN	0.642	1.900	0.479	0.946	0.678	0.500	-1.212	2.496
WASMS	-1.101	0.332	0.486	0.874	-1.261	0.210	-2.814	0.612
YASAL	**2.547**	**12.773**	**0.387**	**0.933**	**2.729**	**0.006**	**0.718**	**4.376**
YASPA	1.430	4.178	0.294	0.991	1.443	0.150	-0.512	3.372
YASMN	0.506	1.659	0.448	0.960	0.527	0.600	-1.376	2.388
YASMS	**-0.734**	**0.480**	**0.410**	**0.369**	**-1.988**	**0.047**	**-1.457**	**-0.011**
YAWAL	**2.666**	**14.380**	**0.353**	**1.031**	**2.585**	**0.010**	**0.645**	**4.687**
YAWPA	**2.398**	**11.001**	**0.279**	**1.019**	**2.353**	**0.019**	**0.401**	**4.395**
YAWWI	**3.283**	**26.650**	**0.357**	**1.004**	**3.270**	**0.001**	**1.315**	**5.251**
YAWMN	1.504	4.500	0.373	1.090	1.380	0.170	-0.632	3.640
YAWTX	**-1.847**	**0.158**	**0.796**	**0.769**	**-2.401**	**0.016**	**-3.354**	**-0.340**
YAWMS	0.143	1.154	0.354	0.160	0.893	0.370	-0.171	0.457
WCSAL	0.748	2.113	0.513	0.898	0.833	0.400	-1.012	2.508
WCSPA	0.727	2.068	0.328	1.048	0.693	0.490	-1.327	2.781
WCSMN	0.510	1.666	0.483	0.962	0.530	0.600	-1.376	2.396
WCSMS	**-2.212**	**0.109**	**0.559**	**0.343**	**-6.458**	**0.000**	**-2.884**	**-1.540**
YCSAL	1.808	6.096	0.417	0.963	1.877	0.061	-0.079	3.695
YCSPA	1.126	3.082	0.301	0.991	1.135	0.260	-0.816	3.068
YCSMN	0.763	2.144	0.438	0.944	0.808	0.420	-1.087	2.613
YCSMS	**-1.131**	**0.323**	**0.474**	**0.238**	**-4.747**	**0.000**	**-1.597**	**-0.665**
YCWAL	**2.922**	**18.587**	**0.392**	**0.999**	**2.927**	**0.003**	**0.964**	**4.880**
YCWPA	1.721	5.588	0.278	1.063	1.618	0.110	-0.362	3.804
YCWWI	**3.368**	**29.026**	**0.357**	**0.928**	**3.631**	**0.000**	**1.549**	**5.187**
YCWMN	1.469	4.345	0.348	1.135	1.294	0.200	-0.756	3.694
YCWTX	**-6.190**	**0.002**	**4.615**	**1.090**	**-5.677**	**0.000**	**-8.326**	**-4.054**
YCWMS	0.226	1.253	0.339	0.513	0.440	0.660	-0.779	1.231
WCWAL	**2.360**	**10.588**	**0.448**	**1.011**	**2.334**	**0.020**	**0.378**	**4.342**
WCWPA	1.600	4.954	0.290	0.959	1.668	0.095	-0.280	3.480
WCWWI	0.680	1.975	0.326	0.875	0.778	0.440	-1.035	2.395
WCWMN	1.526	4.599	0.373	1.014	1.505	0.130	-0.461	3.513
WCWTX	**-1.784**	**0.168**	**0.566**	**0.549**	**-3.251**	**0.001**	**-2.860**	**-0.708**
WCWMS				**Baseline**				

Life Cycle Cost Analysis

Many studies have assessed the performance of pavement markings using cost [**11, 12, 14, 22, 23**]. However, all of the studies considered a fixed value for the service life of the pavement markings and did not take into account the uncertainty involved in the expected service life of the respective marking materials. The Kansas DOT adopts the Brightness Benefit Factor (BBF) for assessing the benefit/cost ratio for pavement markings used on Kansas highways. The BBF represents the combined effects of a material's useful retroreflectivity over a period of expected service life and installed cost [**101**]. Nevertheless, a fixed value is assumed for the service life of the pavement marking. Salem et al., adopted a methodology to consider uncertainties involved in the service life of pavements using Monte Carlo simulation applications for pavement rehabilitation and construction alternatives evaluation [**114**]. A similar method is proposed in this study for assessing the net present value under uncertainty. However, it is to be noted that the major assumption in this analysis is that the degradation observed in NTPEP test deck is similar to the degradation of actual longitudinal lines. Since NTPEP testing procedures are performed in actual field conditions, for the purpose of this analysis, this research recognizes that the NTPEP test deck degradation is a representative of actual longitudinal line degradation.

