QUANTIFYING PAVEMENT PRESERVATION PERFORMANCE USING PROBABILISTIC DETERIORATION MODELING

by

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A dissertation submitted to the Graduate Faculty of
Auburn University
in partial fulfillment of the
requirements for the Degree of
Doctor of Philosophy

Auburn, Alabama
August 8, 2020

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ABSTRACT

Throughout the last few decades, the pavement industry has slowly transitioned from construction and rehabilitation to pavement preservation. Pavement preservation can be described as a proactive approach for protecting and maintaining existing pavements. Preservation techniques are and will remain indispensable to an industry where sustainability has been a major focus. Today, there are numerous preservation techniques available. These techniques are regularly being refined and expanded, as owners recognize that pavement preservation is a cost-effective approach.

The prospects of conducting exclusive research on pavement preservation led the National Center for Asphalt Technology (NCAT) to build innovative preservation test sections to quantify their life-extending benefits. In the summer of 2012, pavement preservation treatments were placed on a low-volume county roadway in Auburn, Alabama that is located close to NCAT's main facility. The sections are continuously being monitored since then for cracking, rutting, rideability, macrotexture, and skid resistance. Prior to treatment application, the roadway structural condition was assessed to ensure the pavement was in good condition. Moreover, structural integrity was checked through the length of the roadway to ensure that treatments were placed on a pavement with a uniform structural condition, thus, engendering fair performance assessments for different treatments.

The half-mile roadway was laid with 23 treatments and 2 sections left untreated as a baseline condition which reflects a 'do-nothing' strategy. The pairwise comparisons of treatment performances with the untreated sections help quantify the performance, or more precisely, calculate the benefits that are derived from preservation applications. Among all the performance measures collected, only cracking showed an increasing trend, and hence, it was used as a single

performance index to developed models. However, a similar methodology described herein can be applied on other performance indices in the future.

Two probabilistic models of Markov chain and Survival analysis were used to model deterioration trends. The Markov chain model is non-parametric. As such, treatments were first categorized based on a hierarchical agglomerative clustering analysis to develop models for each cluster of treatments. Survival analysis was used in the second approach. Non-parametric, semi- and full-parametric survival models were applied on the dataset to quantify treatment performances. Results confirmed that preservation strategies significantly increase the potential for extended service life when compared with a “do-nothing” scenario. It was found that pretreatment condition, treatment family, recycled material usage, and crack sealing application have a significant impact on future deteriorations. In addition, life-extending benefits derived using different methodologies were documented for future reference.

It is highly important to note that although results obtained in this study provide a basis for comparisons on various treatments, they should not be interpreted for other climatic regions, traffic levels, pavement types and so forth. The present study is part of a larger study encompassing low- and high-volume roads in hot and cold climates. The present test site was the oldest of these test locations and had enough data for analysis. Data for other test locations are still in their infancy; more years of data collection are needed before comprehensive models can be offered for use in a functioning Pavement Management System (PMS) across the US.

ACKNOWLEDGEMENTS

I dedicate this dissertation to the memory of my dad, Hamid, who always believed in my ability to pursue higher dreams. You are gone but your ever-supportive voice whispering in my head made me persistent in pursuing my dream – your dream. The author would like to thank Dr. Adriana Vargas-Nordcbeck for her guidance, patience and support in the development of this dissertation. The author would also like to acknowledge the advisory committee members including Dr. David Timm, Dr. Michael Heitzman, and Dr. Fabricio Leiva for their time and assistance during this project. Thanks are also due to the staff at the National Center for Asphalt Technology for all their assistance and to the State Departments of Transportation of Alabama, Arkansas, Colorado, Georgia, Illinois, Kansas, Kentucky, Maryland, Michigan, Minnesota, Missouri, Mississippi, North Carolina, New York, Oklahoma, Pennsylvania, South Carolina, Tennessee, Texas, Wisconsin, West Virginia, Federal Highway Administration and Foundation for Pavement Preservation Inc for their continued cooperation and support of this research.

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LIST OF ABBREVIATIONS

AASHTO	American Association of State Highways and Transportation Officials
AIC	Akaike information criterion
AICc	Corrected Akaike information criterion
AMS	Asset Management System
BIC	Bayesian Information Criterion
Caltrans	California Department of Transportation
CDF	Cumulative Distribution Function
CFR	Code of Federal Regulations
DBP	Deflection Basin Parameters
DOT	Department of Transportation
ESAL	Equivalent Single Axle Load
EUAC	Equivalent Uniform Annual Cost
FHWA	Federal Highway Administration
FP2	Foundation for Pavement Preservation
FWD	Falling Wheel Deflectometer
HDM	Highway Design and Maintenance Standards Study
HPMS	Highway Performance Monitoring System
IRI	International Roughness Index
KM	Kaplan-Meier
LaDOTD	Louisiana Department of Transportation and Development
LCA	Life Cycle Cost Assessment
LCCA	Life Cycle Cost Analysis
LTPP	Long Term Pavement Performance

M&R	Maintenance and Rehabilitation
MAP-21	Moving Ahead for Progress in the 21st Century
MCS	Monte Carlo Simulation
ME	Mechanistic-Empirical
MLE	Maximum Likelihood Estimation
MnROAD	Minnesota Road Research Project
NCAT	National Center for Asphalt Technology
NCHRP	National Cooperative Highway Research Program
NHS	National Highway System
PBC	Probabilistic Behavior Curve
PCI	Pavement Condition Index
PCR	Pavement Condition Rating
PDF	Probability Density Function
PH	Proportional Hazard
PMS	Pavement Management Systems
PQI	Pavement Quality Index
PSI	Present Serviceability Index
RAP	Reclaimed Asphalt Pavement
RAS	Recycled Asphalt Shingles
RMSE	Root Mean Square Error
RN	Roughness Number
SD	Structural Deduct
SHRP	Strategic Highway Research Program
TPM	Transition Probability Matrix

CHAPTER ONE

INTRODUCTION

1.1 Background

Each year, transportation agencies spend billions of dollars to manage a wide range of assets to meet public, legislative, and agency expectations. Effective management of the pavement network, which is a significant part of these assets, has proved to be very challenging. Pavements are spread out through a large geographic region with different climatic conditions. They are designed and constructed with different techniques and materials. Construction quality and history, goals and functions are not the same either. Not even two identically designed pavements perform equally because slight variations always exist in the real world.

Sound decision-making is a vital part of managing pavements while ensuring safety and comfort for road users. This becomes even more critical when budgets are scarce and the competition for these limited funds is high. Transportation agencies are increasingly becoming aware that keeping with the old practices in managing roads, like addressing the worst condition pavements first, are just stop-gap measures, and as such, innovative low-cost solutions are needed to address the pavement network deterioration problem more effectively. This is happening despite the fact that the Departments of Transportation (DOTs) have promised and are basically mandated to efficiently spend the tax dollars collected from the general public. An efficiently maintained road network facilitates smooth transportation of goods and brings user satisfaction, which ultimately results in net profits for the greater economy, the private and public sectors, and leads to a win-win situation for all.

Transportation agencies are now well aware that maintenance and rehabilitation (M&R) scheduling is an optimization problem inherently, and should be addressed within a system engineering framework. Hence, in response to the maintenance challenge, attempts are focused in developing pavement management systems (PMS). Sound implementation of a PMS system is the key to the long-term survival of the pavement network.

A key subcomponent of every PMS is the pavement performance modeling module which has been the subject of many studies since PMS introduction. It is worthwhile to review the functions and components of a PMS before discussing the necessity of the present study, which centers around probabilistic preservation modeling and performance quantification. Understanding the role of preservation modeling in a PMS helps to lay the groundwork for next chapters. The following section is a brief overview of a typical PMS.

1.2 Pavement Management System

American Association of State Highways and Transportation Officials (AASHTO) defines PMS as “a set of tools or methods that assist decision-makers in finding optimum strategies for providing, evaluating, and maintaining pavements in a serviceable condition over a period of time” (1). In the broadest sense, pavement management covers all phases of pavement planning, programming, analysis, design, construction, and research (2,3). A PMS helps agencies to understand their current network condition, their lagged maintenance works, future pavement condition expectations, and budget needs. Below is the minimum necessary for a PMS to be implementable (4):

- A **database** for storing pavement condition and inventory information: includes pavement information that an agency is responsible for. This can include but is not limited to the location, limits, size, connectivity to other pavement sections, number of traffic lanes, traffic levels, functional classification, structural information, material properties and so forth (2).

- **Performance models** to represent the pavement deterioration rates where they can be either deterministic or probabilistic. Performance prediction is an integral part of a PMS which enables the prediction of future conditions based on a number of variables. Thereby, enabling accurate workplan suggestions.
- **Treatment rules** for triggering maintenance and rehabilitation activities. Threshold values are identified for individual or composite condition indices to trigger pavement preservation activities (5,6). Rutting, cracking (transverse, longitudinal, area or aggregate cracking) or IRI can be used as individual condition indices. However, most agencies use a composite condition index taking into effect several individual indices, which best represents the distress on their network. Sometimes, the effects of preservation are expressed in terms of financial terms. As such, an Equivalent Uniform Annual Cost (EUAC) will be used (7). More complex frameworks have been proposed for treatment selection. For example, Alimohammadi (8) developed a framework based on historical pavement distresses and treatment cost-effectiveness for optimum treatment selection.
- **Analytical routines** to evaluate the information so that improvement programs can be developed. The timing of asphalt preservation requires following a decision process to determine when the performance or service life of a pavement is maximized, while also minimizing the life cycle cost associated with the pavement (9–11).

Early PMS systems did not bother to forecast future pavement conditions, and no economic analysis was devised either. These were mostly project-level systems that attempted to evaluate project priorities but did not have a broader scope to formally address network planning issues

(12). The first systems incorporating a network-level approach were developed in the 1980s. One such system was developed for the Arizona Department of Transportation (13). Systems developed afterwards, in 1990s, used integrated techniques of performance prediction, network- and project-level optimization, multicomponent prioritization, and geographical information systems (12). Today, PMSs are an integral part of a larger Asset Management System (AMS).

Initially, most studies only dealt with performance modeling for newly built pavements, or reconstructed ones, and fewer studies were conducted for preservation treatments, because their use was not yet prevalent. However, during the past two decades, highway agencies are becoming more aware of the benefits of pavement preservation, and consequently, many studies attempted to develop performance models for preservation treatments. Regarding the type of the models, either deterministic or probabilistic, a common issue with most studies is the wide range of service lives reported for preservation treatments. This wide range leads to unaccounted uncertainty, when the underlying variables such as pretreatment condition, traffic, etc. are not adequately examined. Typically, it is because such studies did not use sound statistical concepts, or where they did, the preservation data were itself from a study that was not controlled. As such, the effect of different variables on performance could not be gauged effectively.

Rare controlled studies and modeling issues have led to a body of literature replete with a wide range of performances for life-extending benefits of preservation treatments, which are documented in Chapter Two. The present dissertation tries to propose statistical frameworks that can explain the effects of different variables with a probabilistic outlook.

These are not the only issues surrounding the pavement preservation modeling and performance quantification. The preservation industry is fast evolving year by year, with advances in materials and innovations in applications made constantly. Previous studies that tried to quantify life-extending benefits mostly used typical treatments in use. For instance, many studies used Long Term Pavement Program (LTPP) data where only a few treatment types were available for analysis. As described above, the preservation industry is coming up with newer treatments which performance has not been quantified so far. The present study would be a first attempt to quantify the benefits for innovative treatments, and results could be of interest to pavement managers and system engineers.

Before starting to review the literature for preservation modeling and performance quantification, it is useful to get familiar with the pavement preservation and preventive treatment definitions and their subtle differences. The following two sections provide a brief summary on definitions.

1.3 Pavement Preservation

Pavements deteriorate over time due to changes in materials properties, e.g. aging and weathering, and/or progression of cracks within the pavement structure. Pavement preservation includes activities ranging from light rehabilitation to routine and preventive maintenance. By this definition, preservation activities consist of strategies with life-extending benefits that are aimed to restore the functional condition of the pavement (14,15). The pavement preservation strategies, along with proven PMS frameworks, give the DOTs confidence that they are getting the most benefit for limited funds.

Preventive treatments should be considered a subset of preservation strategies which are proactively applied to existing pavements and are geared toward retarding future deteriorations. Recognizing the urgent need to revamp the road pavement system, the industry has been keen to develop a full range of preventive treatments to address different situations and needs. These treatments range from very light applications such as a crack sealing/filling to more elaborate techniques such as chip seals, micro surfacing, and thin overlays. A major criterion in treatment selection is the existing pavement condition, which is often neglected. Not all treatments are appropriate for all pavement conditions.

The benefits are maximized if treatments are applied at the right time, when the pavement is still in good condition. Although it may provide marginal improvements to the structural condition, its main role is to retard deterioration, and by doing that, to maintain the pavement structure at a good level of service. Thus, the indirect impact on the pavement structure is highly important and often neglected. The Federal Highway Administration (FHWA) previously defined pavement preservation as "all activities undertaken to provide and maintain serviceable roadways; this includes corrective maintenance and preventive maintenance, as well as minor rehabilitation projects (16,17)." However, definitions were recently revised: "Preservation consists of work that is planned and performed to improve or sustain the condition of the transportation facility in a state of good repair. Preservation activities generally do not add capacity or structural value, but do restore the overall condition of the transportation facility (18)."

Also, it is to be noted that the maintenance groupings are now omitted from the definition, making it based on the treatment function, not type. To illustrate, a chip seal layer might be used on a pavement with poor condition as a corrective maintenance only to add 1-2 years of service until a rehabilitation fund is available. Yet, the very same chip seal can be applied on a pavement with relatively good condition which can extend the life of the pavement for 5-7 years or more. This illustrates how treatment grouping may be misleading if definitions are strictly followed without contemplation. The AASHTO Lead State Team on Pavement Preservation defined preservation as "applying the right maintenance treatment to the right road at the right time." A firm understanding of pavement preservation concepts and their application philosophy is a necessary first step in gathering support for their inclusion into a highway agency M&R work plan activities (16). These definitions all promote the use of preventive maintenance along with minor rehabilitation strategies – subsets of preservation activities – in an integrated PMS program.

1.4 Preventive Maintenance

Preventive maintenance strategies are low cost treatments that can extend pavement lives if coupled with a sound PMS program. It is to be noted that preventive maintenance is a tool for pavement preservation. The 1998 workshop on pavement preservation was the first forum held to define a road map for the future of pavement preservation (16). At the time, preventive maintenance definition attributed to AASHTO Standing Committee on Highways as "a planned strategy of cost-effective treatments to an existing roadway system and its appurtenances that preserves the system, retards future deterioration, and maintains or improves the functional condition of the system (without significantly increasing the structural capacity)." NCHRP Synthesis of Highway practice 153 (19) defines preventive maintenance as “a program strategy intended to arrest light deterioration, retard progressive failures, and reduce the need for routine maintenance and service activities.”

Preventive maintenance is generally a planned maintenance and cyclic in nature. Preventive maintenance activities do not significantly improve the load-carrying capacity of pavements but extend the useful life and improve the level of service (20).” The line separating preventive maintenance treatments from other treatments is blurred. For example, the Michigan Department of Transportation (DOT) considers any hot mix overlay that is not intended to improve pavement strength (that is, non-structural overlay) to be a preventive maintenance treatment (21).

NCHRP report 810 (22) confirms that preventive maintenance is not directly associated with a specific treatment; rather, it is associated with the condition of the pavement when the treatment is applied. As such, in its latest memorandum announced in 2016, FHWA defined preventive maintenance as “a cost-effective means of extending the useful life of the Federal-aid highway (18).” A common message carrying through all of these definitions is that preventive maintenance is programmed to retard deterioration in a proactive planning; it is not defined by the type of the treatment that is applied (2).

1.5 Problem Statement

The body of the literature suggests that there are benefits for preservation treatments. However, despite many years of research, there is no consensus on the extent of these benefits since different studies have approached the life estimation problem from a certain angle and typically with a limited scope. Most of these studies were isolated attempts where individual research teams used their local or regional data to produce such life-extending benefit estimates. Where a national-level experiment such as LTPP was involved, the type and innovation used in the test sections were very limited due to the study having started decades ago.

The quantification of the preservation benefits needs years of data collection whereas developments in the preservation industry are typically faster-paced; innovative materials and techniques are being proposed regularly to address a range of today’s needs that considers budgetary limitations. This study uses part of the data from a new national-level experiment where both traditional and innovative preservation treatments were applied on low- and high-volume roads in both cold and hot climates. The present study uses data from the low-volume hot-climate part of the study where 7 years of data were available. This research work also tries to shed light on the influence of different variables in defining the treatment performances, and has also approached the performance issue from a probabilistic standpoint. Probabilistic models that are developed here can be extended to include other test locations, and thus can present a more precise picture of performance in different regions and traffic loading conditions.

The highway agencies and pavement management and preservation practitioners may benefit from this study by knowing the extent of performance gains realized for a variety of preservation treatments. The life-extension benefits are not simply reported as definitive numbers, rather, ranges are provided for different reliability levels. This study should be considered a first step to quantify the life-extending benefits of preservation treatments and to develop probabilistic performance models that can easily be incorporated into PMS programs.

1.6 Objectives

The primary objective of this study is to develop probabilistic performance models to quantify the life-extending benefits of various innovative flexible pavement preservation treatments. A second objective is to present the performance results of the treatments for a low-volume road after 7 years of service.

1.7 Scope of Work

To achieve the stated objectives, data from the MnROAD-NCAT partnership Preservation Group (PG) study were used. The PG study is quantifying the life-extending and condition-improving benefits of different pavement preservation treatments and treatment combinations on low-volume and high-volume roadways in both northern and southern climates. By determining the field performance of treatments applied at various stages of pavement life and decay, historically broad performance expectations for various preservation options will be discretely quantified to allow agencies to make objective decisions regarding treatment selection.

As part of the cooperative research, preservation test sections were built in the summer of 2012 in Auburn, Alabama which is the oldest of the four open-road testing sites in the US. Twenty-three treatments were laid out over Lee Road 159 (LR-159) for the hot-climate low-volume part of the study. LR-159 is a dead-end road to a quarry and an asphalt plant. Treatments range from lighter preservation applications such as crack sealing, crack filling and rejuvenating fog seals, to single and double course applications of chip seal and micro surfacing. Moreover, LR-159 includes other treatments such as scrub seal, cape seal, thin overlays and various other combinations.

Data collection has been ongoing since the treatment construction using a semi-automated data collection vehicle. Performance measures such as rutting and roughness are being collected on a weekly basis, whereas cracking data is being collected and mapped monthly. Among the performance measures that were collected, only cracking showed a tangible upward trend, and hence, were used as the performance indicator in this study.

The present study uses 7 years of cracking data to create probabilistic deterioration models using two approaches. First, a Markov chain was developed and a Monte Carlo Simulation (MCS) algorithm was implemented. Markov chain was selected because due to its ease of implementation relative to other methods, and MCS was used to incorporate the reliability aspect. Transition Probability Matrices (TPM) are reported for use in a possible PMS framework. Second, modeling was performed using different survival analysis methodologies and related performance models are presented in the form of parametric equations. The effects of explanatory variables such as recycled material usage, primary crack sealing, etc. were assessed. Finally, life-extending benefits of preventive treatments were quantified using different methodologies, compared, and documented.

1.8 Organization of the Dissertation

This dissertation is organized into five chapters, including the present introductory chapter. Chapter One started by explaining the need for pavement management systems, following by a section to define what a PMS is and what its components are. Then, pavement preservation and preventive treatment terms are defined. Through Chapter one, the case for conducting the current dissertation research is laid out. Chapter Two is a literature review on two subjects. First, studies that dealt with performance quantification of preservation treatments and second, studies on deterministic and probabilistic pavement performance modeling, with more emphasis given to probabilistic modeling. Chapter Three is the methodological framework, and starts by describing the low-volume hot-climate PG study on Lee County Road 159 (LR-159), and expands to probabilistic methodologies used for performance quantification. Chapter Four presents the results for the different types of analysis and documents the life-extending benefits of preservation treatments. Also, discussions are presented regarding the use of recycled materials, pretreatment conditions, crack sealing benefits and so forth. Finally, Chapter Five presents the conclusions obtained from 7 years of traffic on LR-159 and recommends needed continued research for future.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

This chapter starts with a literature review on performance of preservation treatments. Next, the rationale and necessity of performance modeling in pavement management is discussed. Two broad categories of performance modeling, namely deterministic models and stochastic models are identified and reviewed. Next, previous research and advances in probabilistic modeling are reviewed, as are used in this dissertation.

2.2 Pavement Preservation Treatments and their Performance

Pavement preservation treatments are designed to address specific needs of pavement maintenance. The immediate and long-term maintenance effect of preventive treatments are not the same for different pavement conditions and different distresses. The life-extending benefits are tied to a set of variables specific to each project. These variables include climatic conditions, pretreatment condition, traffic volumes, and choice of the performance indicator. Moreover, the choice of the trigger values for each performance indicator affects the life-extending benefits.

The following section investigates treatment life predictions reported in different studies along with brief recommendations of treatment application. This information is presented separately for general categories of preservation treatments.

2.2.1 Crack Sealing/Filling

Cracks are inevitable, and neglect leads to accelerated cracking and potholing. Crack sealing and filling operations have been routinely conducted by maintenance crews in highway agencies. It was only in the past decade or so that their preventive role was recognized.

Crack sealing is the placement of specialized treatment materials above or into working cracks using unique configurations to prevent the intrusion of water and incompressibles into the crack. Crack Filling is the placement of ordinary treatment materials into non-working cracks to substantially reduce infiltration of water and to reinforce the adjacent pavement (23). Figure 2-1 shows steps for a rout and seal procedure.

Step 1: Crack routing

Step 2: Cleaning with compressed air and drying with heat lance

Step 3: Crack sealing

Figure 2-1 Crack rout and fill procedure (photos courtesy of NCAT)

Normally, working cracks with limited edge deterioration should be sealed, whereas non-working cracks with moderate to no edge deterioration should be filled. The incompressible objects will not compress as the crack contracts in warm weather. The pavement actually expands, making the crack width smaller, and breaking the asphalt along the edge of the joint. By keeping water out, sub-base erosion is eliminated and freeze-thaw damage decreases (24).

Sealing in moderately cool temperatures (45° to 65°F) is beneficial from two standpoints. First, cracks are partly opened so that a sufficient amount of material can be placed in the crack if cutting is not to be performed. Second, the width of the crack channel, whether cut or uncut, is nearly at the middle of its working range. This is important to the performance of the sealant material because it will not have to undergo excessive expansion or contraction (23).

Several preservation treatments can be used to treat cracking. The choice depends on the density of cracking and its physical characteristics. If cracks are abundant and do not exhibit a high degree of edge deterioration, they may best be treated through chip seals, slurry seals, or the like. If cracks are low to moderate in density and have typically progressed to a point of high edge deterioration, then crack repair strategies, such as partial-depth patching or spot patching, may be warranted. If cracks are moderate in density and show moderate to no deterioration at the edges, then they may be treated effectively through sealing or filling operations (23).

Life extending benefits of crack sealing were investigated for the Ohio DOT’s crack sealing program. Results showed that maximum gains can be achieved by treating pavements with a PCR range of 66 to 80. Performance prediction models showed up to 3.6 years of life extension (25). Another study by the Ontario Ministry of Transportation concluded that crack sealing can extend the service life of a flexible pavement by at least 2 years (26).

2.2.2 Spray Applied Surface Seals

Sprayed oil/emulsion applications such as fog seals and rejuvenating fog seals are low-cost preventive treatments used to extend the life of the pavements. Fog seals are a light spray (typically 0.05 to 0.15 gal/yd^2) of a diluted asphalt or rejuvenator emulsion that is applied by a distributor truck (27). The emulsions are diluted to allow an even application of a very small amount of asphaltic material to the pavement surface (28). Figure 2-2 shows the application of a rejuvenating fog seal using an emulsion distributor truck.

Figure 2-2 Rejuvenating fog seal application on LR-159 (photo courtesy of NCAT)

Fog seals renew the surface asphalt, and delay further oxidation, weathering and raveling. They seal micro-cracks and are a very low cost and effective pavement preservation treatment when applied correctly on pavements in good condition.

Rejuvenating fog seals are used to specifically alter the chemistry of the asphalt on the surface. Typically, they include oily fractions developed to restore the viscoelasticity of oxidized, hardened asphalt (27). Rejuvenators are designed to penetrate into the existing asphalt cement and modify and improve existing chemical and rheological properties.

Rejuvenator products are most typically used on dense-graded asphalt surfaces, while fog seal products are more commonly used on chip seals and friction courses where binding or enrichment is the main purpose (28).

Until recently, a spray applied seal was considered more of a restorative treatment than a life-extending solution. As such, few studies attempted to quantify its life-extending benefits. Based on historical performance, Peshkin et al. (29) suggested that 1 to 2 years of life extension is possible when applied in a preventive maintenance mode. A study in California in which data from Caltrans were utilized showed that spray seals can extend the life of the pavements by up to 5, 3 and 2 years for ‘good’, ‘fair’ and ‘poor’ pavement pretreatment conditions, respectively, based on PCI definitions. However, the method of calculation was not discussed.

2.2.3 Chip Seals

A chip seal is a preservation treatment applied by spraying a bituminous binding agent and immediately spreading and rolling a thin aggregate cover (30). The rolling operation is intended to seat the aggregate into the binder and ensure chip retention. It is usually applied on low volume roadways to eliminate raveling, retard oxidation, reduce the intrusion of water, improve surface friction and seal cracks (31). The number of layers applied depends mainly on the condition of the pavement surface being treated (32).

The bituminous binding agent can be an emulsified asphalt, cutback asphalt, or asphalt cement. The aggregate used is a single-sized crushed aggregate chip (30). Single size aggregates are more uniform in height and have more room for the binder, otherwise, finer aggregates would fill the space within the aggregate structure. Figure 2-3 shows an example of chip seal application.

Figure 2-3 Chip seal application process (photos courtesy of NCAT)

Figure 2-4 shows the life-extending benefits of chip seals reported in different studies. Where a mean value is reported, the figure uses a black and white gradual scale to abstract the situation. For studies where definitive ranges are reported, a single black color is used. A survey of agency chip seal practices in the US showed that chip seal application on existing asphalt pavements has a performance life of 6.5 years for urban arterial routes, and 7.4 years for urban collector and rural local routes (33), as shown in Figure 2-4. Understandably, chip seals on local and collector roads have a higher life extension because of lower traffic Equivalent Single Axle Loads (ESALs) than that of arterials and interstate highways. Also, chip seals are more effective in rural areas where traffic is predominantly low-volume.

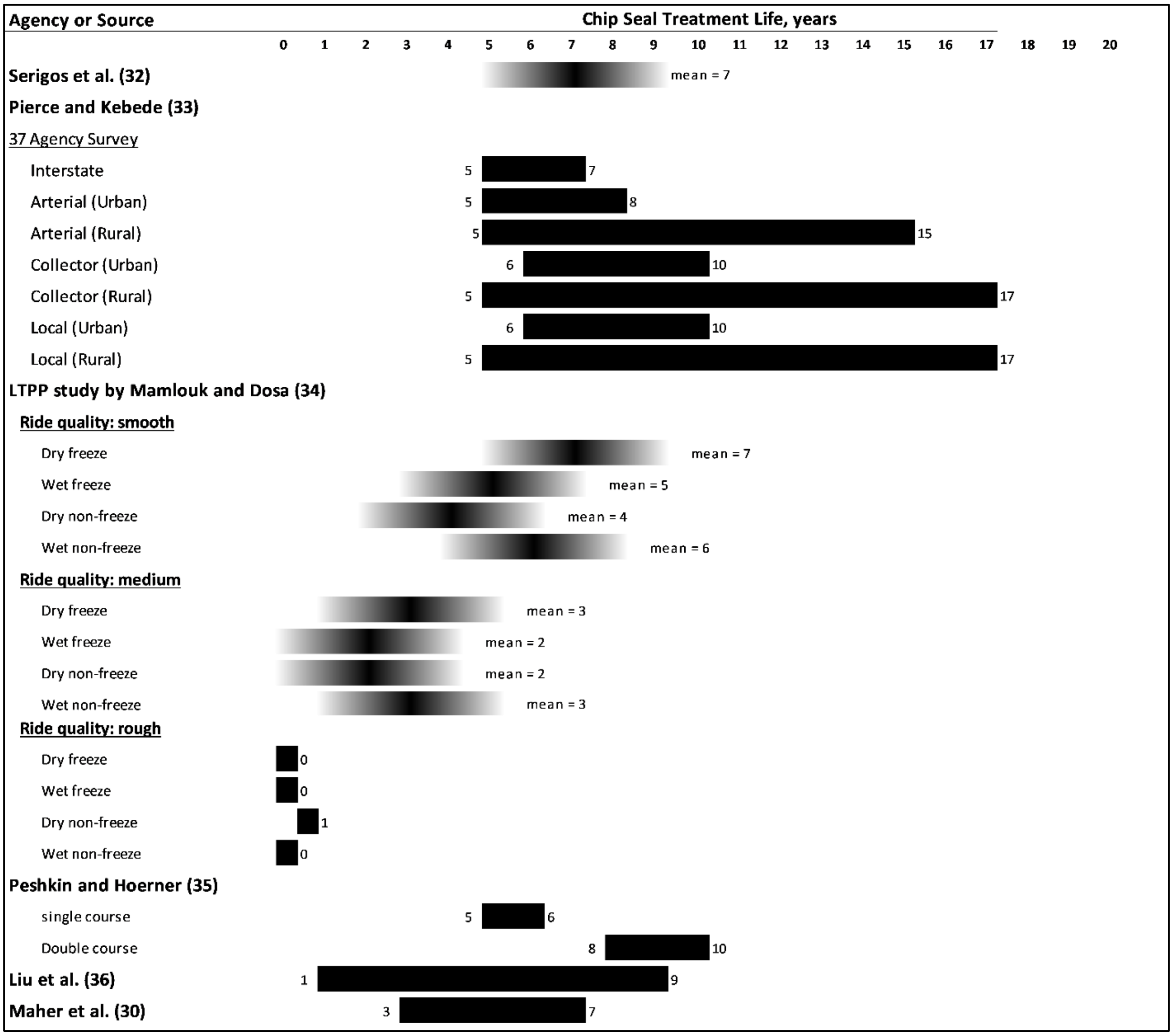


Figure 2-4 Chip seal treatment life reported in the literature

Mamlouk and Dosa (34) used LTPP data as of 2012 to derive average life-extension values for chip seals based on climatic region and initial pavement conditions. As can be seen in Figure 2-4, pretreatment IRI had a direct effect on life extending benefits. For rough roads, these benefits are none or only one year. Liu et al. (36) analyzed the performance of 3,532 chip seal sections applied on Kansas highways from 1992 to 2006. A wide variety of performance can be seen, ranging from 1 to 9 years. The high uncertainty with performance is due to not accounting for influential factors such as pretreatment conditions.

It is to be noted that the treatment effect can be different on different performance indicators. For instance, Mamlouk & Dosa (34) noted that chip seals do not cause an immediate change in IRI, although chip seals are expected to reduce the rate of growth of roughness, and have some effect on pavement performance.

2.2.4 Micro Surfacing

Micro surfacing is an unheated mixture of polymer-modified asphalt emulsion, high-quality frictional aggregate, mineral filler, water, and other additives, mixed and spread over the pavement surface as a slurry. Figure 2-5 shows an example micro surfacing application.

Figure 2-5 Micro surfacing application (37)

Micro surfacing is used to correct surface distresses such as low severity block cracking, raveling and segregation, flushing, and loss of pavement friction. Because micro surfacing contains high-quality crushed aggregate, it is also used to fill-in ruts and surface deformation to a depth of up to 40 mm. Micro surfacing has excellent frictional properties and is used on high speed roads including expressways (21). As a preventive maintenance treatment, it can be used to seal the surface of the pavement protecting the pavement from water infiltration and greatly reducing the rate at which the existing bituminous surface oxidizes. Oxidization of the bituminous surface material leads to raveling and cracking.

Figure 2-6 exhibits the treatment lives of micro surfacing treatments assessed by different researchers, for various regions, performance measures, and under the influence of different factors such as pretreatment condition. Where a mean value is reported, the figure uses a black and white gradual scale to abstract the situation. For studies where definitive ranges are reported, a single black color is used. Some studies reported performance in excess of *n* years. A one-sided black and white gradual scale is used for these cases.

Two studies (40,42) show that micro surfacing can deliver very high rutting performance, probably the highest among other performance measures. Peshkin et al. (35) conducted a questionnaire survey to determine the service life of preventive treatments. As shown in Figure 2-6, the results show some inherent variability ranging from 3 to 5 years. It was noted that in questionnaire type surveys, different understandings of "preventive" term can introduce bias in the results. For example, it became known that some agencies had applied preventive treatments on pavements with 'poor' and 'very poor' pretreatment conditions. Although physically a preventive treatment is applied, in context, a treatment is truly preventive when pretreatment condition is 'good' or 'very good.'

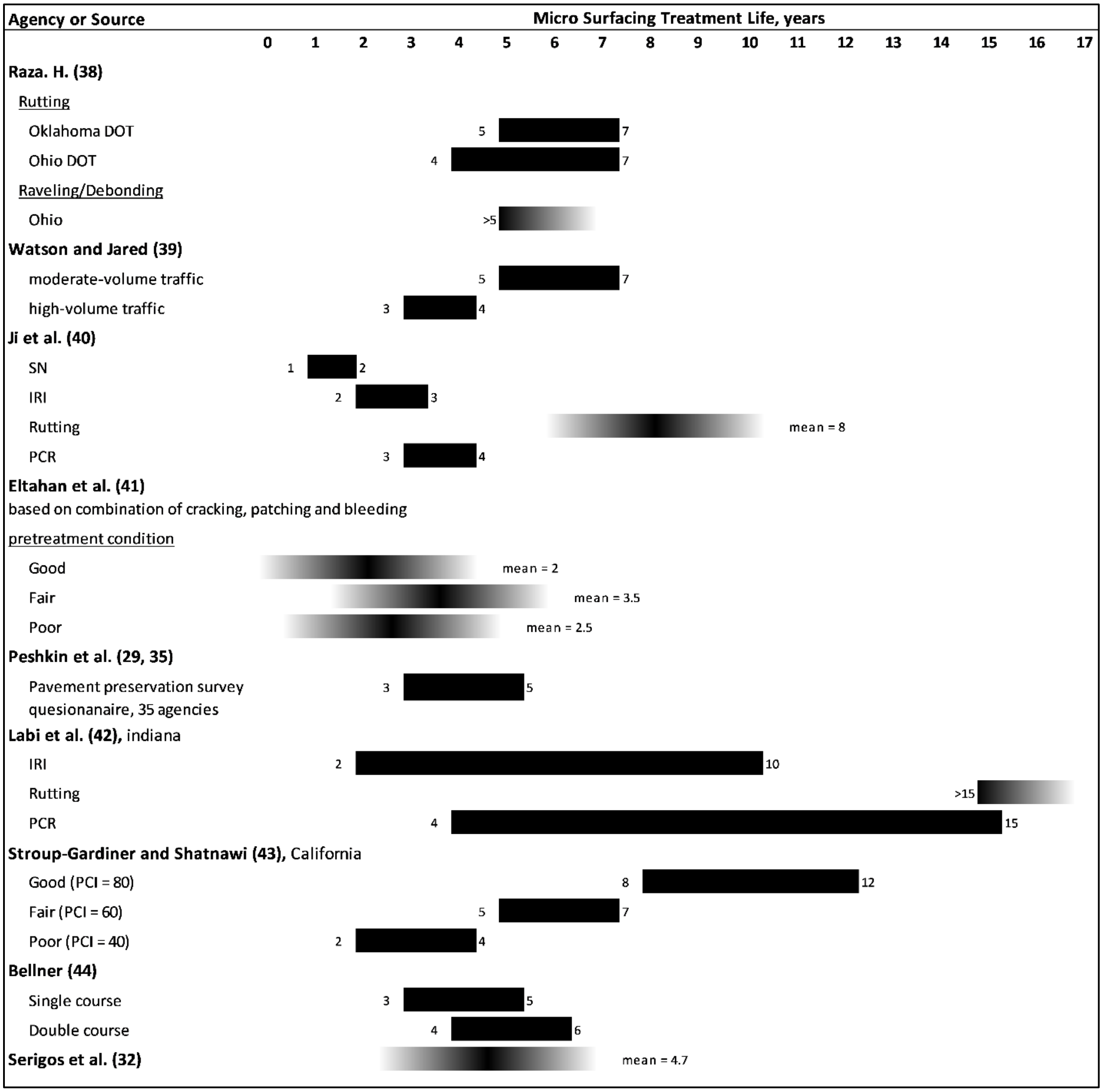


Figure 2-6 Micro surfacing treatment life reported in the literature

A survival analysis study conducted on the LTPP Southern Region SPS-3 sections (41) showed that the probability of failure is two to four times higher for the sections that are in poor condition at the time of the treatment than those sections that were in better conditions. The pretreatment effect can also be seen in the study in California (43) where ‘poor’ pretreatment condition results in 3 to 4 times less treatment life when compared to ‘good’ pretreatment condition. Micro surfacing can be applied as a single course or a double course treatment. Double course treatment ensures better sealing and rut filling performance (14).

Moreover, it is shown that, like all treatment types, the performance of micro surfacing is not the same across all performance measures (40). Consequently, efficient treatment selection at the project level is one that takes individual distresses into consideration, and one that does not solely consider a summary index.

2.2.5 Cape Seals

A cape seal is combination of a chip seal and slurry seal (or micro surfacing), with the slurry seal placed atop the chip seal typically 4 to 10 days after placement of the chip seal. A cape seal is more than the placement of one type of surface treatment over another; it is designed to be an integrated system where the primary purpose of the slurry is to fill voids in the chip seal. The slurry helps prevent chip loss and the chips prevent undue traffic abrasion and erosion of the slurry. Cape seals provide a durable, sealed roadway surfacing that has excellent skid resistance and is smoother than chip seals (30).

Distresses like longitudinal, transverse, and block cracking can be effectively addressed by applying cape seals. In addition, the treatment can address friction loss, raveling, and minor roughness. Cape seals are less prone to damage from snow plowing than chip or slurry seals (30). The primary purposes are the same as a chip seal; the slurry cover increases the life of the chip seal by the enhanced binding of the aggregate chips (14).

Studies on life-extending benefits of cape seals are less frequent, probably because cape seals are less used compared with other treatments such as chip seals or micro surfacing, and as such, fewer databases are available for such analsys. Cape seals have been used with success in South Africa, where they were developed, and Australia for more than 40 years. The technology was introduced to the United States in 1977 (30). Evidence suggests that cape seal applications in the United States have been limited, and only have been used in some areas (e.g. California) altough not in a large scale. Stroup-Gardiner (43) investigated the economics of pavement preservation treatments for the state of California. From the data presented, it can be concluded that use of cape seal has been very limited as of 2009.

Maher et al. (30) reported typical service lives ranging from 7 to 15 years, with an average of 9 years. When the chip seal layer is placed over an aggregate or stabilized base is more prone to failures, as opposed to a chip layer placed over an existing pavement. In another study in Illinois, performance data from the Illinois DOT (IDOT) pavement preservation program were used to create prediction models and to estimate service lives of various treatments. Prediction models showed that cape seals have the highest service lives (more than 7 years on average) when compared to chip seals and micro surfacing (45).

2.2.6 Thin Overlays

A thin overlay is the application of a thin asphalt concrete (AC) layer ranging from ¾ to 1 ½ in. (21), with the ability to provide improved ride quality, reduce pavement distresses, maintain surface geometrics, reduce noise levels, reduce life cycle costs, and provide long-lasting service. Figure 2-7 shows a thin overlay application on an existing pavement.

As with any preservation technique, thin overlays should be placed before the pavement deterioration has reached a critical stage where more extensive rehabilitation is required (46). Thin HMA overlays are not recommended when the pavement exhibits serious structural failures (47).

Thin overlays should be constructed on a uniform platform that bonds well with the overlay. The improvements to the existing surface may include precision milling to improve ride quality and cross-section, an application of a leveling course or a scratch course, patching, full-depth repairs, and an application of a tack coat (21).

Figure 2-7 Thin overlay application (48) (photo courtesy of NCAT)

The majority of agencies use a tack coat prior to placing a thin overlay. The tack coat strengthens the bond between asphalt concrete layers. The bond increases the strength of the pavement structure (by limiting slippage between layers) and the durability of the overlay (by reducing the possibility of delamination). A tack coat is also required to seal the underlying pavement layers when an open-graded overlay is used (21).

Figure 2-8 compares the performance of thin overlays in different regions, pretreatment conditions, and using different performance measures. It seems most researchers agree on 7 to 10 years of life-extension for thin overlays. The very high variability seen in some studies generally stems from not controlling the influential variables. Thereby, it is imperative to use data from a highly controlled study to shed light on the effects of influential variables such as pretreatment conditions, climate, traffic and others.

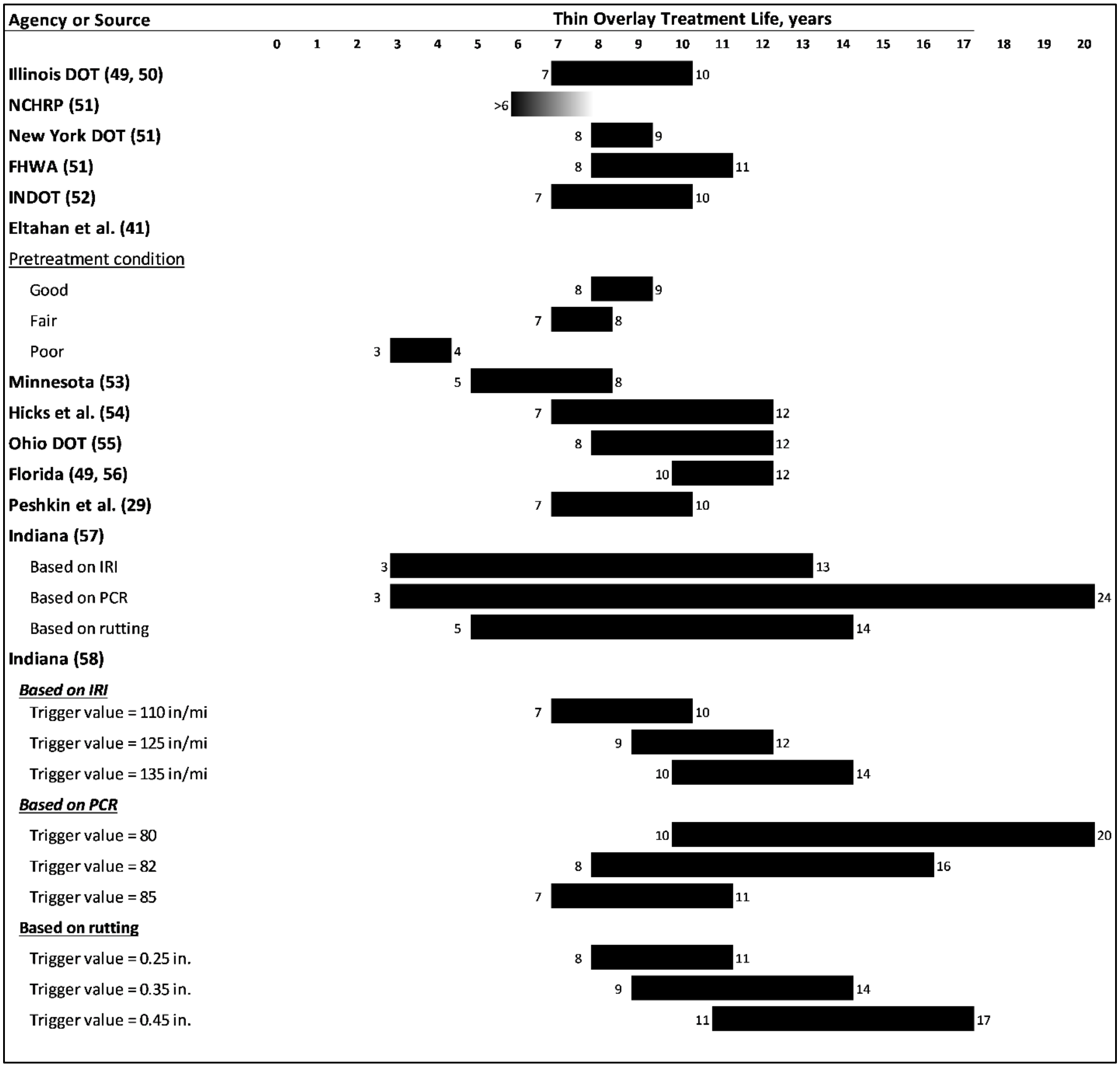


Figure 2-8 Thin overlay surfacing treatment life reported by Irfan et al. (58)

Despite many attempts for quantification, conclusive life-extension numbers are yet hard to find. This is not surprising given the fact that advances in treatment types and applications have created a fluid area in need of constant research.

Treatment types, material quality, traffic volumes, construction qualities, performance requirements, pretreatment conditions, climatic regions, measures of performance, mixture design, and analysis methodologies have all contributed to varying degrees of life-extension predictions. Confounding factors are also inevitable in many studies, which are deemed to be the primary source of inconsistency in assessments.

Any functioning PMS should have treatment-specific performance models that take into account these different effects for prediction of future conditions. The following section is a review on history of performance modeling for pavements, and different types of performance modeling including deterministic and probabilistic models.

2.3 Performance Modeling

Although perhaps arguable, the modern era began with the explosion of Post-World War II road building in the late 1940's and continuing on for the next several decades. The AASHO Road Test, 1958-61, and researchers associated with it, made an enormous contribution to the technology base of pavement management (3). The serviceability-performance concept was first introduced in the AASHO experiment. Before the AASHO experiment, the emphasis was primarily on 'service life' instead of a performance concept (59).

Since the inception of the serviceability-performance concept, great strides have been made in developing performance models. Nevertheless, pavement performance modeling has been one of the most difficult tasks facing pavement engineers as of today (60). Large studies such as the ongoing LTPP studies of the Strategic Highway Research Program (SHRP) have been conducted to understand pavement deterioration behavior.

The serviceability of pavement decreases over time due to the combined effects of environment and traffic loading (32). Pavements deteriorate over time due to changes in material properties, e.g. aging and weathering, and cracking within the pavement structure. Deterioration models predict pavement condition over time, which is a necessary input for planning, maintenance and rehabilitation activities (61,62).

Figure 2-9 illustrates the concepts used to describe pavement preservation and the effects of pavement preservation treatments on pavement performance for a condition index that increases with worsening condition such as crack percentages (9). The immediate change in condition is a function of pretreatment conditions, treatment type, construction quality, and the performance indicator being considered.

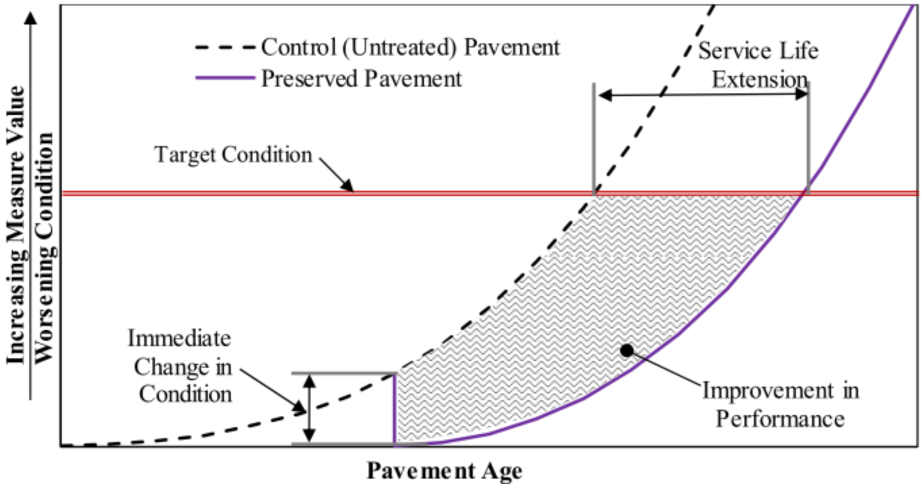


Figure 2-9 Schematic of pavement performance and the effect of preservation features (9)

Sometimes, a specific treatment might not result in an improvement at the time of application, but will have an effect on the deterioration progression. For example, chip seals do not cause an immediate change in IRI, but are expected to reduce the rate of growth of roughness

(34). As discussed in section 1.2, for every PMS some type of cost-benefit analysis should be performed to prioritize different projects. Costs can be simply agency costs (treatment cost) but also include user and work zone delay costs. Benefits can be defined in several ways. One definition is to use the amount of life extension when comparing the treatment with a do-nothing scenario.

The service life extension depends on the target condition threshold. To illustrate, in the example shown in Figure 2-9, a higher threshold results in a wider distance between the control and the treated curves. Another way is to define performance gains as the area bounded by the deterioration curve from the treated and untreated sections and a given threshold value. The optimum treatment would be the one with the lowest cost to benefit ratio.