The primary objective of this life cycle cost analysis (LCCA) is to develop a methodology that takes into account the uncertainty involved in determining the service life of pavement markings. The uncertainty is addressed by using the median survival time obtained from the Cox regression (see Table **4-6**). This way the service life of the markings is based on the empirical evidence rather than being heuristic. The present worth (PW) method which is used widely for the economic analysis of highway project alternatives was adopted for the purpose of this LCCA. The PW method involves discounting all future costs to the present by making use of a specific discount rate. A discount rate of 4 percent and 10 years horizon is assumed for this LCCA. In addition to its simplicity, the PW method can be used to assess alternative pavement markings with different service life, and has the practical appeal of presenting future costs in present-day terms. Eq. **4.1** presents the LCCA model used for the purpose of this economic analysis.

$$
\begin{aligned}
&NPV = C_{initial} + \sum_{n=1}^{N} C_{replacement} * (PWF) \\
&PWF = \frac{1}{[1+i]^{t}} \\
&i = \text{discount rate } 4\,\% \\
&t = \text{median survival time (years)} \\
&C = \text{Incurred cost} = \ 0.06 \ \textit{US\$/linear foot} \\
&C_{initial} \ = C_{replacement} \\
&PWF \ = \text{Present Worth Factor} \\
&N \ = \text{total number of replacements} = \left\lceil \frac{\text{Horizon year}}{t} \right\rceil
\end{aligned}
\qquad \mathbf{4.1}
$$

Table **4-9** presents the summary of the life cycle cost analysis conducted based on the estimated median survival time for the state of Pennsylvania. The results suggest that the cost per mile of pavement markings range approximately between \$ 1475 and \$ 4000, and between \$ 3360 and \$ 4955 for white and yellow markings respectively. This is assuming that the replacement plan is based on the estimated median survival time. The lower and upper limit corresponds to the respective minimum and maximum net present values observed for white and yellow markings (see Table **4-9)**.

On the other hand, for a fixed cycle replacement after every year an estimated amount of $ 3365 is required for maintaining a mile of white or yellow pavement marking for a period of 10 years (see Figure **4-7)**. It is to be noted that the cost values will increase if the actual cross section of the roadway is accounted. However, before that the NTPEP degradation pattern should be associated with the actual longitudinal lines. For the purposes of this analysis heuristic assumptions are made to relate the NTPEP degradation pattern to the actual longitudinal lines. Skiplines tend to be run over by vehicles often and are considered to approximate the wheelpath area degradation, while the edgelines are considered to approximate the skipline area degradation. Table **4-10** presents the association and the corresponding net present values per mile of the longitudinal markings.

As an illustration, consider a typical pavement marking configuration on an asphalt road segment as presented in Figure **4-8** taken from the MUTCD **[8]**. Let us assume that the road segment presented in Figure **4-8** is 5 miles long. According to MUTCD **[8]** the 10 feet skiplines are spaced every 30 feet gaps, thus the coverage of skiplines over 5 miles is 1.26 miles. According to Table **4-10** and the LCCA analysis previously presented, the net present value over the 5 mile section for a 10 year horizon period is close to $ 45,940. The net present value over the same 5 miles section in case of annual replacement over the 10 year horizon period is close to $ 58,920 (see Figure **4-8)**.