Two distinct categories for performance modeling can be found in the literature. First is the deterministic models in the form of physical or conventional statistical-based models, and the second are models that by nature are probabilistic such as survival analysis or Markov process. With numerical simulations, the former group of models can also generate responses in a probabilistic setting, however, at the expense of higher computational effort. Following is a brief discussion on the major categories used to model pavement performance data.

2.3.1 Deterministic Models

Deterministic models predict the condition throughout time using a mathematical function of observed or measured values for independent factors and for the system response (e.g. distress level) without taking into consideration the uncertainties associated with the deterioration process. These are a group of modeling approaches that do not consider variations in input variables. However, it is well-recognized that variations are everywhere and inherent to most problems in real-world scenarios.

Physics-of-failure models are considered as deterministic models and attempt to capture the basic physical principles underlying the failure process (63). Nevertheless, deterministic assumption of the pavement system does not prevent the analyst from developing stochastic models later using numerical simulations. Procedures such as Monte-Carlo simulation (MCS) can be implemented to simulate the variation effect within the input variables and obtain the response in a probabilistic setting (3,64–69). Therefore, the goal of such simulations is to make the performance predictions more realistic as opposed to predicting one precise fixed number for future pavement deterioration (68,70,71). Li et al. (72) suggested using MCS combined with a deterministic deterioration model to develop TPMs for a variety of pavement categories and/or individual pavement sections. In fact, the idea of using MCS allows the stochastic behavior (uncertainty) of the pavement deterioration to be incorporated explicitly in the modeling process of PMS without the employment of TPMs (73). Deterministic models can be categorized further to physical- and statistical-based models which are described below.

2.3.1.1 Physical-based Models

Pavement researchers are usually interested in linking material fundamental properties to pavement long-term performance with consideration of a host of surrounding conditions such as traffic type and levels, climatic conditions, etc. Although these models provide reasonably good prediction results, their development sometimes requires years of research to understand dynamics of deterioration in a pavement system. Physical-based models are broadly classified as follows:

1. Empirical models: where a measure of deterioration such as serviceability is related to a measure or estimated variable such as deflection, traffic loads, etc.
2. Mechanistic-empirical (ME) models: which relies on the mechanics of materials. The performance of the pavement is linked to parameters that are mechanics-based. This

method correlates the pavement distress-specific life to pavement responses. For instance for fatigue life modeling, the model correlates the fatigue life to tensile strains and asphalt layer stiffness (74,75). The damage caused by each passage of load is then accumulated using Miner's Rule. Then, the fatigue models can be calibrated to match the performance data by using a shift factor (76,77).

3. Mechanistic models: the most difficult model. The deterioration of pavement structures relies on separate deterioration models for different distress types. The deterioration models include factors such as traffic volumes and load magnitude distribution, climatic effects, and pavement materials to determine separate curves for each pavement structure (78). This model does not rely on an empirical function.

As a drawback, their deterministic nature does not allow them to be easily used to capture the inherent uncertainty in the process of pavement deterioration. In other words, these models are constrained by the fact that they cannot take the stochastic nature associated with the pavement performance into consideration (65,67,68,79). Mechanistic deterioration models are the most difficult to develop. The deterioration of pavement structures relies on separate deterioration models for different stress types which is also dependent on various factors that are not necessarily available, such as actual layer thickness, moduli of elasticity, and cumulative traffic loading (78,80).

2.3.1.2 Statistical-based Models

Statistical-based models have also been used quite frequently and are usually regression models developed by collecting one or more system responses (e.g. pavement cracking level, IRI, etc.) over a sufficient period of time. Regression techniques are powerful tools for prediction, but it is also true that they merely fit a best line to the data. Regression models should therefore be used prudently. To illustrate this shortcoming, consider a case when a high-degree polynomial is fitted to the deterioration data. It may perfectly fit, but when this function projects beyond the bounds of the data the result can be misleading (62). Depending on the level of complexity and project needs, various regression models can be developed including straight-line extrapolations, S-shaped curves, polynomial constrained least squares, and logistic growth models (81). Also, selection of the final model depends on how good data are fitted and how they can well-represent the deterioration curve expected from the particular pavement or treatment type. Therefore, despite having measures for checking model prediction performance, to a degree, it is a matter of subjective decision making. Use of the mentioned statistical models is relatively simple and does not require extensive mathematical background. Also, models can be updated or adjusted using future analysis results and engineering judgment (81). Some of the disadvantages of regression models reminded by Silva et al (81) include:

1. The models require an accurate and abundant set of data. Any regression model is only as good as the data used to develop it.
2. It is necessary to include all significant variables affecting deterioration.
3. Accuracy of the performance model is affected by minor rehabilitation or maintenance activities.

2.3.2 Stochastic Models

Probabilistic models take uncertainties into account and predict the pavement condition as the probability of occurrence in a range of possible outcomes (82). One clear advantage for the majority of probabilistic models is that less data and knowledge of the matter in question is needed. Usually, the underlying fundamental material properties are not required for such an analysis, as opposed to a mechanistic analysis in comparison. The probabilistic models can be categorized into two classes. With the first class, survival analysis methods, the effect of different variables can be gauged similar to a regression statistical procedure. In the second class, Markov models, only a minimal amount of data such as pavement class, pavement condition in year 1, pavement condition in year 2, and the pavement section geometry (78) are needed.

2.3.2.1 Survival Analysis

Survival analysis is an advanced statistical technique which is specifically designed to model time to failure data and has vast applications in the medicine and manufacturing industry (83). Actually, the term "survival analysis" comes from medical fields where, for example, time to death of a cancer patient is forecasted by considering a host of predictors and the corresponding levels. In engineering, the term is more known as "reliability analysis." For pavement deterioration modeling, the very same mathematical concepts are applicable when dealing with a dying pavement. Survival analysis is defined as a method for analyzing data where the outcome variable is the time until the occurrence of an event. The death of a pavement hence can be considered the point in time where a desired distress or set of distresses reaches a predefined threshold.

Survival analysis is useful when dealing with time to failure type data for several reasons. First, time to event data is non-negative and usually does not follow a normal distribution as it is expected in regression or analysis of variance (ANOVA). Second is the issue of censored or truncated data, that happens quite often with ongoing studies when for instance, some subjects have not yet experienced an event (in this case, pavement failure) at the end of the analysis period; and third, non-parametric and semi-parametric models make survival implementation more accessible to various datasets because it does not assume any specific distribution.

For a brief introduction, different types of survival analysis are explained here. If the goal of modeling is to explore the data visually and to find clues on different influential factors, a non-parametric method such as Kaplan-Meier (KM) and Nelson-Aalen estimator (84) are useful for survival and cumulative hazard function estimation, respectively. This is also done prior to running parametric models to get an idea of the survival function (85). A more robust approach would be to use semi- or full-parametric methods, capable of assigning specific distribution to pavement (or treatment) families and extract important information such as risk factors in a setting highly desirable to pavement engineers and practitioners for prediction and decision making. Expressing the probability model for the failure time using a parametric function allows the computation of the expected failure time as well as the variability of the failure time and the computation of confidence intervals and percentiles (86). Perhaps, one of the first comprehensive studies of survival analysis on pavements was conducted by Winfrey and Farrell in 1941 in which pavements in 26 states were evaluated over a 35-year period (87). Approximately, 210,000 miles of construction up to January 1, 1937, of various surface types were involved in the average service life analysis. The average service lives for various surfaces were as follows: 1) soil surfaces, 5-14 years, 2) gravel or stone, 6-13 years, 3) bituminous surface treated, 11-21 years, 4) mixed bituminous, 14-22 years, 5) bituminous penetration, 15-17 years, 6) bituminous concrete, 13-20 years, 7) Portland cement concrete, 17-24 years and 8) brick or block, 18-21 years.

In a study in Louisiana (86), survival fitting was used to model pavement deterioration in a full-scale pavement testing experiment in 1999. The main purpose was to investigate the deterioration trend for pavements with different base designs including the prevalent flexible crushed-stone and in-place soil cement stabilized base compared with a number of other alternatives. It is emphasized that not only predicting the trend is an important goal, understanding the variability in the influential factors is equally important; this will explain why in a pavement section some locations develop more cracks or potholes and some parts do not. Distribution of the pavement service lives coming from the Louisiana DOT (LaDOTD)-AASHTO 1993 Pavement Design Guide methodology was compared with the survival model built using observations and good agreement was reported. However, despite using the parametric survival analysis, the influence of potential predictors was not addressed within the framework of survival analysis and thus the benefits of survival modeling were not fully exhausted.

More recently, Prozzi and Madanat used survival techniques to analyze the AASHO Road Test data. They found that the survival models were superior to the original AASHO method (88). Gharaibeh and Darter (89) conducted a nonparametric survival analysis to investigate pavement longevity for new and rehabilitated pavement sections in Illinois. Both hot mix asphalt (HMA) and Portland Cement Concrete (PCC) pavements were included in the study and separate analyses conducted for the northern (cold) and southern (warm) regions. Failure curves were developed for different families of the pavements in different climates. However, this was mostly a nonparametric study and hence cannot be used for inclusion in a pavement management program. A regression equation was provided to capture the shape of the deterioration curve. However, the equation did not include the covariates affecting the service life.

When data are abundant, a parametric survival analysis is recommended to quantify the effects of different variables. Such survival study was undertaken by Wang et al. (90) to model fatigue cracking life for flexible pavements based on long-term pavement performance (LTPP) data. Initially, 22 explanatory variables available in LTPP dataset were entered into the model. Crack percentage was considered for defining failure and for simplicity and uniformity it was necessary to convert longitudinal cracks to area (fatigue) cracking. On the bases of previous research, an 18 in. influence area was considered based on wheelpath width. Also, a failing threshold is needed to be defined in survival analysis. LTPP cracking data analysis revealed that for all the studied years, when area cracking reaches 20 m^2, a sudden increase in cracked area will happen for the following year. Hence, this value was considered a failing point. It is to be noted that each LTPP section is 500 ft long and 12 ft wide. Therefore, the total area of a section is 6000 ft^2 and 20 m^2 (215.3 ft^2) of cracking corresponds to 3.6 % of the section area. From the Moving Ahead for Progress in the 21st Century (MAP-21) criterion established by FHWA, 5% is designated as threshold from good to fair condition and therefore, 3.6% is a bit conservative. Out of 22 variables, the regression analysis suggested that only 6 were significant. These were asphalt layer thickness, PCC base layer thickness, freeze-thaw cycles, intensity of precipitation and average traffic levels.

Liozos and Karlaftis (91) developed a probabilistic duration model to predict crack initiation for a large European database encompassing 15 countries. In distress prediction, one important question is whether pavements that resisted cracking (or any distresses) up to a certain point, will have a higher chance of cracking in the next period of time, or conversely, it might be the case that the probability of cracking actually becomes less since the pavement has already exhibited high resistance to cracking for a long time. Deterioration modeling can provide an answer to this question through assessing the hazard rate (also known as instantaneous rate of failure). Several theoretical distributions were fitted to data and the log-logistic was selected based on the log likelihood ratio test. As expected, traffic and climate had a considerable effect on crack initiation.

Irfan et al. (58) determined the service life of thin hot mix asphalt overlay for Indiana using survival analysis. In the past, one serious issue with preservation life estimation was that no universal value was agreed upon for the different distresses threshold values. All other factors remaining the same, the perceived life of a given treatment may vary from agency to agency depending on the established applied threshold for that treatment. This shortcoming is well addressed as part of the Indiana study by generating several survival plots showing the different deterioration curves where threshold values for international roughness index (IRI), pavement condition rating (PCR) and rut depth were different. Today, condition-based threshold values are defined as part of the MAP-21 legislation. Hence, the perception of pavement failure is unified across the board. The study found that the thin overlay service life is in the range of 7 to 11 years.

Survival analysis was performed on flexible pavements constructed between 1985 and 2000 for both the priority and general highway systems in the State of Ohio (92). The authors concluded that survival analysis can be used to determine influential factors relating to treatment performance. The Highway Design and Maintenance Standards Study (HDM), along with the World Bank, incorporated survival analysis to predict the fatigue cracking initiation in the HDM-III model (93).

Yu et al. (92) applied a semi-parametric survival analysis known as Cox proportional hazard model to estimate the effects of influential variables on pavement service lives in Ohio. It was found that the overlay thickness and annual average temperature have positive effects on pavement service life, which means that thicker pavements and those in higher temperature areas have longer service life. Traffic loading, structural deduct and precipitation decrease the survival life. Structural Deduct (SD) is contained within the PCR, but indicates those distresses which may be related to the structural integrity of the pavement (94). Higher traffic loading, higher structural deduct and higher precipitation all lead to shorter service life. Eltahan et al. (41) investigated the effect of different asphalt preventive maintenance strategies using survival analysis. It was concluded that the failure probabilities of pavements that initially were in poor condition are two to four times higher than those in better condition. It is well-established that the application of preservation treatments can delay the deterioration rate of pavements if the right treatment is selected at the right time for the right place (29,95,96).

For performing the survival analysis, a common assumption in past research was that the hazard function (i.e., the conditional probability that a pavement lives beyond time *t*, given that it has survived up to time *t*) and the effect of the influential variables on the asset service life are homogenous across observations. Anastasopoulos and Mannering (97) considered these limitations by exploring heterogeneity in the survival process and in the explanatory variables. It means that some influential variables may have varying effects on time to failure of different pavement sections, while others may have definitive effect.

Survival analysis has also been used to assess effectiveness of rehabilitation strategies. In a forensic study conducted by Chen et al. (98) four types of composite pavement rehabilitation methods including mill and fill, overlay, heater scarification (a technique for hot-in-place recycling), and rubblization were evaluated. Different distress indicators of IRI, PCI and reflective cracking were considered and it was shown that survival curves would be dependent on the choice of performance indicators; for example, composite pavements are highly susceptible to reflective cracking. A univariate survival analysis (Kaplan-Meier) was first conducted to visually explore the survival lives of different strategies. After gaining an understanding of the deterioration path of different rehabilitation strategies, a full-parametric analysis was followed to quantify the effects of potential explanatory variables on survivability of pavement sections. HMA thickness for the mill and fill, scarification and overlay had the predominant impact in extending the pavement lives.

Such data-driven analysis helps decision makers to choose the best option for their maintenance activities.

Wang (99) did a non-parametric (distribution free) survival study to assess time to failure for AC overlays from the LTPP sections including mixtures with and without Reclaimed Asphalt Pavement (RAP). Since it was a non-parametric study, pavement sections were grouped based on the overlay thickness, pre-overlay treatment condition, and climatic region. Based on these analyses, results consistently indicated that the field-performance of mixtures containing RAP is driven by their fundamental material properties (i.e., the reduced cracking resistance and increased stiffness). Such information and applications of survival analysis is critically important for life cycle cost analysis (LCCA) or life cycle assessment (LCA) of different types of pavements.

2.3.2.2 Markov Chain Model

The Markov probabilistic model is the primary stochastic model used in deterioration modeling of infrastructure assets. Its application has been widely reported for infrastructure management such as water and electricity networks (100,101). For a pavement network, pavements with similar conditions are grouped to build a model representing a family of pavements. It is of interest to have models for different predictors and levels, however, one shortcoming of such modeling will be the lack of enough data, since in the process of grouping, the database for each pavement family shrinks to a degree that prediction strength may no longer be desirable. Thus, the grouping stage becomes a compromise between model prediction accuracy and the number of pavement families. Where possible, a probabilistic approach is favorable compared to a deterministic one, like a regression method, because regression models do not inherently recognize the latent nature of pavement deterioration. Deterioration is an unobservable quantity, whereas its indicators are observable in the form of surface distresses such as cracking, rutting, etc. (61). After the grouping phase, transition probability matrices (TPM) need to be developed. Traditionally, they have been derived using one of two methods. The standard approach is to segment the historical pavement conditions into ranges, then the probability of migrating from one condition to another is calculated using the available historical data (61,68). Alternatively, a panel of experienced engineers estimate the probabilities using expert opinion (68). This second method should be considered as a last resort option where the historical pavement data for the region is not available.

Pavement deterioration is said to be probabilistic because pavement deterioration cannot be predicted with certainty because of the effect of unobserved explanatory variables, presence of measurement errors, and the underlying stochastic nature of the deterioration process (61). The condition index to be used can be the individual performance indices such as roughness, rutting and cracking, or a composite index. In pavement preservation, such effectiveness typically indicates an improvement of the surface condition (e.g., pavement condition rating (PCR), rutting depth, pavement quality index (PQI), surface deflection, present serviceability index (PSI), etc.) or a deterioration of the surface roughness (e.g., international roughness index (IRI), roughness number (RN), etc.) (102). The Markov model is considered an alternative to deterministic models because it is well-developed and based on simple multiplication of matrices (103). Kulkarni (104) outlined several advantages in using Markov probability decision process in pavement management:

1. Future decisions on preservation actions are not fixed but depend on how the pavements actually work.
2. Actions to be taken at present can be identified; also, likely actions to be taken in the next few years can be identified with a high degree of probability.

3. It is possible to compare the expected proportions in given condition states with the actual proportions observed in the field, and in this way possible defects in construction, materials, quality control, and so on, can be identified.
4. The probability-based Markov deterioration model ensures that modeled pavements will continue to have the classic pattern of worsening condition with age; and
5. The Markov process is a natural tool to use in alliance with dynamic programming to produce optimal solutions.

It should be reminded that a Markov prediction model is governed by three restrictions:

1. The process is discrete in time whereas pavement deterioration is continuous in time; to treat as discrete in time, the condition of the network is analyzed at specific points in time. This usually takes the form of duty cycles of 1 year (68).
2. The process should have a countable or finite state space (68). Actually, in a real world scenario, infinite number of condition states are possible. However, to satisfy the Markov assumption, a finite number of conditions is considered by discretizing the range of possible outcomes.
3. A Markov process is a mathematical model for the random evolution of a memoryless system (105). The process should satisfy the "Markov property". The property states that the future state of the process only depends on its present state. In other words, it is not important which path a pavement section has taken to reach its current condition. This assumption holds when traditional Markov chains are to be used.

The major challenge in using Markov models is the difficulties related to estimation of the transition probability matrices (TPM). Most TPMs are constructed by one of the two methods outlined below (66):

1. Pavement condition deterioration is modeled as a time-independent Markov process, and the probabilities of moving from one condition to another are identified using individual interviews and questionnaires. This happens mostly in places where an inventory of the pavement system monitoring is not accessible.
2. A large number of functionally and structurally categorized pavement maintenance history data are observed under different pretreatment conditions.

Butt (62) enforces the case for using the probabilistic methods by emphasizing that “the rate of deterioration is uncertain, therefore, the predictive model should portray this rate of deterioration as uncertain, rather than using the erroneous assumption of deterministic behavior.” The Arizona Department of Transportation (ADOT) was among the first states to report successful integration of Markov Chain modeling techniques in a PMS. The PMS developed by Golabi et al. (106) for ADOT implemented a dynamic programming and probabilistic model. During the first year of implementation, fiscal year of 1980-81, the system saved 14 million dollars (almost one-third of Arizona's preservation budget) (104).

One shortcoming of Markov models is that the transition probability matrix is considered homogeneous or stationary (107). It means that, regardless of the pavement age, deterioration behavior is the same throughout the life of the pavement, which intuitively is not a good assumption since variations always exist in traffic, weather, etc. and the fact that an aged pavement is expected to behave differently than a new surfaced road. Despite that, the assumption is generally accepted in many studies to avoid mathematical complexity (71). In a paper published in 1987, the issue was tackled by using the zoning scheme for the Markov model which was also used for the ADOT PMS (62). The design life of the pavement was divided into zones, each one representing a specific number of years. The choice of zone duration depends on data availability and model prediction ability.

Other uses of the Markov process are abundantly reported in the literature. Jiang et al. (108) used a Markov model to develop a comprehensive bridge management system for Indiana Department of Highways (IDOH). In their methodology a zoning technique borrowed from the previous study by Butt et al. (62) was used. Also, to determine transition probabilities from one state to another, a procedure involving a non-linear optimization technique was implemented and the model was validated by comparing measured and predicted bridge condition values. Jiang and Sinha (109) introduced and recommended the MCS technique to be used in conjunction with transition probability matrix on the findings that condition predictions using the Markov chain alone could be biased. It is shown through a working example on bridge performance modeling that Markov chain analysis results in overestimated costs, and unrealistically, a large proportion of bridges were determined to be in need of repair where in reality, repair needs were lower. Wang et al. (69) conducted a study to address the inadequacies of the original PMS prediction model used by ADOT; TPMs used before were only able to model pavement deterioration, and could not account for condition enhancements taking place by rehabilitation strategies. The Chapman-Kolmogorov method was used to develop logical extension of the transition probability matrices from a single step to long-term pavement behavior. As a result, the concept of pavement probabilistic behavior curves (PBC) was established (69).

Silva et al. (81) compared the Markov probability model with a logistic growth model using data from two Michigan counties. It was shown that both models provided adequate predictive ability to be used in the Michigan PMS named RoadSoft. It was noted that a probabilistic model makes more sense since it represents future performance as a probability distribution, not as a single condition state. From a different perspective, the Markov TPM can predict the distribution of future pavement conditions in a network of roads, rather than the future condition of a single pavement (68). Therefore it is more suitable for a network level management process (73). In a study conducted for the Ohio Department of Transportation (ODOT), Tack and Chou (78) used the Markov process to investigate whether or not significant differences exist in pavement performance for pavements in different districts. Their goal was not to develop performance models but to perform hypothetical tests using the Markov model to investigate if differences exist among districts. A novel MCS procedure was used in conjunction with Markov models to realistically model the deterioration path. It was shown that there are significant differences among districts, but possible contributing factors should be investigated using a different approach.

Abaza et al. (110) developed an integrated pavement management system with a discrete-time Markovian prediction model. A discrete-time model considers transition probabilities to remain stationary throughout the life of the pavement, which is a simplifying assumption but has been used because of its simplicity. Also, the number of possible state conditions was reduced to 5, representing excellent, good, fair, poor, and bad conditions, respectively. This was a divergence from previous studies where higher number of condition states were usually considered. The authors explained that “the use of a larger number of condition states requires a larger number of M&R variables which complicates the computational process, and requires more detailed and expensive pavement distress records for the estimation of the corresponding transition probabilities.” Ortiz-Garcia et al. (68) published their work focusing solely on TPM estimation. Their work was in recognition of the fact that many practitioners have difficulty extracting transition probabilities from the historical pavement condition data. In their work, three new methodologies were proposed and the most suitable was recommended. The first method assumed that the original raw data are available. In the second method, a regression equation obtained from the original data was assumed to be used, and in the third method, the distribution of the original data (aggregated to the condition rating bands) were used. All of the methods relied on the non-linear optimization of an objective function which minimized the distance between the measured and the forecasted property in question. It is shown that method number 3 produces the most favorable results.

Markov modeling can also be used to enhance the decision-making process at a network-level PMS as well as for specific research purposes. In a study conducted by Nasseri et al. (111) on the pavement condition survey database for the Florida Department of Transportation (FDOT), it was demonstrated through a statistical analysis that grouping pavements is helpful and a necessity when constructing TMPs. Two major groups consisting of pavements with low-structural-integrity sections (implied by high cracking index at the time of rehabilitation) and another group consisting of high-traffic roads were considered. An interesting finding was that contrary to the general funding schemes that prioritizes higher trafficked roads over the lower trafficked ones, there can be cases where a lower volume road with high cracking should be prioritized over a higher volume road with less cracking. Because a highly cracked section (due to a delayed rehabilitation) is shown to perform worse even when having lower volume traffic and therefore should be prioritized (111).

Many pavement maintenance scheduling optimization programs have used Markov modeling for their pavement performance prediction. In one such work, Wu and Flintsch (71) explained how engineering judgment might be used in constructing TPMs. For example the assumption of Markovian transition probabilities could be that 1) the condition of pavement sections will not improve without any maintenance applied and 2) pavements sections will not deteriorate to more than one or two lower conditions in one transition, which is typically one year.

2.4 Summary

Modern PMSs use pavement performance models to predict future conditions for different types of pavements. The reliable prediction of future conditions is instrumental in long-term planning of the road M&R activities. In recent decades, a lot of research has been conducted to provide such models for newly constructed as well as treated pavements. To be reliable, the performance models should come from studies that were highly controlled, which was seldomly the case. Besides, in controlled studies such as LTPP, the types of the applied treatments are limited, as the study sections were built decades ago. As such, the type and innovation of preservation treatments used cannot satisfy today's needs. In addition, many studies were typically concerned with one type of treatment rather than looking at the broader range of treatments. In such a context, broader conclusions and comparative assessments cannot be made. The present study is an attempt to address the mentioned shortcomings.

This chapter was also a literature review on different modeling techniques, their underlying assumptions, benefits and shortcomings. In the next chapter, the preservation study is explained, field observations are explored, and the methodologies used to model treatment performance are provided.

CHAPTER THREE

METHODOLOGICAL FRAMEWORK

3.1 Field Study Description

Given the important role that preventive treatments play in a PMS, understanding the survivability of these treatments has the potential to provide improved resource allocation and more effective use of public funds. Past research has been instrumental in expanding the knowledge on pavement preservation (4–6,9,14,29,35). Most studies relied on databases of state DOTs, highway agencies and the long-term pavement performance (LTPP) program. The types and innovation used in such studies are usually limited in scope since local and state agencies are unwilling/unable to accept the risks associated with innovative yet unproven preservation techniques.

To address that concern, NCAT as one of the leading research institutions in the field of flexible pavements, included pavement preservation in the facility's fifth research cycle in the summer of 2012, which then was initiated and sponsored by seven state DOTs, plus FP2 Inc. As of 2019, the research is still ongoing and the number of sponsors has increased to 23 including 21 state DOTs, FHWA and FP2 Inc.

The prospects of conducting exclusive research on pavement preservation lead NCAT to build test sections on a low-volume roadway, Lee County Road 159 (LR-159), in a location close to its main facility (Figure 3-1). The off-track test location provided ample opportunities for placing and testing innovative treatment types and combinations by leveraging live traffic. It is to be noted that models developed here are a first step toward life-extending quantification of the treatments and should be refined over time using actual pavement management performance data (112).

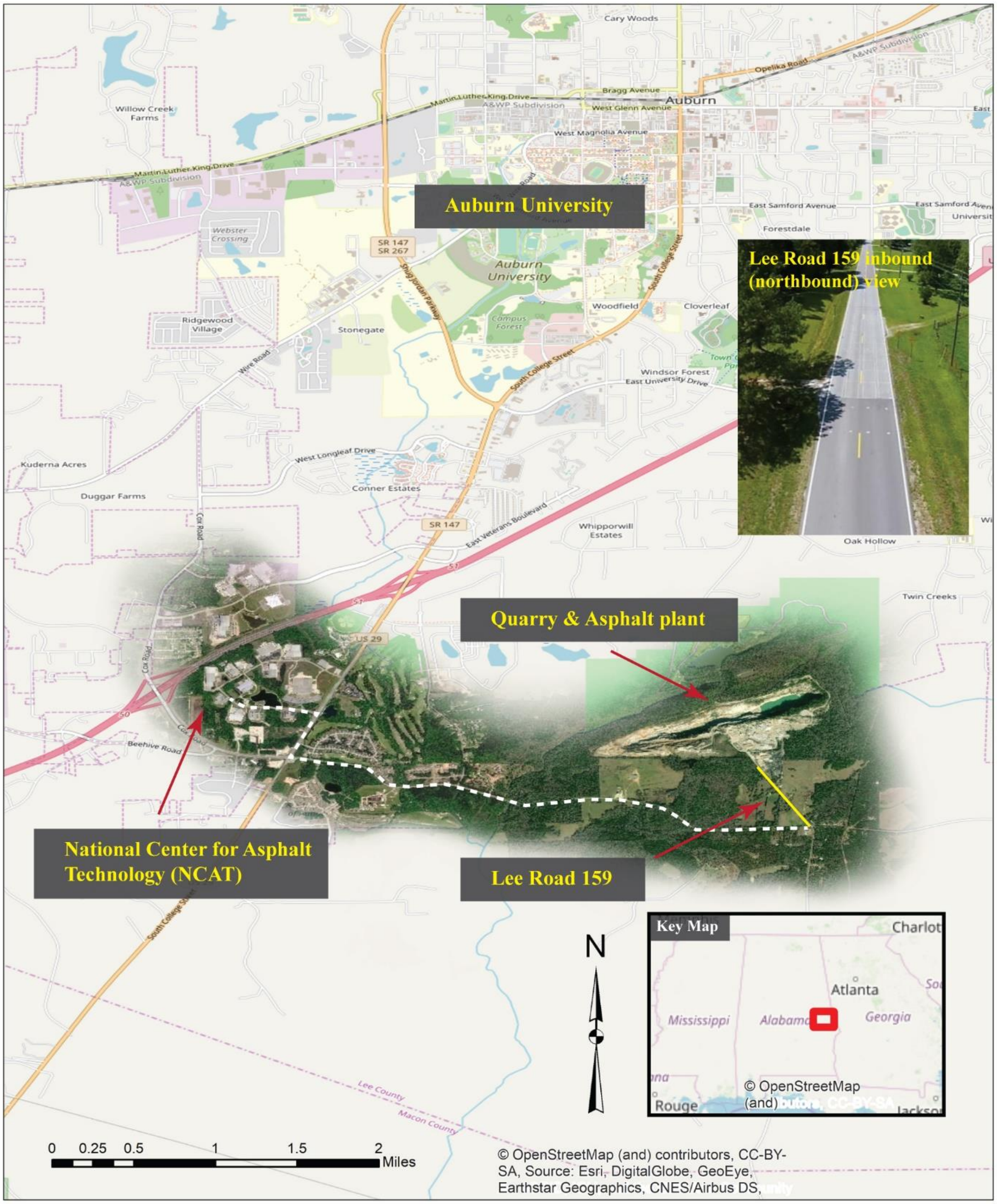

Lee Road-159 Location in Auburn, Alabama

Figure 3-1 Lee Road 159 location close to NCAT main facility

3.1.1 Traffic Condition

LR-159 is a two-lane county road that provides a dead-end access to a quarry and asphalt plant, as shown in Figure 3-2. Traffic on LR-159 includes more than 60% trucks due to the trucking operation to and from the quarry. It has a unique condition in terms of traffic loading because trucks are empty in the inbound direction (northbound), and return full in the outbound direction (southbound), producing a largely different number of equivalent single axle loads (ESALs) in each direction. Thus, this one experiment can be thought of as two experiments, composed of lower and upper traffic loading bounds, but both in the domain of low volume roads. After 7 years, the inbound and outbound directions had accumulated approximately 100,000 and 1,000,000 ESALs, respectively. Traffic level is one of the factors influencing the treatment performance. To reflect the traffic loading impact, the ‘lower bound’ and ‘upper bound’ traffic level terms are used throughout this study instead of using the ‘traffic direction’ term.

Figure 3-2 Traffic loading conditions for LR-159

3.1.2 Construction History and Preventive Treatments

County records indicate that original construction of Lee County Road 159 was conducted in 1974. Since then, two resurfacing activities were performed prior to the application of the treatments for the PG Study, the last of which took place in 1999. The existing pavement structure at the time of the application of preservation treatments consisted of approximately 5.5 inches of HMA layer over 6.0 inches of granular base. Figure 3-3 shows the results from eight cores taken along the length of the project.

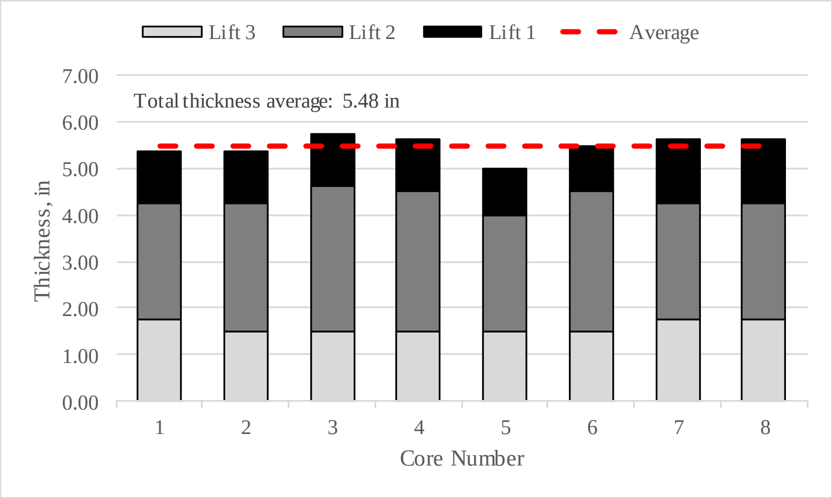


Figure 3-3 HMA thickness from cores **(113)**

Cores were taken from locations in the left and right wheel paths, as well as between wheel paths. The results confirmed the presence of three HMA lifts with a total thickness average of 5.48 inches. Test sections consist of 23 different preservation treatments and 2 control sections, which covers a broad range of treatments; from light preservation strategies such as crack filling/sealing and rejuvenating fog seals to more elaborate techniques such as chip seals, cape seals and thin overlays. Combinations of them were also included for assessment. Two sections were left untreated as control sections with low and high initial cracking conditions. Table 3-1 provides the treatment names and their definitions.

Table 3-1 Preventive treatment definitions applied on LR-159

Section No.	Treatment	Definitions
1	Rejuvenating fog seal	Light emulsion CMS-1P(QB) grade sprayed at a diluted rate of approximately 0.085 gal/yd^2 using a distributor truck.
2	FiberMat® chip seal	Glass fibers sandwiched between two layers of emulsion CRS-2L grade, using a specially developed vehicle by chopping the fibers on-the-move and prior to application of ASTM D448 size no. 89 granite aggregate, which was then rolled into the surface.
3	Control section w/low cracking	Untreated HMA section with 4.0% cracking at the time of treatment in the summer of 2012.
4	Control section w/ high cracking	Untreated section with 16.1% cracking at the time of treatment in the summer of 2012.
5	Crack sealing only	Standalone crack sealing using rout & seal method in the inbound lane with crack width equal to 5/8 in. and blow & seal in the outbound lane with the crack width less than 1/4 in. Sealant material conformed to ASTM D6690.
6	Single layer chip seal	Single layer of chip seal designed using the McLeod method (114) with an asphalt emulsion grade of CRS-2HP and a rate of 0.29 gal/yd^2 prior to application of a single-size ASTM D448 no. 89 granite aggregate. Finally, rolling operation was performed using a pneumatic tire roller.
7	Single layer chip seal with crack sealing	Crack sealing was applied followed by a chip seal layer with the same materials and application rates as sections 5 and 6.
8	Triple layer chip seal	Chip seal layers designed using the McLeod method (114) and applied in three consecutive layers with single chip sizes of 7 , 89, and W10 for the first, second and third layers, respectively. CRS-2HP emulsion grade with as built rates of 0.28 gal/yd^2 for the first and the second layers, and 0.16 gal/yd^2 for the last layer were used.
9	Double layer chip seal	Chip seal layers designed using the Mcleod (114) method and applied in two layers with single chip sizes of 7 and 89 for the first and second layers respectively. CRS-2HP emulsion grade with as built rates of 0.30 and 0.39 gal/yd^2 for the first and the second layers was used.
10	Cape seal	A chip seal layer was applied followed by a Type II micro surfacing layer. For the chip seal, CRS-2HP grade emulsion and a single-size no. 89 aggregate were applied. The micro surfacing emulsion grade was CSS-1HP, and the aggregate type was limestone. Portland cement was used as filler. Micro surfacing was designed and applied following the guidelines outlined in ISSA A143 (115).
11	Single layer micro surfacing	A Type II micro surfacing treatment was designed and applied following the guidelines outlined in ISSA A143 (115). Emulsion grade was CSS-1HP, aggregate type was limestone. Portland cement was used as filler.
12	Single layer micro surfacing with crack sealing	Crack sealing was performed first, followed by application of a single layer micro surfacing, with the same procedures and materials indicated for sections 5 and 11, respectively.

Table 3-1 Continued. Preventive treatment definitions applied on LR-159

Section No.	Treatment	Definitions
13	Double layer micro surfacing	Two layers of micro surfacing were applied consecutively, after allowing proper cure time (approx. 45 minutes).
14	FiberMat® cape seal	A FiberMat® chip seal layer was applied as described for section 2, followed by the application of a Type II micro surfacing layer as described for section 11.
15	Scrub cape seal	A process similar to a conventional cape seal layer described for section 10 was followed with the difference that the first layer consisted of a scrub seal.
16	Scrub seal	Scrub layer application was performed by spraying a layer of emulsion CMS-1P(CR) grade, and pushing it into the asphalt surface by a set of brooms, followed by spreading the ASTM D448 size no. 89 granite aggregate with an as built applicate rate of 19.9 lb/yd^2 and rolling it.
17	FiberMat® chip seal	Same as section number 2.
18	[1]HMA cape seal	A 4.75 nominal maximum aggregate size (NMAS) thin virgin mix with PG67-22 binder applied over a FiberMat® chip seal layer.
19	Virgin thinlay with PG67-22	A 4.75 NMAS thin virgin mix with PG67-22 binder was applied on pavement surface.
20	Virgin thinlay with PG67-22 on 100% foamed recycle base	A 4.75 NMAS thin virgin mix with binder PG67-22 applied on 100% foamed recycled 6 in. inlay.
21	Virgin thinlay with PG76-22	A 4.75 NMAS thin virgin mix with PG76-22 binder applied on pavement surface.
22	Ultra-thin bonded surface course	The mixture used had a 12.5 mm NMAS and was designed with a compactive effort of 50 gyrations. Granite was used as the aggregate source with a gap graded gradation. The asphalt binder used was a polymer modified PG 76-22 grade at an in-place optimum content of 5.4%.
23	50% RAP thinlay	A 4.75 NMAS with 50% fractionated RAP (54% aged binder) overlay with PG67-22 virgin binder
24	5% RAS Thinlay	A 4.75 NMAS with 5% post-consumer RAS (19% aged binder) overlay with PG67-22 virgin binder
25	HiMA Thinlay	A 4.75 NMAS virgin overlay with PG88-22 high polymer-modified binder.

[1] Note: The thin overlay was designed using the Superpave method with a compactive effort of 75 gyrations and an air void content of 4.0%. The virgin aggregates used were limestone and sand. All mixes contained 1.0% hydrated lime (by weight of dry aggregate) as an antistripping agent.
In all thin overlay sections, the design overlay thickness was 3/4-inch for an HMA placement rate of 80 lb/yd^2. A tack coat was applied to the existing surface using a NTSS-1HM emulsion (trackless tack) at an undiluted rate of 0.06 gal/yd2. In Section 20, a full-depth reclamation was performed where the entire HMA thickness and part of the underlying base material were removed and treated with foamed asphalt to produce a 6-inch base.

3.1.3 Data Collection and Preparation

Field data collection has been in progress since August 2012. Each test section is 100 feet long and is divided into 40 subsections, 20 in each direction, with dimensions of subsection equal to 5 by 10 feet, as shown in Figure 3-4. This translates into a total of 1,000 subsection units, having varied initial conditions. Also, shown in the figure is the red shaded area that is not considered part of the crack mapping scheme. This area often contained longitudinal cracks which are due to the construction joint when LR-159 widened from a one-lane to a two-lane road well before the preservation study began.

Subsections act as the smallest analysis units, creating a more favorable size population for the analysis. An interesting feature of these subsections is that they can be excluded from the analysis if a special issue arises, such as a failure due to a drainage problem because it would not be fair to attribute such failures to the performance of the treatment itself.

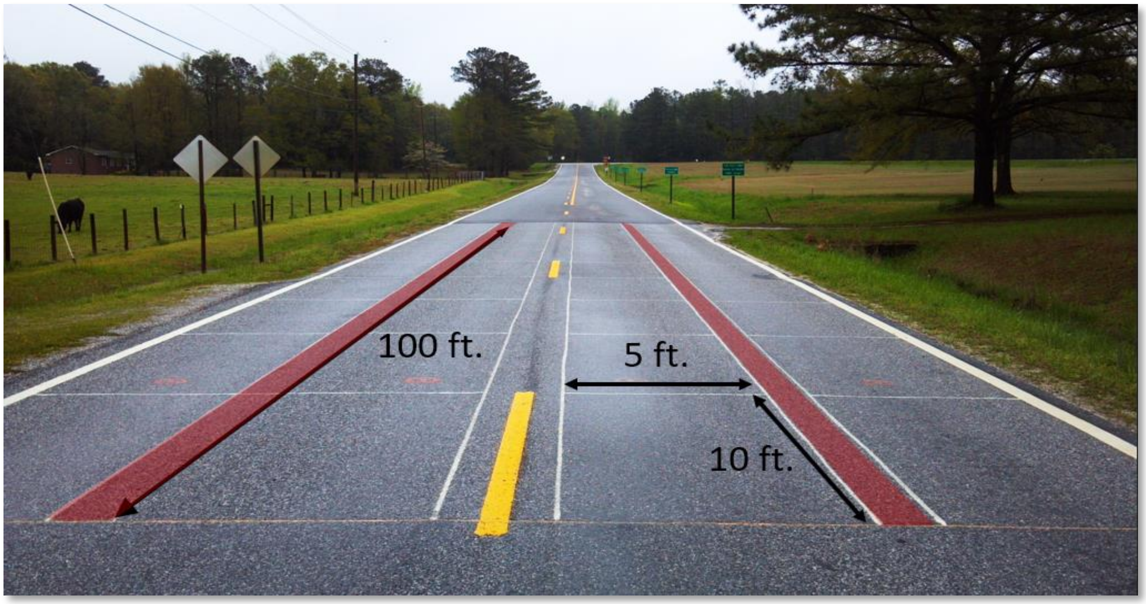


Figure 3-4 Subsection dimension and layout for LR-159. (Shaded area is not counted in crack percentage calculations)

Data collection is performed using the vehicle shown in Figure 3-5. This vehicle is equipped with a laser system for measuring rutting, an inertial profiler for IRI measurement, and high-resolution cameras for pavement scanning. In addition, other parameters such as macrotexture, friction, surface deflections, and moisture were measured. Roughness, rutting and macrotexture have been measured on a weekly basis, while crack mapping, Falling Wheel Deflectometer (FWD) testing, and surface friction testing have been performed on a monthly basis.

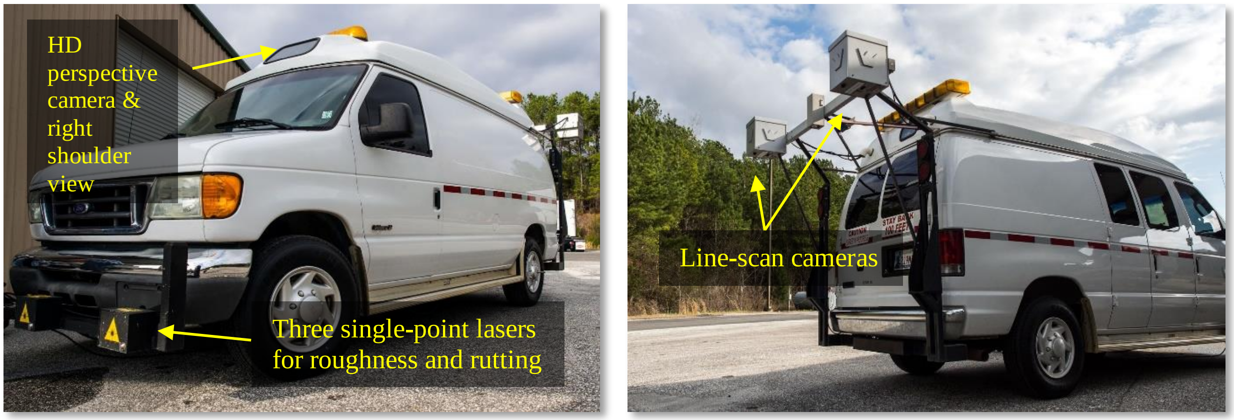


Figure 3-5 Digital inspection vehicle for distress data collection

3.1.4 Data Error Filtering

Data collection and collation procedures are subject to errors and unusual observations. As such, certain data quality controls were performed: 1) crack percentages should always be increasing since no maintenance or rehabilitation was done after the initial preservation at the start of the study. By looking at specific dates where such instances occur and also dates before and after it, proper corrective actions were applied; 2) a handful of subsections had premature failure due to a drainage issue related to the adjacent culvert and thus were removed from the dataset. Other example was in a section where trucks are constantly turning to enter/exit the RAP yard at the asphalt plant. It was agreed that inclusion of these subsections would be unfair since road conditions should be approximately uniform across all treatments to engender an impartial analysis; 3) abrupt increases in cracking followed by a retreat to previous values were observed in some cases. These anomalies happened mostly in crack sealed sections where the sealed area was mistakenly counted as cracking. The whole dataset was checked by looking not only at the isolated incidents but also at the entire spectra of data for the specific subsections. This was done using a more stringently applied quality control procedure for several dates, accompanied by field visits. These more tightly controlled dates were then used as benchmarks for checking other dates. Necessary corrections were made using said benchmarks to make sure other dates conform to the benchmark's cracking levels. As an example, for section 12, micro surfacing with crack sealing, the cracking level unusually increased on a particular date, which led to a field visit for data quality check. It was found that some of the crack sealed areas were mistakenly mapped as cracks. To address the issue, the section was re-mapped. In many cases, forensic investigations were accompanied along with digital mapping in order to establish similar benchmark values so that cracking dataset can be checked against physical evidence. Similar dataset issues were commonly reported in previous works (62,65).

3.1.5 Performance Measures and Threshold Values

The Moving Ahead for Progress in the 21st Century Act (MAP-21) legislation required that performance measures be established for the Interstate Highway System (IHS). In January 2017, the Federal Highway Administration (FHWA) issued the Final Rule (effective February 17, 2017) to implement the performance management requirements of MAP-21 and the Fixing America's Surface Transportation Act (116).

The National Performance Management Measures: *Assessing Pavement Condition for the National Highway Performance Program and Bridge Condition for the National Highway Performance Program (PM2) rule* established ride (IRI), rutting, faulting, and cracking percent as the pavement condition metrics, per 23 CFR 490.309 1 – “Data Requirements.” States must collect and report these condition metrics to the Federal Highway Administration (FHWA) Highway Performance Monitoring System (HPMS) in accordance with the HPMS Field Manual (117). Based on the HPMS manual definition, cracking percent is the percentage of the total area exhibiting visible fatigue type cracking for all severity levels in the wheelpath in each section reported to the nearest 1% (118). Although MAP-21 cracking threshold was followed to define failure, there are some differences in the way cracks were measured in this study versus MAP-21. Table 3-2 compares MAP-21 cracking percent estimation with the current study.

Table 3-2 Cracking percent estimation in MAP-21 and the present study

	MAP-21	**Current study**
Analysis unit	0.1-mile section	5 ft. wide by 10 ft. long subsection
Cracking type being mapped	Fatigue type	Fatigue, longitudinal, transverse
Severity	Considered	Not considered
Wheelpath width/Crack zone of influence	39 in. (Wheelpath width)	12 in. (zone of influence)
Crack Sealing differentiation	No differentiation	Sound sealing/filling measured as crack treatment not cracks
Maximum cracking percentage	65% for 10-feet-wide lane	100% for a section

Note that crack measurements for LR-159 were performed on individual subsections and then calculations were aggregated for the entire section, whereas cracks in MAP-21 are mapped and estimated for a 0.1-mile-long section. Also, different types of cracks were mapped in this study and unified into a single percentage while for MAP-21, only fatigue cracking in the wheelpath is considered. This leads to a maximum 65% cracking for the MAP-21 and 100% for the current study for a test section. Hence, 20% failure threshold defined based on MAP-21 and the one implemented in this study would not be exactly identical. For MAP-21, 20% cracking in a 10-footwide section means approximately one-third of the section has fatigue cracking, but for this study, it implies one-fifth has various cracking types. The two approaches can yield close crack percentages if fatigue cracking is dominant in a section.

Some of the differences in crack estimation methodology stems from the differences in analysis units defined for MAP-21 and the present study. For instance, consideration of a 65% maximum cracking is logical if the entire section is considered for analysis since between wheelpath areas do not contain fatigue cracking and will not be counted. Yet 65% is not tenable if subsections are to be considered as analysis units, because when cracks spread across the pavement width, cracks and its impacted region usually covers the entire subsection. Thus, cracking level can reach 100% of the subsection area. The maximum cracking area that can be considered in MAP-21 in a 0.1-mile segment is 3,432 ft^2. Therefore, maximum cracking percentage for different section widths using a wheelpath width of 39 in. can be calculated, which is shown in Table 3-3.

Table 3-3 Maximum asphalt concrete cracking percentage for different section width for MAP-21

Width, ft.	Max AC cracking, %
8	81.3
9	72.2
10	65.0
11	59.1
12	54.2
13	50.0
14	46.4
15	43.3
16	40.6

Note that the subsection consideration was essential for estimating the effect of initial condition in this study. In fact, dividing each section into smaller units has simulated a very large experiment where several sections with the same features (i.e. structure, treatment, etc.) but different initial conditions were needed. Such an experiment would need years of preparation, data collection and would be very expensive to conduct.