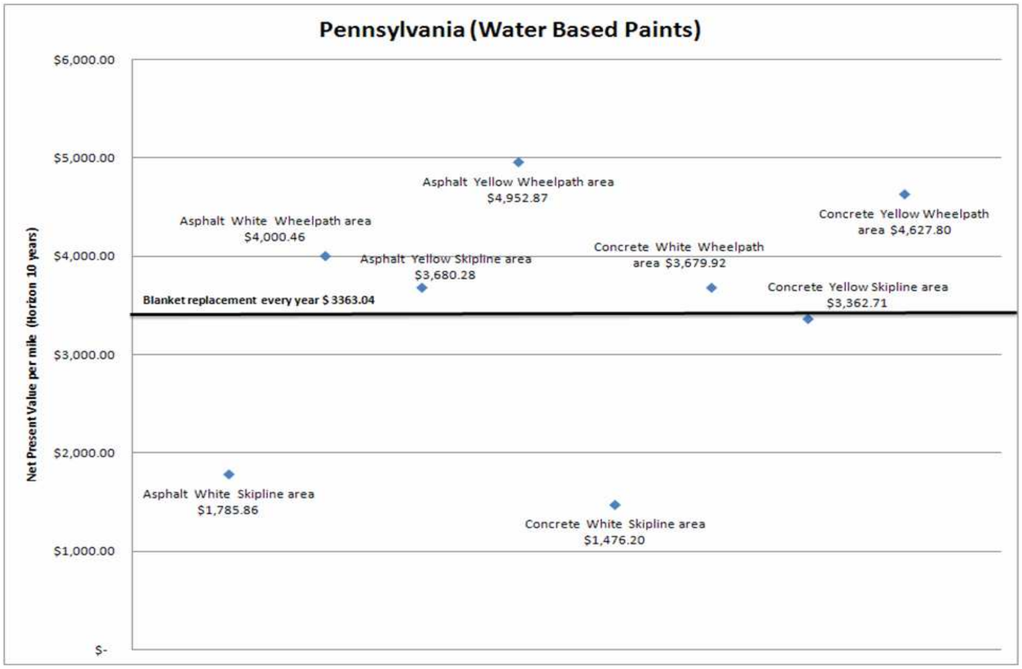
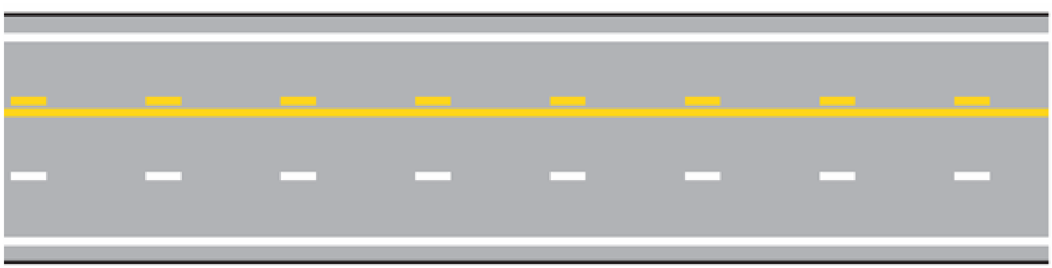


Figure **4-7**: Net present value per mile (10 years horizon)



Line configuration	Total marking coverage over 5 mile section	Total lines	Net PV (median survival time)	Net PV (annual replacement)
Yellow Centerline	5	1	$ 18,401.40	$ 16,815.20
White Edgeline	5	2	$ 17,858.60	$ 33,630.40
Yellow Skipline	1.26	1	$ 4,637.15	$ 4,237.43
White Skipline	1.26	1	$ 5,040.58	$ 4,237.43
Yellow Edgeline	5	0	$ -	$ -
			$ 45,937.73	**$ 58,920.46**

Figure **4-8**: Net present value for a 5 miles section of a typical 3-lane, 2-way with passing in one direction

Table **4-9**: Summary of Life cycle cost analysis (Pennsylvania)

Pennsylvania Service life of Water based Paints					Horizon (10 years)					
Pavement type	Marking Color	Reading location	Days	Years	Installation cost per LF	Total replacements	total cost incurred	PWF	NPV per LF	NPV per mile
Asphalt	White	Skipline area	702	1.92	$ 0.06	5.00	$0.30	0.9274	$ 0.34	$ 1,785.86
		Wheelpath area	294	0.80	$ 0.06	12.00	$0.72	0.9690	$ 0.76	$ 4,000.46
	Yellow	Skipline area	330	0.90	$ 0.06	11.00	$0.66	0.9652	$ 0.70	$ 3,680.28
		Wheelpath area	230	0.63	$ 0.06	15.00	$0.90	0.9756	$ 0.94	$ 4,952.87
Concrete	White	Skipline area	828	2.27	$ 0.06	4.00	$0.24	0.9149	$ 0.28	$ 1,476.20
		Wheelpath area	331	0.91	$ 0.06	11.00	$0.66	0.9651	$ 0.70	$ 3,679.92
	Yellow	Skipline area	366	1.00	$ 0.06	10.00	$0.60	0.9615	$ 0.64	$ 3,362.71
		Wheelpath area	265	0.72	$ 0.06	14.00	$0.84	0.9720	$ 0.88	$ 4,627.80