MAP-21 considers severity levels for fatigue cracking. Although severity was not directly considered in this study, the notion of influence zones addresses the severity levels indirectly. When there is a high severity fatigue cracking, the width of the cracking area is larger, and so is the extent of the areas influenced by the cracked region. Likewise, the rationale is valid for low severity cracking where a smaller cracked area results in a smaller extent of the influenced area.

Also, there is no distinction between sealed and unsealed cracks in the MAP-21 procedure. Since crack sealing/filling are considered preservation strategies, crack sealed areas that are in good condition (crack channel not re-appearing on top of the seal) were not mapped and thus not counted as cracks.

For the current study, preliminary assessment of the performance data revealed that among all the collected measures, only cracking shows an upward trend and therefore was used as the performance index for the analysis. The failure criterion considered was 20% cracking for the entire section which corresponds to ‘poor’ condition, as defined by MAP-21 by the Federal Highway Administration (FHWA), as shown in Table 3-4. No meaningful trend is observed for roughness and rutting after 7 years of service and these indicators remained in ‘good’ category based on said definitions.

Table 3-4 Condition ratings for MAP-21 performance measures **(119)**

Condition Rating	% of Area Cracked	Rutting, in (cm)	IRI, in/mi (m/km)
Good	< 5%	< 0.20 (0.51)	< 95 (1.5)
Fair	5 – 20%	0.20 – 0.40	95 – 170
Poor	> 20%	> 0.40 (1.02)	> 170 (2.7)

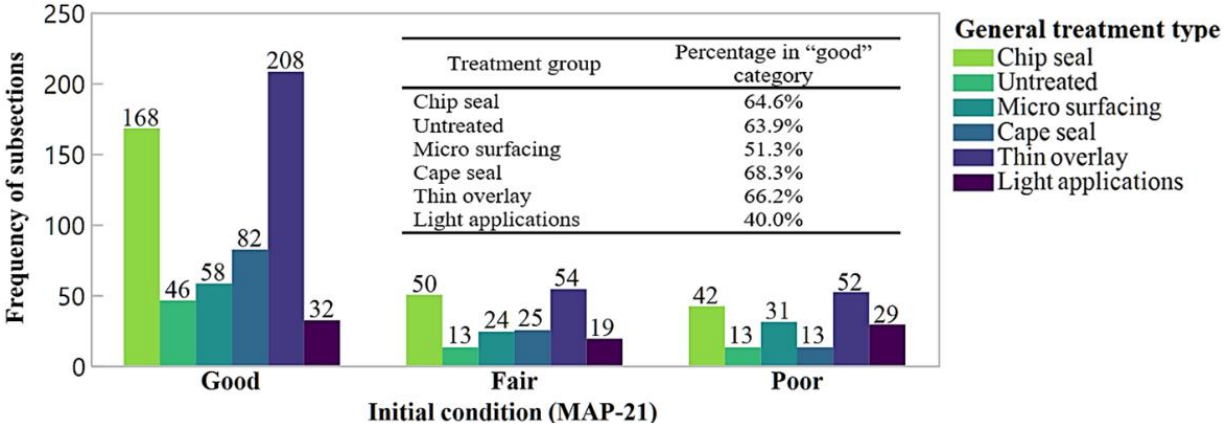
3.1.6 Treatment Grouping

From a DOT or a highway agency perspective which implements PMS, it is more practical to have models for treatment groups rather than individual treatments. Therefore, all treatments with similar techniques in construction were categorized into groups, including light preservation applications, chip seals, micro surfacing, cape seals and thin overlays. The control group represents the untreated sections, as shown in Table 3-5.

Table 3-5 Defined Categories for Preservation Treatments on Lee Road 159

Treatment Categories	Representative Treatments
Untreated	Control sections with low and high cracking
Light preservation application	Stand-alone crack sealing, rejuvenating fog seal
Chip seals	Single (with & without crack sealing), double, and triple layer chip seals, FiberMat® chip seal, scrub seal
Micro surfacing	Single layer micro surfacing, single layer micro surfacing with crack sealing, double layer micro surfacing
Cape seal	Conventional cape seal, [1] FiberMat® cape seal, scrub cape seal
Thin overlays	Thin overlay over FiberMat® chip seal, Virgin thin overlay with PG67-22, Virgin thin overlay with PG67-22 on 100% foamed recycle base, Virgin thin overlay with PG76-22, Ultra-thin bonded surface course, 50% RAP thin overlay, 5% RAS thin overlay, [2] HiMA thin overlay

Figure 3-6 shows the distribution of subsections considered in this study for different treatments and condition categories. The higher proportion of subsections were in ‘good’ category for all treatment groups at the time of treatment application as shown and tabulated in the graph. After performing data quality control, a total of 959 subsections were available for the analysis where 594, 185 and 180 subsections were in ‘good’, ‘fair’ and ‘poor’ condition, respectively. Approximately two-thirds of subsections were in ‘good’ condition for chip seals, untreated, cape seals and thin overlays. Micro surfacing and lighter applications had considerably lower percentage of ‘good’ pretreatment condition subsections. Overall, 62% and 81% of the subsections were in ‘good’ and “good and fair” conditions at the time of treatments, respectively. It is well documented that future pavement performance is highly affected by pretreatment condition (29,120–122).



Treatment group	Percentage in "good" category
Chip seal	64.6%
Untreated	63.9%
Micro surfacing	51.3%
Cape seal	68.3%
Thin overlay	66.2%
Light applications	40.0%

Figure 3-6 Number of subsections by treatment type and initial condition for cracking percentage

From Figure 3-6, it can be assumed that in terms of surface conditions, most treatments were placed at around the right time to achieve maximum life-extending benefits. The number of subsections for each treatment category and pretreatment conditions is also shown.

3.1.7 Pre-treatment Structural Condition

Preventive treatments should be applied on pavements with good structural condition. In this study, deflection data from FWD testing were used to conduct such an assessment. Horak (123) has reported a benchmarking classification for various pavement types using deflection basin parameters (DBPs). For instance, the deflection under the center of the load plate (D_0) is indicative of the overall structural condition. Horak showed that for a flexible pavement with granular base and load level of 9 kips, D_0 less than 500 μm corresponds to 'sound' structural condition, D_0 between 500 μm and 750 μm corresponds to a 'warning' zone, and D_0 larger than 750 μm relates to 'severe' structural condition. Figure 3-7 and Figure 3-8 exhibit the average deflections at the center of the loading plate (D_0) for each of the test sections in the inbound and outbound directions, respectively.

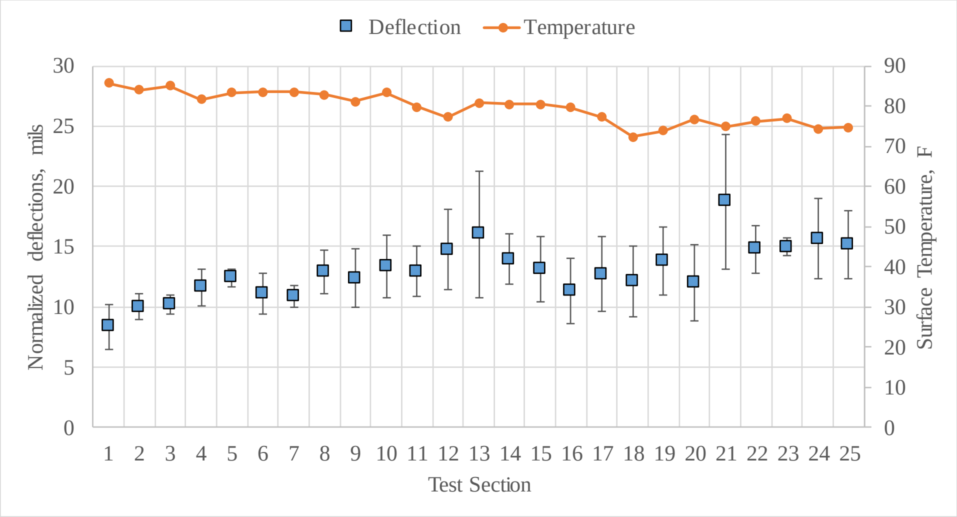


Figure 3-7 Average deflections at the center of the loading plate for the lower traffic bound level (inbound direction) (113)

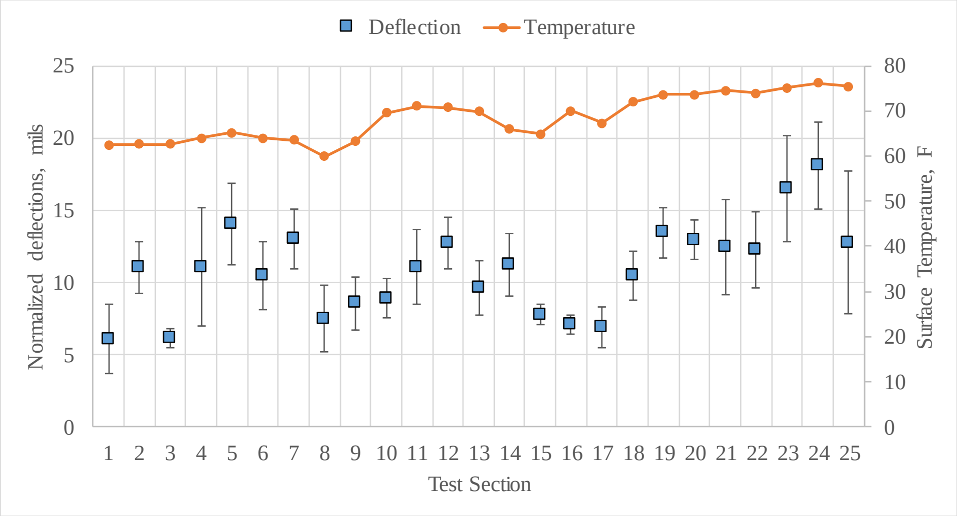


Figure 3-8 Average deflections at the center of the loading plate for the upper traffic bound level (outbound direction) (113)

The deflections shown have been normalized to a standard load of 9 kips. It is evident that the structural deflection response to loading is more uniform in the inbound direction, where pavement has accumulated less ESALs in its lifetime compared to the outbound direction. All sections can be considered structurally ‘sound’ based on the recommended deflection threshold of 500 μm (approximately 20 mils) and therefore are candidates for pavement preservation.

Previous studies confirm that the DBPs correlate with structural condition of the pavement (123,124). Vargas and Powell (120) calculated DBPs to characterize the structural condition of the various pavement sections in LR-159. Deflections measured at different distances from the center of the load plate were used to calculate the area under the pavement profile (AUPP), surface curvature index (SCI), base damage index (BDI), and base curvature index (BCI) using Equations 3.1 through 3.4, respectively.

$$AUPP = \frac{5D_0 + 2D_{12} + 2D_{24} + D_{36}}{D_0} \tag{3.1}$$

$$SCI = D_0 - D_{12} \tag{3.2}$$

$$BDI = D_{12} - D_{24} \tag{3.3}$$

$$BCI = D_{24} - D_{36} \tag{3.4}$$

where

D_0 = deflection at the center of the loading plate, mils;

D_{12} = deflection at 12 in. from the center of the loading plate, mils;

D_{24} = deflection at 24 in. from the center of the loading plate, mils; and

D_{36} = deflection at 36 in. from the center of the loading plate, mils.

The AUPP parameter correlates with the horizontal tensile strain at the bottom of the asphalt concrete layer. Higher AUPP values indicate higher strains, and therefore, a higher potential for bottom-up fatigue cracking. Currently, there is no specific threshold value for AUPP in the literature to characterize structural condition. The SCI, BDI, and BCI parameters represent the structural condition of the surface, base, and subgrade layers, respectively. Higher values indicate more damage in the structure (123). Ranges of deflection bowl parameters as developed by Maree and Bellekens (125) and Maree and Jooste (126) are provided in Table 3-6.

Table 3-6 Deflection bowl parameter structural condition rating criteria for various pavement types (123)

Base type	Structural condition rating	Deflection bowl parameters			
		D_0 (mils)	SCI (mils)	BDI (mils)	BCI (mils)
Granular base	Sound	<19.7	<7.9	<3.9	<2.0
	Warning	19.7 – 29.5	7.9 – 15.7	3.9 – 7.9	2.0 – 3.9
	Severe	>29.5	>15.7	>7.9	>3.9
Cementitious base	Sound	<7.9	<3.9	<2.0	<1.6
	Warning	7.9 – 15.7	3.9 – 11.8	2.0 – 3.9	1.6 – 3.1
	Severe	>15.7	>11.8	>3.9	>3.1
Bituminous base	Sound	<15.7	<7.9	<3.9	<2.0
	Warning	15.7 – 23.6	7.9 – 15.7	3.9 – 5.9	2.0 – 3.1
	Severe	>23.6	>15.7	>5.9	>3.1

Based on the thresholds defined in Table 3-6, for a flexible pavement with granular base, SCI, BDI and BCI values less than 7.9, 3.9 and 2.0 mils correspond to a structurally sound pavement.

Figure 3-9 and Figure 3-10 show the deflection bowl parameters for each test section for the lower bound (inbound) and the higher bound (outbound) traffic levels, respectively. Again, more variability can be observed in the outbound direction.

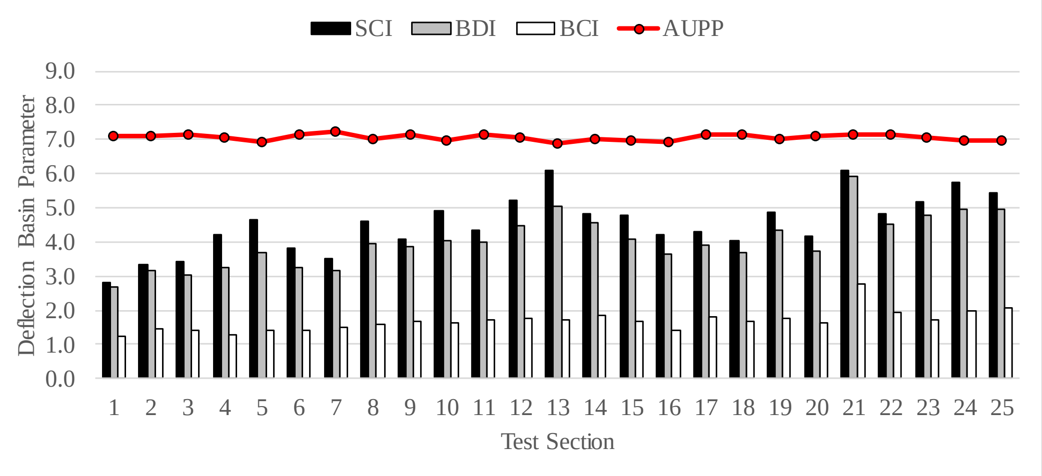


Figure 3-9 Deflection bowl parameters for the lower traffic bound level (inbound direction) (113)

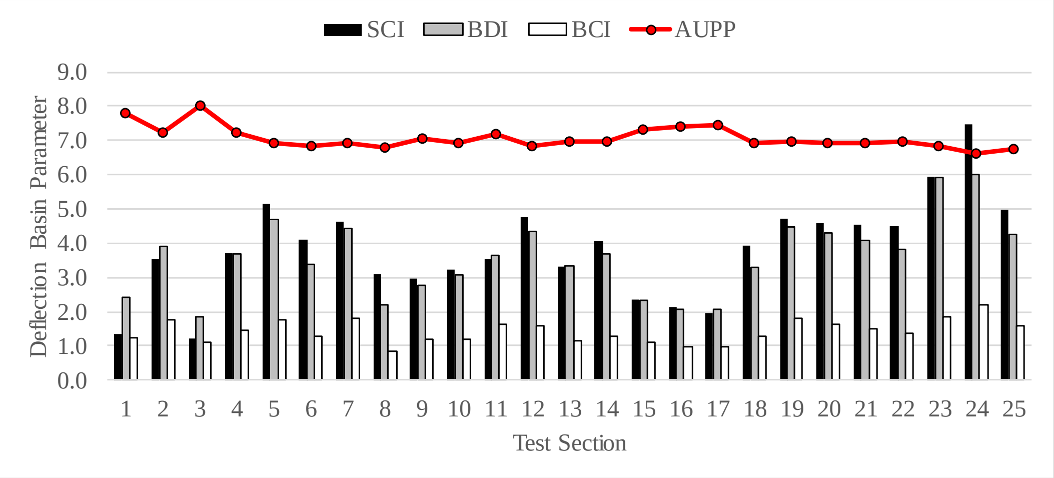
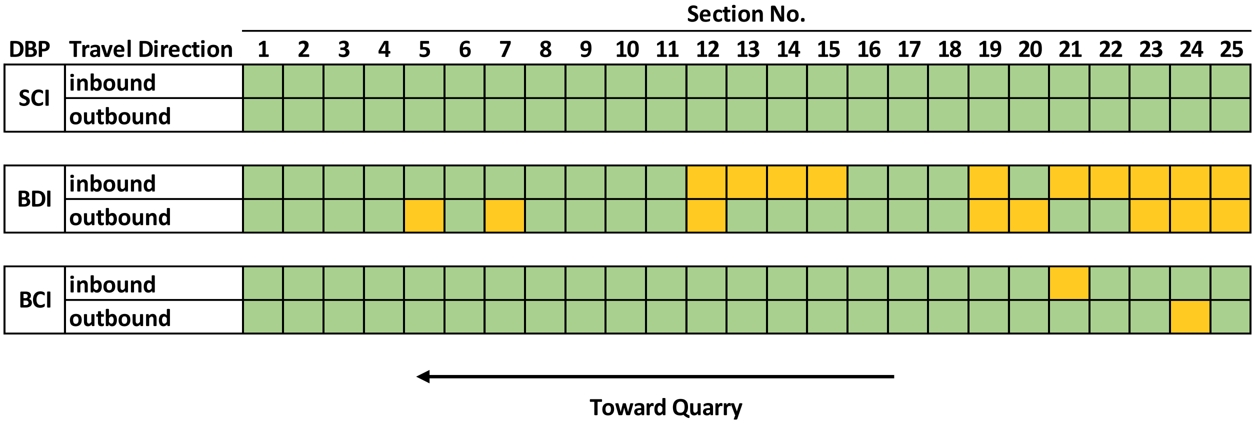


Figure 3-10. Deflection bowl parameters for the upper traffic bound level (outbound direction) (113)

Figure 3-11 exhibits the structural condition rating based on threshold values defined in Table 3-6 with the same color coding. As can be seen, no serious structural deficiency is identifiable for LR-159. Only the BDI measure, which is indicative of the base layer condition, has entered into the 'warning' zone for some sections. Although preservation treatments are not intended to improve the structural capacity of the pavement, FWD results along with surface condition results were used to assign more "robust" treatments to those sections with more damage. It was concluded that structural condition was uniform across the length of LR-159 and all sections were appropriate candidates for pavement preservation.



		Section No.																								
DBP	**Travel Direction**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**
SCI	**inbound**	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	outbound	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
BDI	**inbound**	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟨	🟨	🟨	🟨	🟩	🟩	🟩	🟨	🟩	🟨	🟨	🟨	🟨	🟨
	outbound	🟩	🟩	🟩	🟩	🟨	🟩	🟨	🟩	🟩	🟩	🟩	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟨	🟨	🟩	🟩	🟨	🟨	🟨
BCI	**inbound**	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟨	🟩	🟩	🟩	🟩
	outbound	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟨	🟩

Figure 3-11 Deflection basin parameters calculated for LR-159

3.1.8 Field Observations

Figure 3-12 shows the measured crack percentages for LR-159 from the start of the experiment for each category. Color shading is consistent with MAP-21 performance measures for cracking with light green, yellow, and red shading defining the 'good', 'fair', and 'poor' conditions, respectively. It is evident that all the preventive strategies effectively hinder crack propagation when compared with the untreated sections.

Note that reliable treatment life quantification would not be accurate using the figure because the effects of significant factors such as pretreatment condition or traffic level is not taken into consideration. For instance, the rejuvenating fog seal and stand-alone crack sealing is showing to have different performances, yet, it is not known if they had been subjected to similar pretreatment conditions. A parametric study can reveal these subtleties.

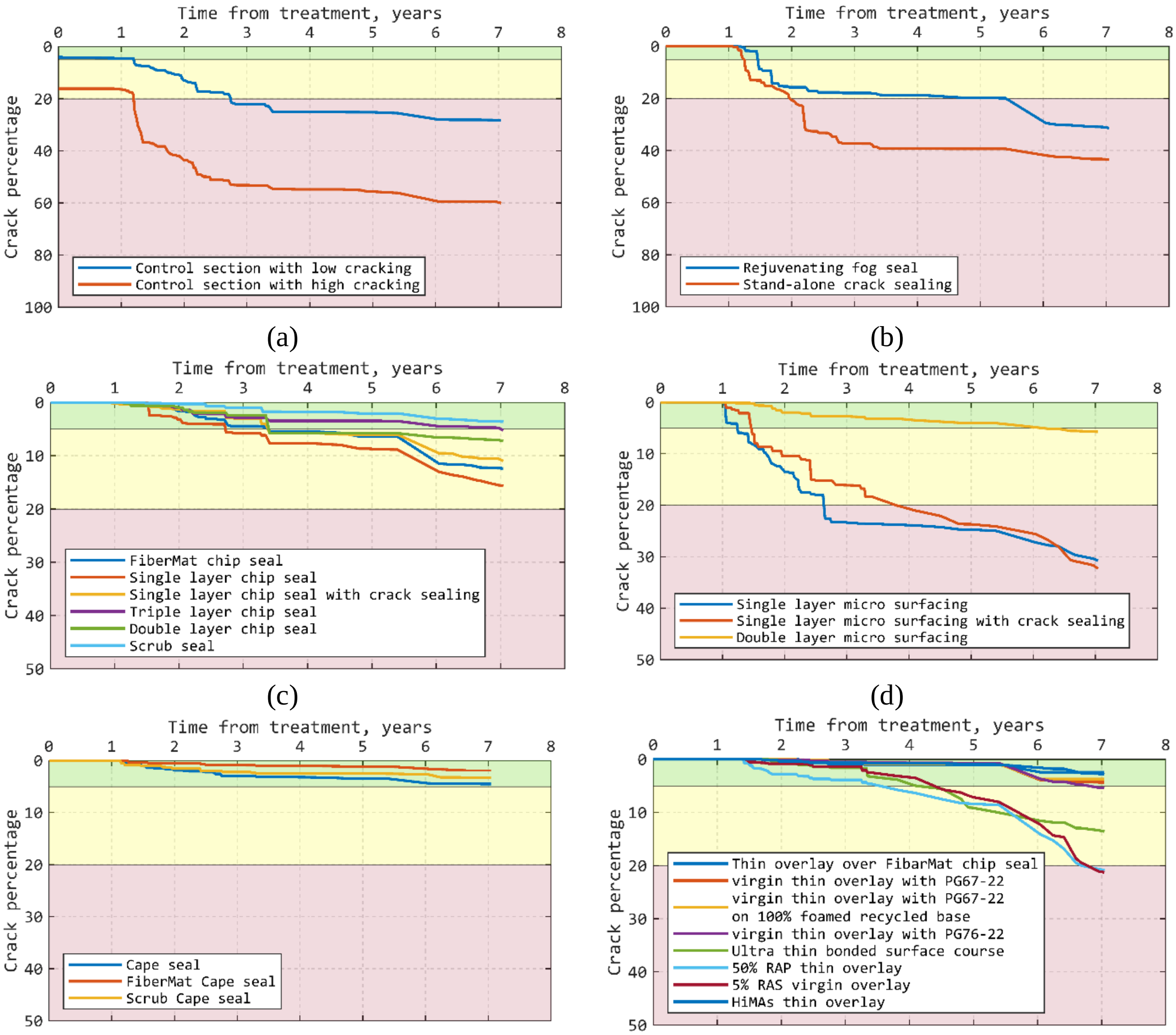

(a) (b) (c) (d) (e) (f)

Figure 3-12 Field measured crack deterioration curves for (a) untreated, (b) light applications, (c) chip seals, (d) micro surfacing, (e) cape seal and, (f) thin overlay sections.

3.2 Survival Analysis Methodology

3.2.1 Introduction

Survival analysis is useful in modeling of phenomena that experience deterioration. Deterioration cannot be stopped; it is present in natural processes (aging) and in all manufactured products, including pavements. Therefore, it is of interest to identify the factors that influence deterioration rates so that proper remedies can be offered in a time which can extend the life of such products/systems. A branch of statistics has been developed to deal with time to failure data. These methodologies were primarily developed for medical sciences, where the effect of specific treatment for a cure, or contributing factors leading to a health hazard such as death can be analyzed. As relevant to humans, it was also important to have a methodology to offer analytical results before the actual occurrence of the failure, i.e. death of the subjects. Therefore, the developed methods should be able to account for data that has partial information.