Table **4-10**: Net present values per mile for actual longitudinal lines on Asphalt pavement based on median survival times for the state of Pennsylvania

Line configuration	NTPEP Degradation pattern assumption	Net present value per mile
Yellow Centerline	Yellow skipline area	$ 3,680.28
White Edgeline	White skipline area	$ 1,785.86
Yellow Skipline	Yellow skipline area	$ 3,680.28
White Skipline	White wheelpath area	$ 4,000.46
Yellow Edgeline	Yellow skipline area	$ 3,680.28

Chapter 5

Conclusions and Future Research

A congressional mandate requires that minimum standards for highway pavement marking visibility be established by the United States Federal Highway Administration. Various research efforts that address this issue in multiple levels are currently in progress. The core motivation behind this research is to move toward an empirical based quality approach in highway pavement marking management decision making process. To assist in the process of effective decision making, it is imperative to be able to reasonably predict the service life of the pavement markings. Many research efforts have been previously undertaken to answer this research inquiry. However, the current status on effective pavement marking management is far from applying and updating empirical evidences in decision making as the industry is evolving. Often the management decisions are heuristic and inconsistent, and varying across states in the U.S. This status-quo is primarily because of extensive the alternatives (manufacturers, marking materials etc…) that are available for providing pavement markings with varying costs and performance levels.

There is a need to better understand the empirical evidences associated with pavement marking visibility degradation over time. This research analyzed pavement marking retroreflectivity inspection data as a time to failure duration data. The National Transportation Product Evaluation Program datasets pertaining to water based paints from a total of nine testing locations in the state of Alabama, Pennsylvania, Mississippi, Minnesota, Texas and Wisconsin were used for this research.

The dissertation began with an explicit objective to provide a consistent analytical framework for the assessment of lifecycle effects relating to the degradation of pavement markings in the United States. To this end, some goals were formulated, i.e., relating to the nature of the degradation process, the type of measurement that would serve as a reasonable proxy for interval data on marking failures, and implications for the assessment of cost effectiveness of marking replacement timelines. The dissertation presents semi-parametric foundations for the analytical framework including Cox-type models accounting for heterogeneity and event dependence. While interval data are typical representations of marking failures, their use in the development and assessment of marking survival curves is fraught with limitations. Methods to incorporate interval data for the estimation of survival curves are scant – in the sense that they are fully representative of the effects associated with both heterogeneity and event recurrence. Furthermore, the properties of estimators are not well understood to the level where robust estimates of parameter variances can be established to assess covariate significance and related impacts on shifts in the baseline hazards or survival.

Given the above-mentioned methodological limitations, this dissertation attempted to address two major issues relating to the degradation of marking survival curves, namely heterogeneity and event dependence by exploring what would be termed as reasonable approximations. The first approximation related to imputation of failure interval data.

Imputation was conducted in order to take advantage of the vast body of methodological work in the area of exact failure data in the areas of heterogeneity and event dependence. The second approximation relates to the separability of heterogeneity and dependence, a well-known phenomenon in event history data.

To the above-mentioned ends, a framework was adopted whereby early benchmarking was conducted in terms of relating imputation-based survival curves to those from interval measurements. The empirical evidence from experimental Pennsylvania decks suggested that mid-point imputation was most closely related to interval estimates of survival curves of marking failures. Based on this empirical support, semi-parametric frameworks were developed whereby the impact of covariates representing pavement, marking and location characteristics can be explored without placing undue assumptions on the baseline hazard function. The classic Cox model was used as the basic structure in this exploration. Extending the Cox framework to heterogeneity and dependence required an approach that leveraged unique empirical characteristics of a pavement marking dataset. It turned out that accounting for manufacturer effects, and interactions between pavement marking color, location on the deck, pavement type and geographic location was sufficient in terms of explicitly minimizing unobserved heterogeneity. The usual assumption about gamma heterogeneity was made in this explorative process. Using the fully-interactive model as a surrogate for a model of heterogeneity, the Cox framework was then extended to account for event dependence effects using established procedures such as the Prentice-Williams-Peterson models based on gap- and elapsed-time assumptions, The elapsed time model seemed to exploit the empirical pattern of event dependence among multiple marking samples on an experimental deck better than the gap-time model. This appears to suggest that exposure to failure is more likely simultaneous than sequential. That is, the failure of one marking type is not succeeded or preceded strictly by the failure of another; rather this could be simultaneous since the markings are closely located in a finite physical space. While this may not be a realistic representation of what occurs in day-to-day driving environments, the suggestive insight is that simultaneity in exposure causes an underlying type of dependence that may affect both skipline stripes as well as shoulder-line stripes. Hence, it may be sensible to account for simultaneous failure of markings along the traveled way rather than treat skipline failures independently from shoulder-line failures. The implication of this finding is that timelines for re-striping may involve skipline and shoulder-line areas simultaneously. This implication may especially be applicable where color-specific survival curve patterns do not vary significantly as a function of pavement type and geographic location.

The global findings discussed above relate to the promise the semi-parametric models hold modeling the duration of degradation in pavement marking visibility. Some methodological issues remain for exploration. First, the impact of distributional assumptions on the parameter estimates. Initial exploratory work on Pennsylvania datasets suggested that the Weibull distribution be used. The distributional assumption problem is one that is influenced by a variety of factors. While the Weibull may be a good starting point, solid theoretical support does not exist in favor of the Weibull over other distributions. Significant work in this area needs to occur prior to determining which distribution is more plausible for pavement marking datasets. While empirical work can guide this type of research, the nature of the physical construct of pavement markings and their interaction with pavement types is expected to influence their performance significantly. In this sense, physical models of pavement marking reflectivity would serve as useful long-term supports for a prior theory on distributional properties. This dissertation has shown with some clarity the impact of heterogeneity and dependence in a context where distributional assumptions are expected to not have much impact on a robust framework such as the Cox type structure.

It is evident from the Cox models that degradation is different in terms of color and how color interacts with pavement type; degradation is different geographically, and as expected degradation is faster on wheelpath areas than skipline areas. To construct economic models of cost effectiveness of marking replacement, one must take these results and run a variety of sensitivity analyses at the least to explore the changes in cost profiles associated with the various assumptions in reflectivity thresholds. This dissertation is based on one threshold, which is 75 mcd/sq.m/lux. A sensitivity analysis that explores the shift in survival curves based on 100 mcd/sq.m/lux or 90 mcd/sq.m/lux would provide a sense of the portion of the survival curve above the median survival line. It must be noted then that different survival curves will arise as a result of the color-pavement-type-state combination. For example, if one were to evaluate the economic cost of Pennsylvania markings, a series of survival curves would need to be generated to assess median survival times. Follow-up on the estimates of survival curves however is tricky. Quantifying the benefit of pavement marking replacement is an area replete with great uncertainties. For example, it is not well established that there is a physical or statistical relationship between pavement marking thresholds and vehicular travel safety. Quantification of benefits also includes the assessment of environmental effects associated with replacements. Hence, thorough work remains in the area of proper identification of direct benefits of pavement marking replacements as opposed to secondary and indirect benefits. The benefit-cost literature is replete with analyses that have purported to assume indirect and secondary benefits as main benefits, thereby inflating the estimated cost-effectiveness of a proposed infrastructure improvement. In the context of pavement marking replacements, this issue needs to be preceded by a thorough evaluation of cost profiles associated with various replacement timelines first. The issues raised above are significant and substantial issues that are outside the scope of this dissertation. It is the recommendation of this author that methodological issues related to censoring effects and measurement effects also be considered prior to development of more experimental decks for pavement marking reflectivity assessment. Furthermore, the impact of pavement marking installation is not well understood. While there are procedures suggestive of installation procedures, much remains to be seen in terms of whether alternative methods of installation might provide consistent yields in terms of glass bead uniformity and marking durability.