The survival methodology can equally be applied to the preservation dataset which is basically a time to failure data. Moreover, many of the subsections have not yet failed after 7 years, which can be included in the analysis as censored data using the survival methodology. Similar to medical studies, factors contributing to deterioration of each treatment type can be identified.

3.2.2 Basic Quantities

The survival function $S(t)$ is defined as the probability that a subject survives longer than t. The function $F(t)$ is defined as the cumulative distribution function (CDF) of T, and the relationship with the survival function is presented in Equation 3.5.

$$S(t) = 1 - F(t) \qquad 3.5$$

Therefore, $S(t)$, will generally decrease and is a function of time t. The hazard function, $h(t)$, also called instantaneous rate of failure, is a measure of proneness to failure as a function of time. Higher hazard rates will translate to lower survivability. The hazard function is defined as:

$$h(t) = \frac{f(t)}{1 - F(t)} \qquad 3.6$$

Where $f(t)$ is the failure probability density function (PDF) and $F(t)$ is the failure CDF. $h(t)$ is particularly useful in determining the appropriate failure distributions utilizing qualitative information about the mechanism of failure and for describing the way in which the chance of experiencing the event changes with time (84). The hazard rate is a fundamental concept in survival analysis. The determination of an increasing or decreasing hazard rate is not readily observed from a graph of the CDF or the density (127).

3.2.3 Hypothesis Testing

For the preservation study, it is of interest to compare hazard rates of $K\ (K \geq 2)$ populations – such as hazard rates for different pretreatment condition, or for different treatment categories – that is to test the following set of hypotheses:

$$H_0: h_1(t) = h_2(t) = \cdots = h_k(t), \qquad for\ all\ t \leq \tau \qquad 3.7$$

$$H_A: at\ least\ one\ of\ the\ h_j(t)\ is\ different\ for\ some\ t \leq \tau$$

Here τ is the largest time at which all of the groups have at least one subject (i.e. subsection) at risk. Our inference is to the hazard rates for all time points less than τ, which is, typically, the smallest of the largest time on study in each of the K groups. The alternative hypothesis is a global one in that we wish to reject the null hypothesis if, at least, one of the populations differs from the others at some time (84).

The test of H_0 is based on weighted comparisons of the estimated hazard rate of the jth population under the null and alternative hypothesis, based on the Nelson-Aalen estimator. If the null hypothesis is true, then, an estimator of the expected hazard rate in the jth population under H_0 is the pooled sample estimator of the hazard rate d_i/Y_i. Using only data from the jth sample, the estimator of the hazard rate is d_{ij}/Y_{ij}. To make comparisons, let $W_j(t)$ be a positive weight function with the property that $W_j(t)$ is zero whenever Y_{ij} is zero. The test of H_0 is based on the statistics:

$$Z_j(\tau) = \sum_{i=1}^{D} W_j(t_i)\left\{\frac{d_{ij}}{Y_{ij}} - \frac{d_i}{Y_i}\right\}, \ \mathrm{j} = 1,\ldots,k \qquad 3.8$$

If all the $Z_j(\tau)$'s are close to zero, then, there is little evidence to believe that the null hypothesis is false, whereas, if one of the $Z_j(\tau)$'s is far from zero, then, there is evidence that this population has a hazard rate differing from that expected under the null hypothesis. The test statistic is given by the quadratic form:

$$\chi^2 = (Z_1(\tau), \ldots, Z_{K-1}(\tau))\Sigma^{-1}(Z_1(\tau), \ldots, Z_{k-1}(\tau))^t. \qquad 3.9$$

When the null hypothesis is true, this statistic has a chi-squared distribution, for large samples with $k \geq 1$ degrees of freedom. A variety of weight functions have been proposed in the literature. A common weight function, leading to a test available in most statistical packages, is $w(t) = 1$ for all t. This choice of weight function leads to the so-called log-rank test and has optimum power to detect alternatives where the hazard rates in the K populations are proportional to each other. The log-rank test has been used in this study for hypotheses testing.

3.2.4 Exact Event Times and Censored Observations

If the exact time of failure is known, the observation is called an event. Censored observations are those having partial information which still are helpful for the estimation. Three main types of censoring can be identified: left, right and interval censoring. Left-censoring is when a subject already has failed at the beginning of the study. Right-censoring is when a subject does not fail at the end of the analysis window. A dataset that contains both left- and right-censored data is called a doubly-censored data (left- and right-censoring cannot happen simultaneously for one subject). Interval censoring is when the event occurs between two specific dates, but the exact time is unknown.

It would be informative to look at the whole failure data graphically using an event plot. In this plot, failure is called an event which can occur in several ways. If the exact event time is known, the data is not censored and is shown with an '×' sign. The left censored, interval censored, and right censored data are indicated by '---ᐊ,'ᐊ---ᐅ ', and '---ᐅ' arrows, respectively, as shown for the PG study in Figure 3-13. It can be observed that the majority of data are interval-censored. For some of the treatment categories, such as cape seals, most of the data are right-censored, meaning that failure has not happened for up to 7 years, which is a sign of high performance. These plots may give a general sense of performance, but statistical methods are necessary for survival calculation, and quantifying the effects of possible factors.

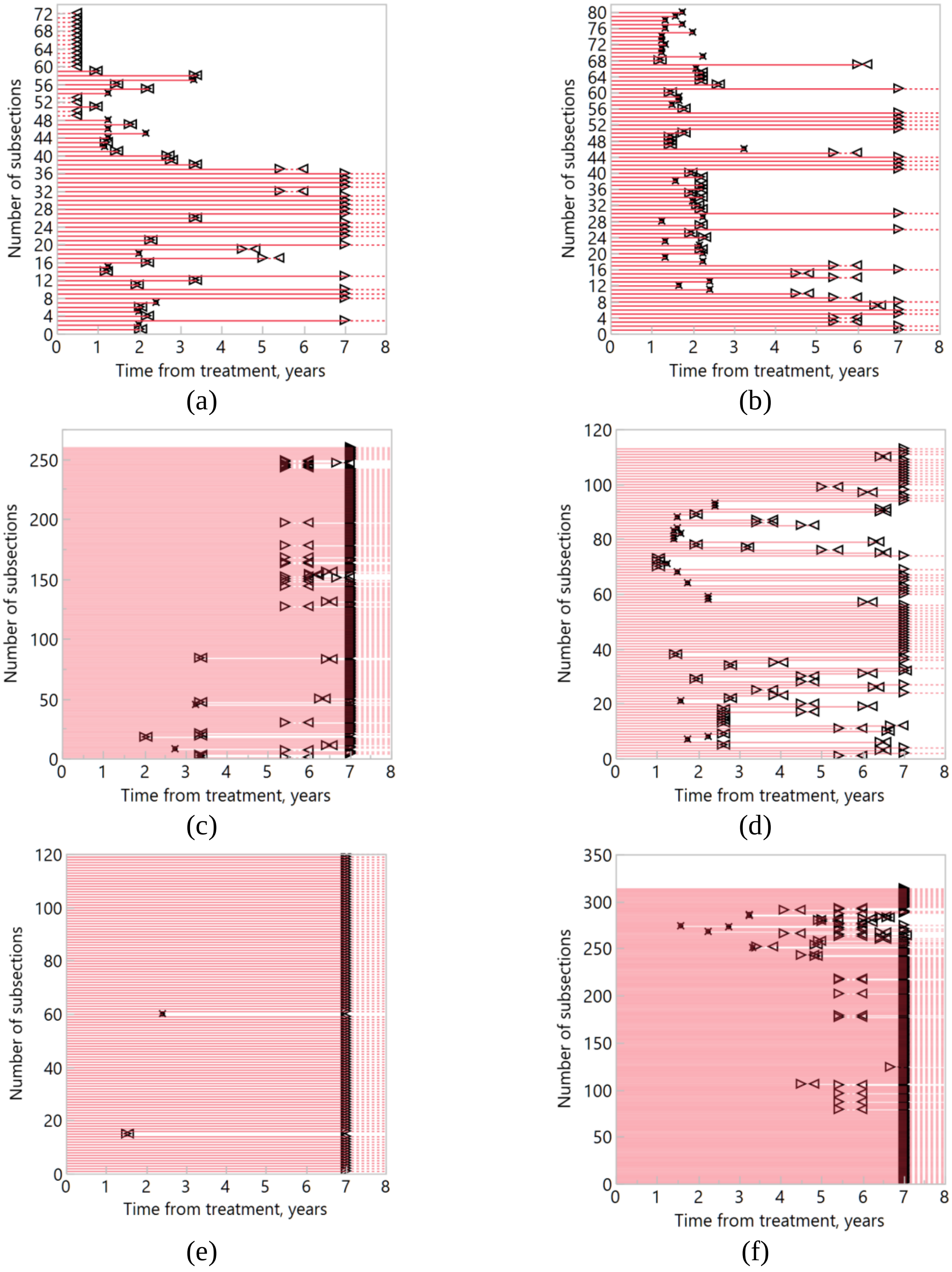


Figure 3-13 Event plots for (a) untreated, (b) light preservation applications, (c) chip seal category, (d) micro surfacing category, (e) cape seal category, and (f) thin overlays.

3.2.5 Non-parametric Survival

An investigator might be interested in using a non-parametric, a semi-parametric or a full-parametric survival model based on study priorities. If the goal is to explore the data visually and find clues on different influential factors, then a non-parametric method such as Kaplan-Meier (KM) and Nelson-Aalen estimator are useful for survival and cumulative hazard function estimation, respectively. Survival probability shows the proportion of subsections in a specific time that have less than 20% cracking. Hazard rate is also known as instantaneous rate of failure, or force of morbidity, which defines the probability of subsections failing as time advances. The cumulative hazard integrates hazard rate.

A non-parametric study is also done prior to running parametric models to get an idea of the survival function (85). A major drawback of the KM method is that the effects of the influential factors, such as climate, pavement thickness, traffic loadings, and pavement condition prior to rehabilitation, on the survival time of the pavements cannot be directly estimated (128). For assessing the effects, continuous explanatory variables such as traffic loading should first be converted into disjointed intervals (levels). Even in this case, quantification of different effects would not be straight-forward because there might be several other variables involved.

3.2.6 Semi-parametric Survival

The semi-parametric method, known as Cox proportional hazards model, is more relaxed in the sense that it does not require any distribution to be fitted but is still a parametric method capable of handling covariate effects. The model due to Cox (1972) is as follows:

$$h(t|z) = h_0(t)exp(\beta^t Z) \qquad 3.10$$

This model consists of two parts. First part, $h_0(t)$, is the baseline hazard rate which is an arbitrary function that does not need any distributions to be fitted to the failure times. It is semi-parametric because a parametric form is assumed only for the covariate effect as it is separated and placed in the second part of the equation (84). β^t is the vector of estimated coefficients. An exponential function is considered for the second part because hazard should always be a positive number. Z is the vector of covariate values. This framework makes it easy to compare hazard risks between any two possible scenarios defined by sets of covariates, as shown in Equation 3.11.

$$\frac{h(t|z^*)}{h(t|z)} = \exp\left(\beta^t (Z^* - Z)\right) \qquad 3.11$$

The Cox model is often called a proportional hazards model because, if we look at two individuals with covariate values Z and Z^* in Equation 3.11, the ratio of their hazard rates remains constant over time.

The KM method may be used directly to compare different groups; however, it is quite natural that other covariates exist within each group explaining the response variable (time to failure). Adjusting for the effect of the risk factors (covariates) in a semi-parametric model makes the comparison of survival times between groups less biased and more precise than a simple visual comparison with KM techniques (84).

3.2.7 Full-parametric Survival

When a distribution provides a good fit to the data, use of a parametric model is preferred because more precise estimates of quantities of interest are expected (84). The models fitted in this study have an *accelerated failure-time model* representation or equivalently a *linear model* representation in log time. The accelerated failure-time model is shown in Equation 3.12.

$$S(x|Z) = S_0[\exp(\theta^t Z)\,x],\ for\ all\ x. \quad 3.12$$

Where x is the time to the event and Z is a vector of fixed-time covariates. The accelerated failure-time model states that the survival function of an individual with covariate Z at time x is the same as the survival function of an individual with a baseline survival function at a time $\exp(\theta^t Z)\,x$, where $\theta^t = (\theta_1, \dots, \theta_p)$ is a vector of regression coefficients. The $\exp(\theta^t Z)$ is called an acceleration factor telling the investigator how a change in covariate values changes the time scale from the baseline time scale (84). This model says that what makes one individual (here subsection) different from another is the rate of which they age. A good example is the conventional wisdom that a year for a dog is equivalent to 7 years for a human. This relationship can be modeled using Equation 5 where $S(x|Z)$ is the survival probability for a human, S_0 is the survival probability for a dog, and $\exp(\theta^t Z)$ is 7 years (129).

3.2.7.1 Model selection

Several distributions could be fitted to the data. In this study, two measures, namely, the Akaike Information Criterion (AIC) and its Bayesian analogue (BIC) were used for model selection. In simple terms, these measures aggregate a penalty to the log-likelihood estimation to avoid models with unnecessary large number of parameters. Similar to R^2_{adj}, sum of the squared residuals (SS_{res}) decreases as more parameters added to the model. The issue becomes whether the decrease in SS_{res} justifies the inclusion of extra terms.

Akaike proposed an information criterion, AIC, based on maximizing the expected entropy of the model. Entropy is simply a measure of the expected information. Essentially, the AIC is a penalized log-likelihood measure (130). Let L be the likelihood function for a specific model. The AIC is shown in Equation 3.13:

$$\mathrm{AIC} = -2\ln(L) + 2p \tag{3.13}$$

Where p is the number of parameters in the model. One issue with AIC is that for small sample sizes, there is a substantial probability that AIC will select models that have too many parameters, i.e. that AIC will overfit. To address such potential overfitting, AICc was developed: AICc is AIC with a correction for small sample sizes. Several Bayesian extensions are also available in the literature. For instance, the Schwartz criterion BIC is shown in Equation 3.14:

$$\mathrm{BIC} = -2\ln(L) + p.\,ln(n) \tag{3.14}$$

Where *n* is the sample size. This criterion places a greater penalty on adding aggressors as the sample size increases.

3.2.8 Survival analysis application for the Preservation Study

Survival analysis works like a linear regression that deals with several independent (explanatory) variables and one independent (response) variable. In survival analysis methodologies, the dependent variable is time to failure for different subjects. The independent variables are the covariates that may accelerate or decelerate the survival rate.

In this study, failure is considered as cracking reaching the 20% cracking threshold defined by MAP-21, as explained in section 3.1.5. Thus, the independent variable is defined as the time duration, from the treatment application to treatment failure. For some of the subjects, such as the several subsections belonging to the untreated group, time to failure may equal zero since failure (20% cracking) was already reached at the beginning of the study. These subsections are called left-censored. On the other hand, some of the higher performing sections have not yet reached the failure threshold. The known information is that these subsections have survived for at least 7 years, although the exact survival time is not known. These instances are called right-censored data. The rest of the data include subsections with failure times occurring between two data collection dates. It is seldom that subsections reach 20% cracking exactly on the day of data collection. This third category is called interval-censoring.

Covariates that were considered are specific treatment types, pretreatment condition, traffic level, recycling effect, and crack sealing effect. Survival curves can be developed for all treatments at different covariate levels. From the survival curves, the median life, or any other percentile life, can be derived. Moreover, the life-extending benefits can be calculated by comparing the median survival time to a baseline treatment, such as the untreated section.

3.3 Markov Process & Monte Carlo Simulation Approach

3.3.1 Hierarchical Agglomerative Clustering

Although Figure 3-12 confirms the life-extending benefits, treatments are showing considerably different behavior in each of the categories defined in Table 3-5. Hence, for this nonparametric model, it is prudent to further subclassify treatment groups to produce more representative performance curves when generating TPMs. To do so, a hierarchical agglomerative clustering method was implemented using JMP® statistical software. This method classifies treatments based on the 'nearness' of the treatments' mean crack values for each date throughout the service life. For each category, a maximum number of two clusters was chosen to balance cracking curve representation and to maintain model simplicity, as shown in Table 3-7. Also shown in the table is the increase in cracking percentage for each of the defined clusters in 6-month durations.

Note that cluster 1 is the higher performing subclass in each category. There are two untreated sections in LR-159, one with lower initial cracking and the other with high initial cracking. The goal of including separate control sections was to assess the effect of initial conditions on performance. Both of the untreated sections consist of subsections with different degrees of cracking at the time of the treatment application. In this study it was decided to combine these untreated sections into one, and to assess the effect of pretreatment conditions using the subsection information from the unified untreated category.

Table 3-7 Average and 95th percentile values for crack increase in 6-month durations

Treatment Category	Cluster Number	Treatments in each cluster	Pretreatment Cracking, %	Increase in cracking in 6-month durations	
				Average	95th Percentile
Untreated	–	Untreated sections were combined into a single cluster	9.4	2.23	12.55
Light preservation application	1	Rejuvenating fog seal	5.4	2.01	9.66
	2	Crack sealing only	25.4	3.13	18.75
Chip seals	1	Double layer, triple layer chip seal and Scrub seal	4.7	0.39	2.51
	2	FiberMat® chip seal, single layer chip seal and single layer chip seal with crack sealing	9.3	0.96	6.44
Micro surfacing	1	Double layer micro surfacing	14.1	0.62	3.95
	2	Single layer micro surfacing, Single layer micro surfacing with crack sealing	12.2	2.28	11.82
Cape seals	1	FiberMat® cape seal	7.0	0.15	1.07
	2	Cape seal and Scrub cape seal	6.5	0.28	1.68
Thin overlays	1	Thin overlay over FiberMat® chip seal, Virgin thinlay with PG67-22, Virgin thinlay with PG76-22, Virgin thinlay with PG67-22 on 100% foamed recycled base, HiMa thinlay	9.0	0.27	1.41
	2	Ultra-thin bonded surface course, 5% RAS thin overlay, and 50% RAP thin overlay	5.5	1.38	8.77

3.3.2 Discrete-Time Markov Chain Modeling

Markov modeling has been utilized numerously in development of deterioration models in civil engineering applications. It was first introduced by Butt et al. (62) for pavement deterioration modeling. The pavement surface condition will be restored, devoid of any cracking, when a preservation treatment is applied to the pavement. The rate in which different treatment types deteriorate would be expectedly different since different design concepts, materials, construction techniques, and engineering effort have been applied for each type.

3.3.2.1 Duty Cycles

A duty cycle is typically defined as 1 year of treatment subjected to traffic and weather conditions (62,68,81,111). However, a 6-month duty cycle was considered more appropriate because 1) research level data were readily available; 2) the resulting model can better represent changes in deterioration slope since a shorter duty cycle means it can adapt itself to changes in deterioration in a shorter time; and 3) a cyclic pattern related to seasonal effects was not observed in deterioration trends.

3.3.2.2 TPM Structure

After data filtering, transition probabilities need to be estimated for each of the treatment groups. As mentioned, cracking percentage was used to develop TPMs. First, continuous cracking data were discretized into a number of condition states. The required number of states is a matter of practicality and model performance. Fewer condition states results in a wider cracking interval for each state, and as such, subsections with close cracking levels will get placed under the same state which ultimately sacrifices model accuracy. Also, considering a larger number of states becomes impractical since it translates into a narrower cracking range for each state and for LR-159, the data is not large enough to support the model. Moreover, a very large number of condition states beyond a threshold does not necessarily mean higher accuracy. Initial assessments showed that 10 condition states are practical and also computationally efficient. The cracking range covered in different states can be either even or uneven. As is explained in the following paragraph, selection of an uneven interval range can better model the deterioration phenomenon for this study.

A 10x10 TPM was used for the analysis; yet, two more issues arise with respect to TPM definition. First, how much deterioration should be allowed in one duty cycle, and second, whether intervals should be of equal length as was the case in previous studies. To answer the first, the average and 95th percentile of increases in cracking during the 6-month duty cycles were assessed from the field data. Based on the 95th percentile values, it was noticed that for some sections, cracks can increase by as much as 19% in one duty cycle, as shown in Table 3-7. Therefore, TPMs should be designed to allow for this maximum conceivable value by allowing a subject to experience such increase in one duty cycle, which itself is defined by the number of allowed condition drops in the TPM. For instance, if a subsection cracking level increases by 19% in one duty cycle, but the TPM can only accommodate for up to 10% increase, the model reaches its limit mathematically, and the generated curve will underpredict the cracking level. The increases in cracking levels, in one duty cycle, are reported for clusters of treatments in Table 3-7. These clusters are in good agreement with Figure 3-12 when compared visually. Pretreatment cracking levels are also exhibited.

Regarding the intervals, a typical approach is to consider intervals of equal width (e.g. 10% cracking). However, initial analyses revealed that having equal intervals for state conditions cannot produce favorable outcomes because dividing the entire cracking range (0-100%) to 10 states (or intervals) results in only two condition states in the domain of 0-20% cracking where MAP-21 thresholds are. Because of the mathematics of Markov Chain, accurate deterioration modeling for treatments with excellent performance (i.e. low cracking levels) is not possible. As such, narrower intervals for the lower crack percentages are desirable. In addition, having equal narrow intervals in a 10 state TPM cannot cover the full spectrum of cracking. Therefore, a smarter approach is to design the TPM for higher sensitivity in MAP-21 region by choosing narrower intervals, and to widen the interval for higher percentage cracking. In this way, the TPM is designed to be practical (10x10), sensitive to low crack values, and capable of handling higher crack percentages such as those for untreated sections, and therefore adequately covering the entire range of cracking levels.

Equation 3.15 sketches the form of the TPM matrix used to estimate transition probabilities. *Pij* is the probability of a subsection migrating from condition *i* to condition *j*. It was assumed that crack percentages cannot increase by more than 20% in a 6-month duration. Unequal interval ranges were decided by equally dividing a log transformation of the range 0-100 and then performing some rounding. It is to be noted that depending on the cracking level, a subsection may remain in the same condition or drop by up to 5 condition states. Also, because of the unequal interval ranges, the number of condition drops is different in different crack ranges. The value of 1 in the last element of the matrix indicates a holding or trapping state where crack percentage is 50 to 100%. Hence, at this point, pavement condition cannot improve unless rehabilitation work is performed, which was not the case in this study.

$$\begin{array}{cc|cccccccccc|}
 & & \multicolumn{10}{c}{\overbrace{\hphantom{\text{0-1.5 1.5-2.5 2.5-5 5-9 9-14 14-20 20-30 30-40 40-50 50-100}}}^{\text{Condition state numbers}}} \\
 & \textbf{Interval} & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 \\
 & \textbf{Ranges} & \textbf{0-1.5} & \textbf{1.5-2.5} & \textbf{2.5-5} & \textbf{5-9} & \textbf{9-14} & \textbf{14-20} & \textbf{20-30} & \textbf{30-40} & \textbf{40-50} & \textbf{50-100} \\
\hline
1 & \textbf{0-1.5} & P_{11} & P_{12} & P_{13} & P_{14} & P_{15} & P_{16} & 0 & 0 & 0 & 0 \\
2 & \textbf{1.5-2.5} & 0 & P_{22} & P_{23} & P_{24} & P_{25} & P_{26} & P_{27} & 0 & 0 & 0 \\
3 & \textbf{2.5-5} & 0 & 0 & P_{33} & P_{34} & P_{35} & P_{36} & P_{37} & 0 & 0 & 0 \\
4 & \textbf{5-9} & 0 & 0 & 0 & P_{44} & P_{45} & P_{46} & P_{47} & 0 & 0 & 0 \\
5 & \textbf{9-14} & 0 & 0 & 0 & 0 & P_{55} & P_{56} & P_{57} & P_{58} & 0 & 0 \\
6 & \textbf{14-20} & 0 & 0 & 0 & 0 & 0 & P_{66} & P_{67} & P_{68} & 0 & 0 \\
7 & \textbf{20-30} & 0 & 0 & 0 & 0 & 0 & 0 & P_{77} & P_{78} & P_{79} & 0 \\
8 & \textbf{30-40} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & P_{88} & P_{89} & P_{8\,10} \\
9 & \textbf{40-50} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & P_{99} & P_{9\,10} \\
10 & \textbf{50-100} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1
\end{array} \tag{3.15}$$

3.3.2.3 Future Condition Prediction

To calculate the state vector for future *n* periods, the initial state vector, *S(t=0)* should be multiplied by the TPM raised to the power of *t*, as demonstrated in Equation 3.16.

$$\begin{aligned}
&Cr(t = 6months) = S(t = 0) \times TPM^{\frac{6}{6}} \\
&Cr(t = 12months) = Cr(t = 6months) \times TPM^{\frac{6}{6}} = S(t = 0) \times TPM^{\frac{12}{6}} \\
&. \\
&. \\
&Cr(t = n\,months) = S(t = 0) \times TPM^{\frac{n}{6}}
\end{aligned} \qquad 3.16$$

Where *Cr* is the cracking percentage after *n* months. The state vector denoted by *S(t)* indicates the condition of pavement sections at specific duty cycles. Each element on the vector represents the discretized crack percentages in intervals defined in Equation 3.16. For a newly preserved section with no cracking, the initial state vector *S(t=0)* is (1, 0, 0, 0, 0, 0, 0, 0, 0, 0). For untreated sections, unlike the rest of the treatments, sections have some cracking at the beginning of the study. As such, the scalar crack levels should first be vectorized to enable matrix multiplication operations.

3.3.2.4 TPM Estimation

For estimating the transition probabilities for the TPM and for the initial state vector, an objective function was defined to minimize the sum of the squared errors (SSE) of crack percentages obtained from the Markov predicted and observed crack percentages, as shown in Equation 3.17. By minimizing the objective function, the Markov model produces crack values close to field observations. This objective function solves for 36 elements in the TPM and is subjected to two constraints. The summation of each row in the TPM should be equal to 1, and each probability element should be between 0 and 1.

$$SSE = \sum_{t=0}^{t} \sum_{subsection=1}^{n} \left(Cr_{observed} - Cr_{predicted}\right)^{2} \qquad 3.17$$

Where:

SSE: sum of squared errors

t: number of duty cycles each equal to a 6-month period

n: number of subsections in each cluster defined in clustering analysis

$Cr_{observed}$: crack percentages for each subsection at the end of period t

$Cr_{predicted:}$ predicted crack percentages for each cluster using Markov methodology

Equation 3.17 takes the form of a non-linear equation. In a previous study, the Fletcher Powell algorithm was used to solve it (62). In another study, the generalized reduced-gradient (GRG2) nonlinear optimization algorithm using Solver module in Excel was implemented (111). In this study, the Pattern Search algorithm in MATLAB was found more convenient since the rest of the computations were also done in the same platform. Pattern search is a numerical optimization method that does not require a gradient. As such, it can be used on functions that are not continuous (131).

3.3.3 Monte Carlo Simulation

MC is a numerical simulation technique used in reliability assessments of various systems. Reliability of treatments can be explained using performance percentile curves. In this study, an MC technique devised by Tack and Chou (2001) was modified and implemented. In engineering applications, most often MC applies to an equation with inputs with known distributions to account for uncertainty in an output. However, the only difference in the case of Markov modeling is that probabilities of crack occurrences are defined in a TPM instead of the usual closed-form equations such as a normal or Weibull distribution. To better understand the process for MC, a working example for one cycle of MC for the untreated section with low cracking is described in the following steps:

1. A cumulative TPM is developed using the TPM by summation of columns from left to right. Two generated matrices for the untreated category with ‘good’ pretreatment condition are shown in Figure 3-14.
2. Depending on the initial cracking percentage, the algorithm starts either from row 1- in the case of renewed surface condition - or another row - in the case of untreated sections. Pretreatment cracking percentage for the untreated category is 9.4% (Table 3-7), which corresponds to row 5 on the cumulative TPM (Equation 3.15).
3. MC starts with generation of a random number between 0 and 1.
4. Starting from the selected row (step 2) and from left to right on the cumulative TPM, if the random number is less than the first probability, here 0.208, condition state 5 (9%-14% cracking) will be selected for the first duty cycle. Based on this random number, the pavement will not deteriorate to a lower state (state 6) at the end of this duty cycle.
5. For the next duty cycle, another random number is generated, and if the value is again less than 0.208, then the pavement remains in the first condition state. Otherwise, it migrates to the lower conditions. In the latter case, if the random variable is between 0.208 and 0.727, next step should be applied on the seventh row, corresponding to the seven condition state.
6. This process of random number generation continues until the end of the analysis period is reached.
7. Step 2 through 6 represents a cycle of simulation. For each date thoundands of simulations were run to identify the cracking level distributions.

$$\begin{bmatrix}
0 & 0.999 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0.999 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0.178 & 0.538 & 0 & 0.182 & 0.102 & 0 & 0 & 0 \\
0 & 0 & 0 & 0.201 & 0.654 & 0 & 0.145 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0.208 & 0 & 0.519 & 0.272 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0.758 & 0.242 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0.981 & 0 & 0.019 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.995 & 0.005 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.759 & 0.241 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1
\end{bmatrix}$$

(a)

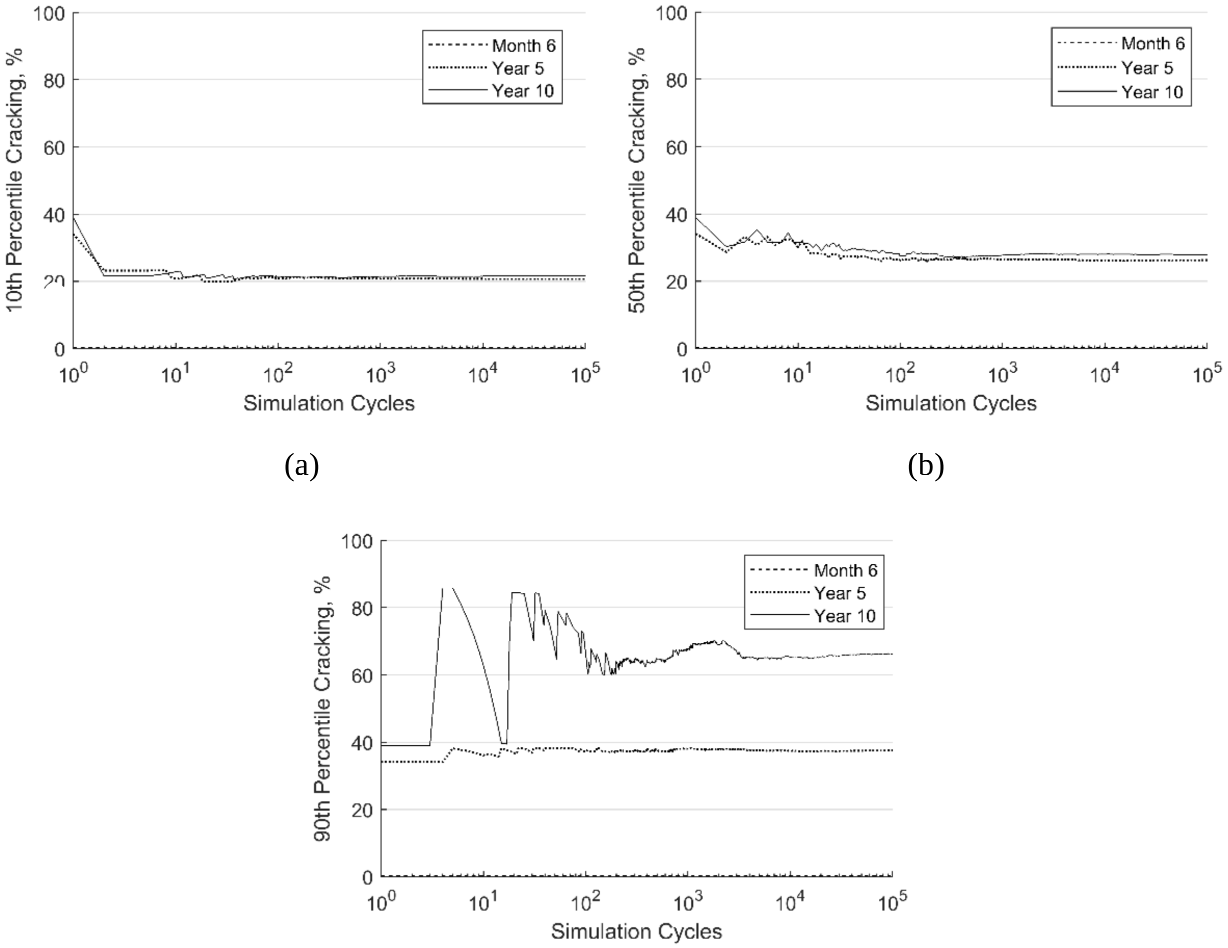
$$\begin{bmatrix}
0 & 0.999 & 0.999 & 0.999 & 0.999 & 0.999 & 0.999 & 0.999 & 0.999 & 0.999 \\
0 & 0 & 0.999 & 0.999 & 0.999 & 0.999 & 0.999 & 0.999 & 0.999 & 0.999 \\
0 & 0 & 0.178 & 0.716 & 0.716 & 0.898 & 1 & 1 & 1 & 1 \\
0 & 0 & 0 & 0.201 & 0.855 & 0.855 & 1 & 1 & 1 & 1 \\
0 & 0 & 0 & 0 & 0.208 & 0.208 & 0.727 & 0.999 & 0.999 & 0.999 \\
0 & 0 & 0 & 0 & 0 & 0.758 & 1 & 1 & 1 & 1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0.981 & 0.981 & 1 & 1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.995 & 1 & 1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.759 & 1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1
\end{bmatrix}$$

(b)

Figure 3-14 (a) Transition probability matrix; (b) cumulative transition probability matrix for untreated category with good pretreatment condition.

To identify how many cycles would be adequate, the derived distributions need to be checked for stability. As an indication of the distribution stability, crack levels at the median and at the tails of the distibuition were checked for the start, midpoint, and the end of the observation date over simulation cycles, as shown in Figure 3-15.

It was decided that the *X*-axis scale should be logarithmic because most of the fluctuations happened in the first hundreds or thousands of cycles, and by scaling, these fluctuations are magnified. For the untreated category with ‘good’ pretreatment conditon, Figure 3-15 shows that the cracking percentile values are becoming a straight line after 10,000 cycles. Similar findings were observed for other treatment groups.



(a)

(b)

(c)

Figure 3-15 Visualizing the MCS convergence for (a) 10th percentile, (b) 50th percentile and (c) 90th percentile for untreated category with ‘good’ initial condition

In computer simulations, pseudo random number generation takes place by using complex algorithms. These artificially generated random numbers follow the properties of random numbers and work fine for simulation purposes. One hurdle in computer simulations, like MCS, is the fluid state of randomization which alters the results in each run of the program. One solution is to fix the state of the random number generator module, so that the computer produces the same random numbers across all simulation runs. A more comprehensive solution would be to run the MCS multiple times, with different pseudo-random numbers and check for the needed simulation cycles where MCS becomes reliable across multiple runs. This was performed for the present analysis and one example is shown in Figure 3-16.

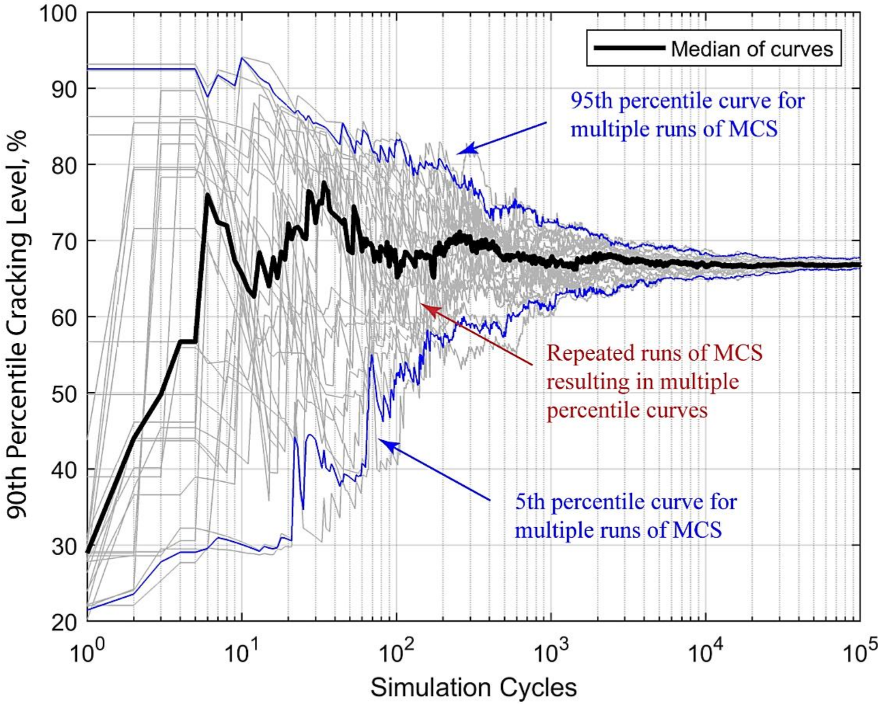


Figure 3-16 Multiple runs of MCS for 90th percentile cracking at year 10 for the untreated category with 'good' initial condition

It should be further clarified that Figure 3-16 is showing cracking results at year 10 for multiple simulation runs for the untreated section described in Figure 3-15c, which itself was for the 90th percentile cracking level. The percentile curves that are shown in blue are different than the percentile values discussed before. In Figure 3-15, percentile values were for the cracking levels, whereas in Figure 3-16, 5th and 95th percentile curves are showing the lower and upper boundaries for the 90th percentile cracking curve, respectively, if it were run for multiple times. This was done because it is also necessary to check the repeatability of the Monte Carlo methodology. As evidenced by the straight line trend, it can be seen that after 10,000 cycles all runs of MCS converge to a single cracking value.

3.3.4 Markov chain application for the Preservation Study

The required steps to create performance models using the Markov chain methodology were explained in this section. The main hurdles in modeling were that, first, this methodology is nonparametric by nature, so the preservation dataset had to be categorized first using an acceptable procedure. This was done using the common sense engineering judgment and also a clustering methodology. Second, textbook definitions for a TPM or the ones used in the previous studies would not be effective here, because of the higher sensitivity that model demands in the MAP-21 criteria region. Third, the Monte Carlo simulation should be implemented on a matrix rather than a formula, as such, an algorithm was devised to enable such a simulation.

For this methodology, only parts of data were used, as opposed to the survival methodology where all data were used. Cracking levels at 6-month intervals, up to 7 years, were used to estimate TPM for clusters of treatments. Pretreatment cracking levels were also used to generate the initial condition vectors. MCS results were then used to derive treatment lives at different percentile values.

Life-extending benefits of preservation treatments can be obtained by running the MCS for specific preservation clusters and comparing each to that of an untreated section. This comparison can be taken place based on an average, the 50th percentile, or higher percentile values, depending on the significance of the tentative road project in question.

3.4 Summary

Pavement performance modeling is an area of increasing interest among pavement researchers. Of special interest is the probabilistic preservation modeling where variability in life of the treatments can be explained with proper statistical methods. This chapter started by describing the low-volume preservation study, defining the preservation test sections, explaining the data collection method and frequency, and finally explaining the quality control procedure. For the failure threshold, 20% cracking of the entire area of a section was considered. The combined effect of fatigue, longitudinal and transverse type cracking were used in crack estimation, and the differences with MAP-21 crack estimation procedure were explained. The structural and surface condition of the pavement at the beginning of the study were explored. It was shown that preservation treatments were applied at the right time on this pavement. Seven years of field performance clearly showed that there are benefits in using preservation treatments.

Three survival methodologies and a Markov chain Monte Carlo methodology were explained in detail. For each of the methodologies used in this study, the application steps were briefly provided. In the next chapter, results for both methodologies are presented and discussions are followed.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Survival approach

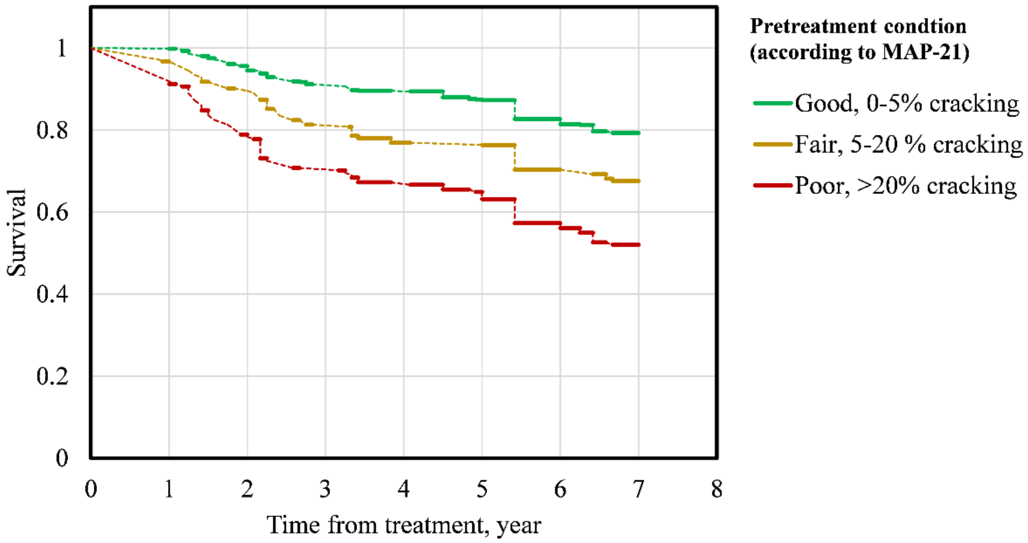
4.1.1 Non-Parametric Survival Technique

Non-parametric or distribution-free methods are easier to understand and apply. They are less efficient than parametric methods when survival times follow a theoretical distribution and more efficient when no suitable theoretical distributions are known (85). Usually, it is more convenient to run a non-parametric analysis, like the KM method, to visually acquire a clearer picture of deterioration trends and the associated risk factors before conducting any more rigorous techniques for quantifying the effects. In the following section, survivability of preventive treatments under various effects such as the treatment effect, pretreatment condition, crack sealing prior to treatment application, and recycled material usage were investigated.

4.1.1.1 Pre-treatment Condition Effect

The AASHTO Lead State Team on pavement preservation promotes the idea of "applying the right maintenance treatment to the right road at the right time." Much emphasis has been given to selection of the optimal time for treatment application (2,132). If treatments are applied too early, they are perhaps an unnecessary expenditure which may lead to other complications such as flushing. If they are applied too late, perhaps the damage to the underlying structure has already happened and the treatment effectiveness will be reduced as a result, leading to partial waste of much-needed resources.

Survival curves for all sections with different pre-treatment conditions are shown in Figure 4-1. As shown, pretreatment condition influences the deterioration rate; being in the ‘poor’ category at the time of the treatment application, pavement sections experience a steeper deterioration curve compared to better conditions, as was confirmed in previous studies (9,29).



Note: Dashed lines visually connect the survival estimates derived accross intervals.

Figure 4-1 Survival curves for all sections stratified by different initial conditions

The generalized log-rank test was used to test if survival curves for different pretreatment conditions are statistically different. The test results are shown in Table 4-1.

The low p-value associated with the generalized log-rank test of homogeneity conclusively rules out the null hypothesis that the survival curves are the same. However, the test does not reveal where the differences exist. To further investigate which curve or curves have caused the rejection of the null hypothesis, the similarity of curves, a pairwise comparison test was used. P-values lower than 5% indicate that curves are statistically different. This observation stresses the importance of applying treatments when the underlying pavement is still in 'good' condition, as opposed to opting for a "worst-first" maintenance policy.

Table 4-1 Generalized Log-Rank test and pairwise group comparisons (Tukey test)

Test of homogeneity over strata (Initial Conditions)

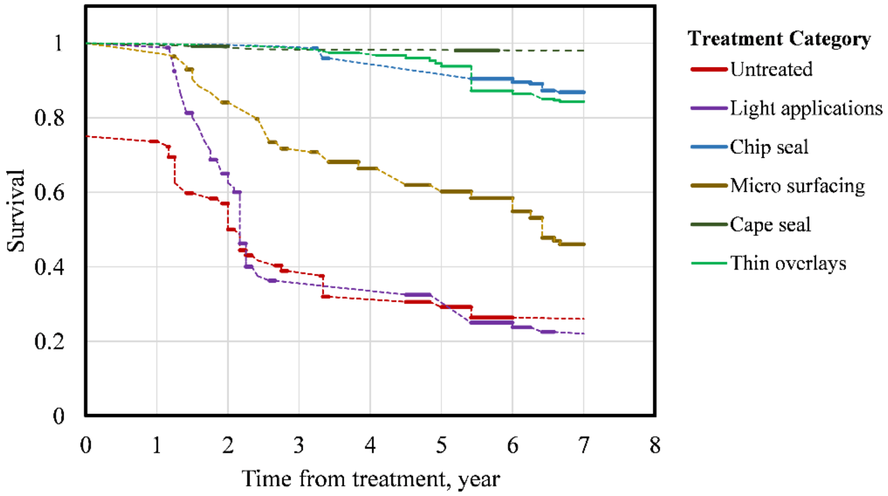
Chi-Square	**DF**	**Probability > Chi-Square**
57.5075	2	<.0001

Pairwise group comparisons

Pretreatment Condition		**Chi-Square**	**p-values**	
(1)	**(2)**		**Raw**	**Tukey-Kramer**
Fair	Good	21.65	<.0001	<.0001
Fair	Poor	11.70	0.0006	0.0018
Good	Poor	56.51	<.0001	<.0001

4.1.1.2 Treatment Type Effect

It is reasonable to expect that different treatment categories would exhibit different performances since different materials, methodologies, and efforts are spent for each; their goals are not the same either in the first place. These different performance expectations were checked using the KM methodology by generating survival curves, as shown in Figure 4-2.



Note: Dashed lines visually connect the survival estimates derived accross intervals.

Figure 4-2 Cracking-specific survival curves for different treatment categories applied on LR-159

Cape seals are exhibiting excellent performance with a survival rate close to 100% after 7 years of traffic. Some treatments such as chip seals and thin overlays exhibited close behaviors. It is to be noted that naturally one expects higher performance for thin overlays. However, two of the treatments in the thin overlay group included high amounts of RAP and RAS which pushed the performance lower to where chip seals stand. Still, when compared with the untreated category, thin overlays and chip seals both provide enormous benefits. To illustrate, 50% survival probability (median life) is 2 years for the untreated group, whereas it is at least 7 years for the said categories.

Micro surfacing median life is about 6.5 years, which is substantial. Yet, compared to the chip seal and thin overlays it may bring the impression that they are not as effective as they should be. This is primarily due to the micro surfacing finer surface texture, which makes it easier to identify hairline cracks in the crack mapping procedure, compared with treatments with a coarser surface textures such as a chip seals where the crack channel should be wide enough to be visible and counted. It is also worthwhile to mention that this assessment is made in terms of cracking, which is not a distress to be effectively addressed with micro surfacing. Normally, micro surfacing should be applied on a pavement with very few cracks. Even so, there is still a substantial benefit obtained from the treatment.

Another observation is that in the light application group, consisting of crack sealing/filling and rejuvenating fog seal, the median survival life is almost equal to the untreated sections, which is around 2 years. This may be subjected to misinterpretation and begs the question that whether light preservation applications are beneficial. To answer the question, several aspects of light application’s performance need to be further scrutinized. First, it can be observed from Figure 4-2 that for the first 2 years after the treatment application, higher survival chance is expected for the light application group, judging by the larger area under the curve compared with the untreated section. This means that for a period of two years, a higher proportion of subsections remained in 'good' and 'fair' conditions for the light application category. Thus, the performance of untreated sections and light preservations were not same during the first 2 years.

Second, the survival methodology considers 20% cracking as 'failed' condition, and calculates the proportion of the failed subsections relative to all of the subsection in the group. Consequently, it is not sensitive to crack values beyond 20%, as it uniformly defines all of such subsections as 'failed' no matter to what extent. This further suggests that there could be some unaccounted benefits for the light application group beyond the 20% threshold which cannot be inferred from the survival plot. To illustrate with numbers, cracking percentages at the 2-year mark were 27.5% and 19.2% for the untreated and light application groups, respectively. The lower cracking level for the light applications clearly shows the unaccounted benefit of light preservation applications in the survival methodology.

Third, lower performance of light applications in this study is not totally unexpected because they were applied when a large portion of subsections (60%) were in 'fair' and 'poor' conditions. Time and again, it has been emphasized that light preservation techniques should be applied early when the pretreatment condition is 'good.'

Similar to what was done for the pretreatment condition effect, Table 4-2 provides tests of similarity among treatments. As indicated by the Log-Rank test, survival curves are conclusively different at a p-value less than 0.0001. Results suggest that different models should be created for different treatment categories.