A common criticism of using the NTPEP data is that it does not necessarily represent longitudinal pavement markings applied to a roadway. It is to be noted however, that the inspection data by the NTPEP are collected in a planned fashion making the data consistent for analysis purposes and therefore allowing valuable insights on pavement marking degradation. Moreover, the data collected by the NTPEP are not analyzed by the program and no conclusions as to the effectiveness of the markings are made. It is left to the participating transportation agencies to make their own interpretations and conclusions. Furthermore, evaluating longitudinal pavement markings over vast areas in time and space will incur huge cost and is a monumental task. Therefore, it is the intent of the author that while efforts can be pursued to evaluate longitudinal pavement markings over a larger area across time and space, NTPEP data should be put to use for obtaining valuable information on the performance of pavement markings as a starting point. This way the state agencies can base their management decisions from an empirical stand point to start with, rather than making heuristic decisions. As an illustration to extent the practical use of the models derived from the NTPEP data, the life cycle cost analysis (LCCA) was performed comparing the fixed cycle annual re-striping and re-striping based on the median survival times. The LCCA suggested that making decisions based on the likely end of the service life of pavement markings is highly likely to be a cost effective approach than having an annual cycle replacement scheduling.

Overall, this study presented an alternative method to analyze typical pavement marking retroreflectivity inspection data using duration models. The method also emphasized that interesting pavement marking maintenance related questions such as replacement times, re-striping strategies, comparison of pavement marking materials, inspection scheduling, and cost effectiveness can be answered. Answering these questions to the fullest extent however, requires data that encompasses both in space and time domains. Nevertheless, the idea is, there exits method to analyze data that can help state agencies maintain minimum retroreflectivity levels of pavement markings based on objective evidence once when the Congress mandate on minimum levels of pavement marking retroreflectivity is established. It is realized that there exists huge amount of variability in modeling service life of pavement markings based on retroreflectivity measurements. Therefore, it should be kept in mind that consistent data be collected carefully over time and space to make use of the analytical methods available to extract useful information that can promote cost efficient decision making.

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Appendix

Pavement Marking Selection Matrices

Table **5-1**: Pavement Marking Selection Guidelines (Colorado DOT)

		ADT > 25000		ADT 6000 - 25000		ADT < 6000	
Pavement Type	**Pavement Condition**	**Center/Skip/ Channelizer**	**Edge/Gore**	**Center/Skip/ Channelizer**	**Edge/Gore**	**Center/Skip/ Channelizer**	**Edge/Gore**
	New	Tape, Thermo, Epoxy	Thermo,Epoxy	Tape, Thermo, Epoxy	Thermo,Epoxy	Epoxy, Paint	Epoxy, Paint
	Good/Fair	Thermo, MMA, Epoxy, Paint	MMA, Epoxy, Paint	Thermo,MMA, Epoxy,Paint	MMA,Epoxy, Paint	Epoxy, Paint	Epoxy, Paint
Asphalt	Poor	Paint	Paint	Paint	Paint	Paint	Paint
	New	Tape, Epoxy	Epoxy	Tape, Epoxy	Epoxy	Epoxy, Paint	Epoxy, Paint
	Good/Fair	MMA, Epoxy, Paint	MMA, Epoxy, Paint	MMA, Epoxy, Paint	MMA, Epoxy, Paint	Epoxy, Paint	Epoxy, Paint
Concrete	Poor	Paint	Paint	Paint	Paint	Paint	Paint

Table **5-2**: Pavement Marking Selection Guidelines (Texas DOT)

Pavement Marking Materials for SURFACE TREATMENTS[1]

(The highest-recommended material is emphasized.)

	Pavement Remaining Service Life		
Traffic Characteristic	**0–2 years**	**2–4 years**	**> 4 years**
AADT[2] < 1,000	*Thermo*[3,4], Water-Based Paint	*Thermo*[3,4], Epoxy[5, 6], Modified Urethane[6], Water-Based Paint	*Thermo*[3,4], Epoxy[5, 6], Modified Urethane[6], Polyurea[6], Water-Based Paint
1,000 < AADT < 10,000	*Thermo*[3,4], Water-Based Paint, Epoxy[5, 6]	*Thermo*[3,4], Epoxy[5, 6], Modified Urethane[6], Polyurea[6]	*Thermo*[3,4], Epoxy[5, 6], Polyurea[6], Modified Urethane[6]
AADT > 10,000	*Thermo*[3,4], Epoxy[5, 6], Modified Urethane[6]	*Thermo*[3,4], Epoxy[5, 6], Polyurea[6], Modified Urethane[6]	*Thermo*[3,4], Epoxy[5, 6], Polyurea[6], Modified Urethane[6]
Heavy Weaving or Turning	*Thermo*[3,4], Epoxy[5, 6], Modified Urethane[6]	*Thermo*[3,4], Epoxy[5, 6], Polyurea[6], Modified Urethane[6]	*Thermo*[3,4], Epoxy[5, 6], Polyurea[6], Modified Urethane[6]

Footnotes:

1. Materials may be used for shortlines or longlines — with the exception of two-component materials, which should only be used for longlines. Other materials may be used on an experimental basis with approval of TRF or CST-MAT. Contrast markings may be used to improve visibility and safety as needed.
2. AADT = Average Annual Daily Traffic.
3. If bleeding or aggregate loss on a new surface treatment is common, consider the use of a temporary pavement marking (for example, paint or thin thermo) prior to standard thermoplastic application until the pavement surface has stabilized.
4. For surface treatments with Grade 3 aggregates or larger, thermoplastic thicknesses greater than 100 mil may be necessary to achieve proper durability.
5. Epoxies specially formulated for use as high-quality, high-durability pavement markings.
6. Experimental material.

Table **5-3**: Pavement Marking Selection Guidelines (Texas DOT)

Pavement Marking Materials for HOT-MIX ASPHALT CONCRETE PAVEMENTS[1]
(The highest-recommended material is emphasized.)

Traffic Characteristic	Pavement Remaining Service Life		
	0–2 years	**2–4 years**	**> 4 years**
AADT[2] < 1,000	*Thermo*, Water-Based Paint	*Thermo*, Water-Based Paint	*Thermo*, Water-Based Paint, Epoxy[3, 4], Modified Urethane[4], Polyurea[4], MMA[4]
1,000 < AADT < 10,000	*Thermo*, Water-Based Paint	*Thermo*, Epoxy[3, 4], Modified Urethane[4], Polyurea[4], MMA[4]	*Thermo*, Preformed Tape, Epoxy[3, 4], Polyurea[4], Modified Urethane[4], MMA[4]
AADT > 10,000	*Thermo*, Epoxy[3, 4], Modified Urethane[4]	*Thermo*, Preformed Tape, Epoxy[3, 4], Polyurea[4], Modified Urethane[4], MMA[4]	*Preformed Tape*, *Thermo*, Epoxy[3, 4], Polyurea[4], Modified Urethane[4], MMA[4]
Heavy Weaving or Turning	*Thermo*, Epoxy[3, 4], Modified Urethane[4]	*Thermo*, Epoxy[3, 4], Polyurea[4], Modified Urethane[4], MMA[4]	*Thermo*, Epoxy[3, 4], Polyurea[4], Modified Urethane[4], MMA[4]

Footnotes:

1. Materials may be used for shortlines or longlines — with the exception of two-component materials, which should only be used for longlines. Other materials may be used on an experimental basis with approval of TRF or CST-MAT. Contrast markings may be used to improve visibility and safety as needed.
2. AADT = Average Annual Daily Traffic.
3. Epoxies specially formulated as high-quality, high-durability permanent markings.
4. Experimental material.

Table **5-4**: Pavement Marking Guidelines (Ohio DOT)

Remaining Pavement Service life (years)	Annual Daily Traffic			
	ADT < 5000	ADT > 5000	ADT < 5000	ADT > 5000
0-2	Polyester Water based paints	Polyester Spray Thermoplastics Water based paints	Polyester Water based paints	Polyester Spray Thermoplastics Water based paints
3-4	Polyester Spray Thermoplastics Water based paints	Polyester Spray Thermoplastics Water based paints	Polyester Spray Thermoplastics Water based paints	Epoxy Spray thermoplastics
> 4	Thermoplastics Polyester Spray thermoplastics Water borne paints	Epoxy Thermoplastics Polyester	`Epoxy Spray Thermoplastics	Epoxy
New Surface				
< 40 F°	Alkyd Paint	Alkyd Paint	Alkyd Paint	Alkyd Paint
40 to 50 F°	Water based paints	Water based paints	Water based paints	Water based paints
> 50 F°	Thermoplastics	Thermoplastics	Epoxy	Epoxy

Table **5-5**: Pavement Marking Guidelines (Ohio DOT)

Remaining Pavement Service life (years)	Multi-lanes or Priority System			
	Asphalt		Concrete	
	ADT < 5000	ADT > 5000	ADT < 5000	ADT > 5000
0-2	Polyester Water based paints	Polyester Spray Thermoplastics Water based paints	Polyester Water based paints	Polyester Spray Thermoplastics Water based paints
3-4	Polyester Spray Thermoplastics Water based paints	Polyester Spray Thermoplastics Water based paints	Polyester Spray Thermoplastics Water based paints	Epoxy Spray thermoplastics
> 4	Thermoplastics Polyester Spray thermoplastics Water borne paints	Epoxy Thermoplastics Polyester	`Epoxy Spray Thermoplastics	Epoxy
New Surface				
< 40 F°	Alkyd Paint	Alkyd Paint	Alkyd Paint	Alkyd Paint
40 to 50 F°	Water based paints	Water based paints	Water based paints	Water based paints
> 50 F°	Thermoplastics	Thermoplastics	Epoxy	Epoxy

Table **5-6**: Pavement Marking Guidelines (Ohio DOT)

Remaining Pavement Service life (years)	2-lane highways			
	Asphalt		Concrete	
	ADT < 5000	ADT > 5000	ADT < 5000	ADT > 5000
0-2	Water based Paint	Polyester Spray Thermoplastics Water based paints	Polyester Water based Paints	Polyester, Spray thermoplastics, Water based paints
3-4	Polyester Spray thermoplastics Water based paints	Polyester Spray thermoplastics Water based paints	Spray thermoplastics Water based paints	Epoxy Spray thermoplastics Water based paints
> 4	Thermoplastics Polyester	Epoxy Thermoplastics Polyester Spray thermoplastics	Epoxy Spray thermoplastics Water based paints	Epoxy
New Surface				
< 40 F°	Alkyd Paint	Alkyd Paint	Alkyd Paint	Alkyd Paint
40 to 50 F°	Water based paints	Water based paints	Water based paints	Water based paints
> 50 F°	Thermoplastics	Thermoplastics	Thermoplastics	Thermoplastics

Table **5-7**: Pavement marking guideline (North Dakota DOT)

Materials	Average Daily Traffic		
	< 1500	1500 – 4000	> 4000
Paint	+-1 yr	1 yr	< 1yr
Epoxy	>5 yr	4-5 yr	3-4 yr
Tapes	>5 yr	>5 yr	>5 yr
Grooved Tape	>8 yr	>8 yr	> 8 yr

Multi-lane divided and undivided

Remaining Pavement Surface life (years)	Average Daily Traffic					
	< 1500		1500 – 4000		> 4000	
	Edgeline	*Centerline*	*Edgeline*	*Centerline*	*Edgeline*	*Centerline*
0-2	Paint	Paint	Paint	Paint	Paint	Paint
2-4	Paint	Paint	Paint	Epoxy	Epoxy	Epoxy
4-6	Epoxy	Tape	Epoxy	Tape	Epoxy	Tape
6+	Epoxy	Grooved Tape	Epoxy	Grooved tape	Grooved tape	Grooved tape

2-lane two way

Remaining Pavement Surface life (years)	Average Daily Traffic					
	< 1500		1500 – 4000		> 4000	
	Edgeline	*Centerline*	*Edgeline*	*Centerline*	*Edgeline*	*Centerline*
0-2	Paint	Paint	Paint	Paint	Paint	Paint
2-4	Paint	Paint	Paint	Epoxy	Epoxy	Epoxy
4-6	Paint	Paint	Epoxy	Epoxy	Epoxy	Tape
6+	Paint	Paint	Epoxy	Grooved tape	Grooved tape	Grooved tape

VITA

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- Effectiveness of Pavement Marking Visibility on Nighttime Driving Behavior
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    - *Evaluating the Effects of Advanced Warning Flashing Lights on Driver Speed Compliance in School Zones*
- 2nd International Conference on the History of Transport, Traffic, and Mobility, Dearborn, Michigan, 2004
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