Table 4-2 Generalized Log-Rank test and pairwise group comparisons (Tukey test)

Test of homogeneity over strata (Treatment Effect)

Chi-Square	DF	Probability > Chi-Square
474.4345	6	<.0001

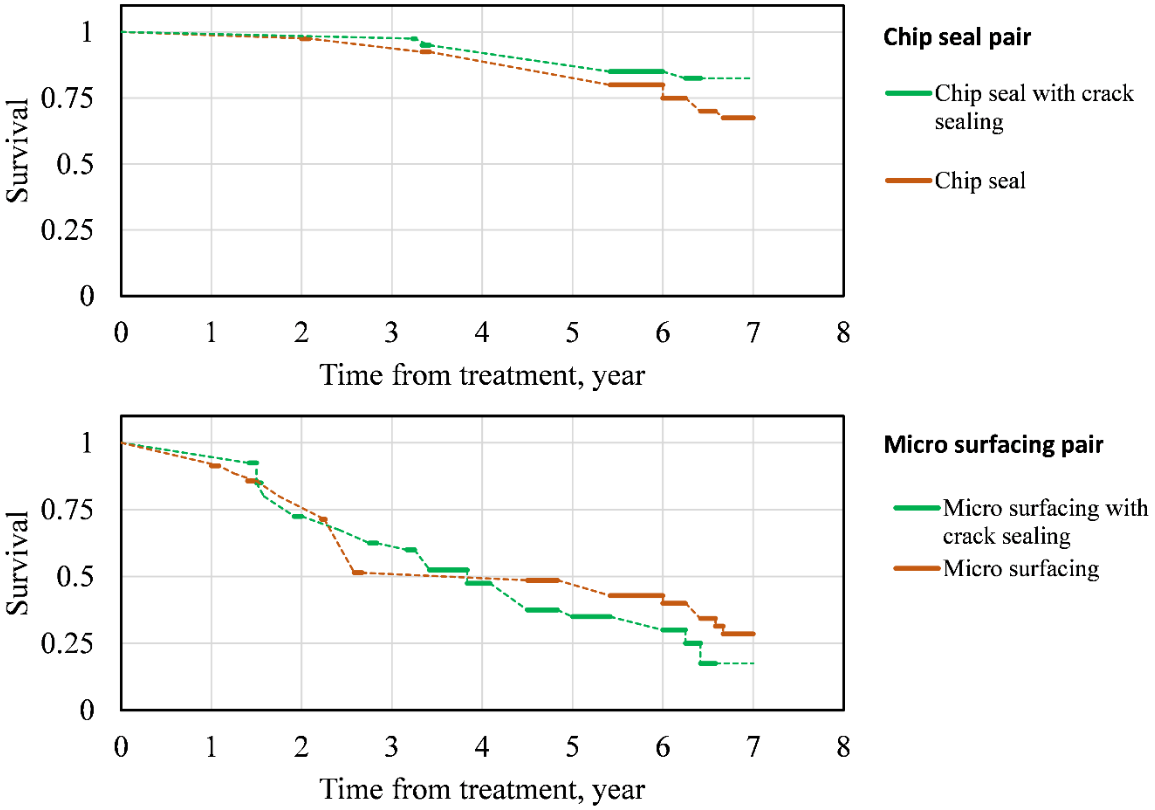
4.1.1.3 Crack Sealing Effect

In a chip seal or micro surfacing application, first, a layer of emulsion is applied to seal the existing pavement. While this approach uniformly seals the entire pavement surface conveniently in a single pass, the same application rate is applied to different areas of the pavement surface. Therefore, an area with deep visible cracks will receive the very same amount of sealing material as another area that has little to no cracking. This approach works perfectly for pavements in 'good' condition. However, for pavements where cracking has already become an issue, the idea of a separate crack sealing application prior to application of the main treatment would be to separately seal off the wider, deeper cracks to ensure a consistent waterproof surface at the end of the sealing operations. To test the benefits for such an approach, two pairs of treatments on LR-159 were crack sealed prior to another treatment. In addition, it was of interest to quantify the benefits of crack sealing when is applied as a stand-alone treatment. This was assessed by comparing a stand-alone crack sealed section with the untreated category. Table 4-3 shows these pairs of sections.

Table 4-3 Treatment pairs on LR-159 with crack sealing in advance

Section no.	Group 1	Section no.	Group 2
3 & 4	Untreated category	5	Stand-alone crack sealing
6	Single layer chip seal	7	Single layer chip seal + crack sealing
11	Single layer micro surfacing	12	Single layer micro surfacing + crack sealing

The KM methodology was run for each of the pairs, and stratified for the sealing effect. Survival curves are shown in Figure 4-3. In the chip seal group, crack sealing prior to chip seal increased the survival rates. The divergence in performance started at year 2 and has expanded as of today. At year 7, the survival rate for the crack sealed section is 15% higher compared to the standalone chip sealed section. More years of data collection are needed for more conclusive evidence. The second year can be interpreted as the time when hairline cracks were already developed, and by that, moisture could enter into the pavement structure and cause higher deterioration rates. In fact, crack sealing would function as an extra net of protection to prevent water and incompressible materials intrusion into the pavement structure.



Note: Dashed lines visually connect the survival estimates derived

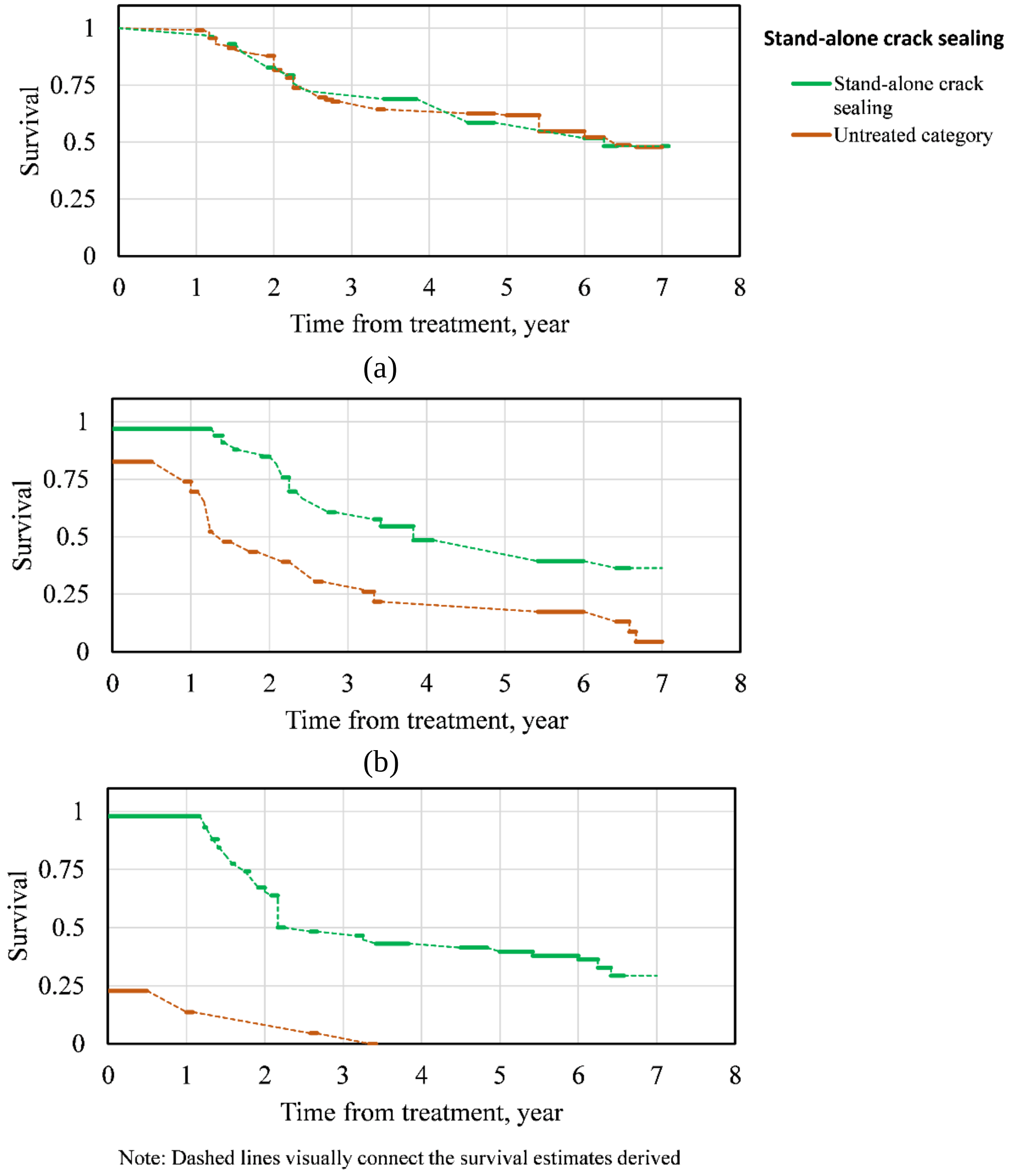
Figure 4-3 Survival curves for the chip seal and micro surfacing sections with and without crack sealing

From Figure 4-3, crack sealing does not seem to have any effect on the performance of the micro surfacing group. However, field visits suggest otherwise. As explained in the previous section, and investigated in a recent study by Vargas and Jalali (133), findings of survival analysis are tied to the way condition categories are defined in the analysis. Particularly, for the ‘poor’ condition category which has a lower bound of 20%, both sections exhibit similar median times to failure, although the average pretreatment cracking percentage was 21.4% for the micro surfacing section and 41.9% for the micro surfacing with crack seal/fill. This suggests there is a benefit that is unaccounted for in this dataset, but as mentioned earlier, the condition ranges were selected to be consistent with the FHWA performance criteria. Figure 4-4 shows side by side pictures of the sections, where it is evident that crack sealing has contributed in delaying cracking from reflecting to the surface.

(a) (b)

Figure 4-4 cracking in (a) micro surfacing and (b) micro surfacing with crack sealing in advance **(133)**

For the stand-alone sealing effect, the initial analysis revealed that there is an interaction effect between sealing and pretreatment condition, meaning that in addition to these main effects, their interaction is also affecting the survival rates. To investigate the interaction effect, Figure 4-5 exhibits the estimated survival curves at different pretreatment condition levels.



Note: Dashed lines visually connect the survival estimates derived

(c)

Figure 4-5 Survival curves comparing stand-alone crack sealing with the untreated category at (a) ‘good’, (b) ‘fair’ and (c) ‘poor’ pretreatment condition levels

Apparently, stand-alone crack sealing does not add any benefits at ‘good’ pretreatment condition level. However, a closer assessment shows that the ‘good’ category dataset had a very low percentage of cracks (near zero) and therefore, the percentage of cracks that were sealed was also very low. Therefore, both sections ended up performing in a very similar way.

The benefits of crack sealing start by the time when the crack levels are to a point that warrants sealing. It is shown in Figure 4-5(b and c) that crack sealing benefits are optimum when surface condition is moderately cracked. Comparisons with the untreated category shows that in the ‘fair’ pretreatment condition, the median life due to crack sealing increases by 2.6 years while for the ‘poor’ condition, the median benefit is 2.2 years.

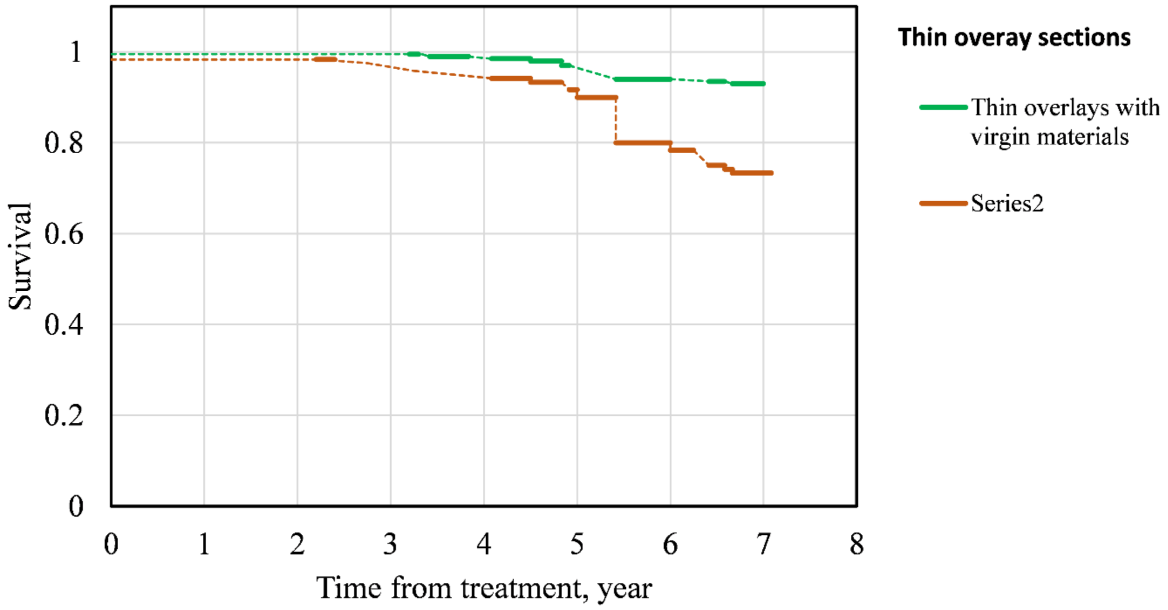
4.1.1.4 Recycled Material Usage

As part of the Preservation Study, it was of interest to quantify the life-extending benefits of thin overlays that have incorporated substantial amounts of recycled materials, and to see how they will perform compared to thin overlays that only used virgin materials. Hence, several sections with virgin and recycled materials were put in place for performance assessment. In Table 4-4, group 1 and 2 are the thin overlay sections with virgin and recycled materials, respectively.

Table 4-4 Thin overlay sections using virgin (group 1) and recycled (group 2) materials

Section no.	Group	Name
18	1	HMA thin overlay over FiberMat® chip seal
19		Virgin thinlay with PG67-22
21		Virgin thinlay with PG76-22
22		Ultra-thin bonded surface course
25		HiMA Thinlay
20	2	Virgin thinlay with PG67-22 on 100% foamed recycle base
23		50% RAP thinlay
24		5% RAS Thinlay

KM survival curves are generated for the two groups in Figure 4-6. First to note is the very high survivability of thin overlays with survival rates of more than 70% for both groups. It is evident, however, that the survival rates for the recycled material group is lower. It seems the diverging trend is to be continued further. As seen from treatments definitions in Table 3-1, the binder replacement for RAP and RAS was high, which means the binder is more aged and thus more susceptible to cracking.



Note: Dashed lines visually connect the survival estimates derived accross intervals.

Figure 4-6 Survival curves for the thin overlays stratified over recycled/virgin materials usage

4.1.2 Semi-parametric Approach: COX PH

The semi-parametric survival procedure known as the Cox Proportional Hazard (PH) model was implemented in the SAS® statistical software to assess the associated risk factors relevant to each treatment group. Several variables can affect treatment survival experience. The survivability comparisons between different preservation treatments and the untreated sections can guide the pavement manager to choose an effective treatment objectively. It should be noted that through this entire study, regardless of the analysis methodology, failure was always defined as the point at which the pavement reaches the ‘poor’ condition category (20% cracking of the entire section area). The Cox model provides the right tool to quantify risks associated with different variables. Hence, before presenting semi-parametric equations, it would be informative to conduct a risk analysis for different scenarios. For such an analysis, three scenarios were considered.

In the first scenario, treatment effect, pretreatment condition effect, and traffic level effects were assessed by running the Cox model on all of the sections in the dataset, in which summary results are provided in Table 4-5.

Table 4-5 Cox Proportional Hazards model documenting significant explanatory variables associated with crack-specific survivability of all pavement treatment sections

Effect	Hazard Ratio	95% Confidence Limits		P-Value	Sections included in the analysis
Treatment group (Untreated)					
Cape seal	0.01	0.001	0.023	<.0001	All sections (Sections 1 – 25)
Thin overlays	0.06	0.037	0.084	<.0001	
Chip Seals	0.06	0.041	0.092	<.0001	
Micro surfacing	0.23	0.158	0.340	<.0001	
Light applications	0.56	0.383	0.816	<.0026	
Pretreatment condition (Good)					
Fair	2.43	1.782	3.324	<.0001	
Poor	3.28	2.241	4.452	<.0001	
Traffic level (Lower bound)					
Upper bound	1.15	0.903	1.477	0.2520	

It should be noted that for each effect, the reference level is cited in parentheses. For instance, for the treatment effect, the untreated category is considered the reference, and the rest of the treatments are compared with it. The hazard ratios are describing relative risks. Hazard ratios greater than 1.0 suggest an increased risk of failure, while values less than 1.0 imply a protective effect. The relative risks should be carefully interpreted in Cox regression. A variable effect should be interpreted in a setting that all the other effects are kept constant.

It is not enough to look at the hazard ratios when interpreting the results. For an explanatory variable to be statistically significant, p-values should be less than 5%, or any other value that may be selected by the analyst depending on the required confidence levels. In the table, p-values close to zero are conclusively significant. However, p-values near 5% or even higher, such as the one for the traffic effect, are not entirely meaningless. They could imply ‘some’ effect, yet that effect would not be significant enough to be considered in the final models. Despite this, these cases may still provide some insights on the section performances.

For the treatment effect, p-values are close to zero for all the treatments which suggests that there is significant evidence that treatments behave differently compared to the untreated (reference) group. For instance, chip seals are 94% (hazard ratio = 0.06) less likely to fail over time in comparison with the untreated group. Likewise, for the pretreatment condition effect, a section with a ‘poor’ condition is 3.28 times more likely to fail than a section with ‘good’ pretreatment condition. This finding reverberates well with the common maintenance lesson that preservation treatments should be applied early on, when the pavement is still in good condition. It is to be noted that relative risks that are not shown in the table, such as risk of ‘poor’ over ‘fair’ pretreatment condition can simply be derived by dividing the two hazard ratios. For the previous example, the relative risk is 1.35 (= 3.28 / 2.43). For the traffic effect, the p-value is 0.25 which is not significant, but there should be some minute effects. There could be that for some of the sections, the effect is higher where it derives the p-value toward lower values. Yet, on average, the effect is not significant and can be ruled out.

In the second scenario, the recycled group consisting of thin overlays were analyzed for different effects and the associated risks. Results can be seen in Table 4-6. The reason why the recycled material effect was not included in the previous section with all of the treatments is that recycled materials were only used in the thin overlays and comparing other virgin-used treatments with this group would introduce bias into the analysis. For that reason, a separate analysis was conducted herein. As can be seen, p-values are significant for the recycling and traffic level factors, but insignificant for the pretreatment condition effect. Field visits confirm the findings in that for the recycled sections, cracks appeared on the entire length of the sections, regardless of the pretreatment condition. Also, most of the deterioration has occurred in the outbound direction where there is higher number of ESALs. From the statistical standpoint, it can be said that incorporating high percentages of recycled materials will increase the risk of failure 4.8 times compared with a virgin thin overlay. Although the reader may be disillusioned by the high risk factor, it should be reminded that the results here are only comparative, and all thin overlays are exhibiting excellent performance after 7 years of service, when compared with the untreated category, as was shown previously with the help of non-parametric plots. Also, recycled overlays used in this study included high amounts of RAP and RAS which is not so typical of these treatments in real projects. Even so, the cracking performance is still satisfactory.

Table 4-6 Cox Proportional Hazards model results for the thin overlay group consisting of virgin and recycled materials

Effect	**Hazard Ratio**	**95% Confidence Limits**		**P-Value**	**Sections included in the analysis**
Recycled material application (Only virgin material)					Thin overlay sections (Sections 18-25)
Recycled material application	4.84	0.947	2.206	<0.0001	
Traffic level (Lower bound)					
Upper bound	5.94	1.026	2.537	<0.0001	
Pretreatment condition (Good)					
Fair	1.40	-0.455	1.1229	0.4071	
Poor	0.75	-1.054	0.4711	0.4537	

In the third scenario, the effect of crack sealing prior to a treatment was investigated for pairs of chip seal and micro surfacing sections. In one case, sections were crack sealed and then treated, and in the second case, sections were only treated with a chip seal or a micro surfacing. These combinations of experiments facilitate the analysis of crack sealing benefits when combined with other strategies. Results of this analysis are presented for the chip seal and microsurfacing section in Table 4-7.

Table 4-7 Cox Proportional Hazards model results for chip seal and microsurfacing treatments with and without crack sealing

Effect	Hazard Ratio	95% Confidence Limits		P-Value	Sections included in the analysis
Crack sealing (No sealing)					For chip seal sections with and without crack sealing (Sections 6 & 7)
Crack sealing in advance of treatment	0.41	0.026	0.788	0.0256	
Traffic level (Lower bound)					
Outbound	1.61	0.636	4.085	0.3143	
Pretreatment condition (Good)					
Fair	4.80	0.966	23.820	0.0552	
Poor	4.68	0.655	33.367	0.1240	
Crack sealing (No sealing)					For micro surfacing sections with and without crack sealing (Sections 11 & 12)
Crack sealing in advance of treatment	0.85	0.482	1.493	0.5692	
Traffic level (Lower bound)					
Outbound	1.09	0.636	1.860	0.7598	
Pretreatment condition (Good)					
Fair	1.62	0.875	2.990	0.1254	
Poor	2.24	1.095	4.592	0.0272	

For the chip seal pair, the p-value for crack sealing effect is less than 5%, and the risk of failure for the crack sealed surface is 59% lower (hazard ratio = 0.412) compared to the standalone chip seal section. Traffic level is not significant. Pretreatment conditions are somewhat significant (p-value = 0.05). The analysis is showing that the risk of failure for a section with ‘fair’ and ‘poor’ conditions is more than 4 times than that of a section treated when in ‘good’ condition.

For the micro surfacing section, only the effect of pretreatment condition was significant. A section in ‘poor’ condition is 2.2 times more likely to fail than a section in ‘good’ condition. Crack sealing effect is not significant. However, field visits suggests otherwise. The reasons why survival analysis does not show the crack sealing effect for micro surfacing section are discussed in the previous section for non-parametric survival analysis. Traffic level was not significant either.

4.1.2.1 Semi-parametric Models for Performance Prediction

In this section, semi-parametric deterioration equations are presented for different categories of treatments. As opposed to the previous analyses, there was no need here to include covariates such as recycled material effect, or crack sealing effect because individual treatments are themselves entered into the analysis directly, and as such, separate equations are presented for each of the treatments, ready to be used for performance prediction. Moreover, using the generated models, median survival lives were generated and are documented at the end of this section. For each of the treatment categories, three main variables were considered: the individual treatment within the category, pretreatment condition, and traffic level.

Table 4-8 shows the results for an analysis of variable significance. Variables with p-values between 0% and 5% are labeled as 'conclusive', around 5% are labeled 'somewhat conclusive' and the ones larger than 5% are labeled as 'not conclusive.' For the rest of the analyses, variables that were either 'conclusive' or 'somewhat conclusive' were included in the Cox model.

One or more variables were identified as significant for the treatment categories except for the cape seal category. No explanatory variable was found significant for the cape seals. In fact, the performance of cape seals were such that none of these factors could affect the exemplary performance. However, more years of data collection may reveal other trends that can change the statistical deductions.

Table 4-8 Significance of variables in each treatment category

Treatment category	**Explanatory variable significance (p-value = 0.05)**		
	Treatment type	**Pretreatment condition**	**Traffic level**
Untreated	Conclusive	Somewhat conclusive	Not conclusive
Light applications	Not conclusive	Conclusive	Not conclusive
Chip seal	Conclusive	Conclusive	Somewhat conclusive
Micro surfacing	Conclusive	Conclusive	Not conclusive
Cape seal	Not conclusive	Not conclusive	Not conclusive
Thin overlay	Conclusive	Conclusive	Not conclusive

Results of the model fittings are presented in Tables 4-9 through 4-13. Table 4-9 shows the statistical results for the untreated category. The pretreatment condition had a high impact on the deterioration trend. This implies that a pavement usually experiences an accelerated deterioration as condition worsens in time, judging by the higher β coefficient – estimated for equation 3.10 and shown in Table 4-9 – for the 'poor' condition compared to the 'fair' condition.

Table 4-9 Analysis results for the untreated category

Effect	β estimate	95% Confidence Limits		Chi-square	P-Value
Pretreatment condition (Good)					
Fair	1.6484	0.9730	2.3238	22.88	<.0001
Poor	16.1714	16.1714	16.1714		

Results for the light preservation applications are shown in Table 4-10. There is no 'section' effect and the only significant variable is pretreatment condition. This means that the performance of crack sealing and rejuvenating fog seals are not statistically different across different pretreatment levels. It may seem contradictory that previously, in Chapter 3, field observations were showing two distinctly different curves for the light preservation treatments. Yet, it should be noted that the difference is due to the differences in pretreatment condition and not due to the section effect. As a reminder, pretreatment cracking levels were 25.4% and 5.4% (Table 3-7) for the standalone crack sealing and rejuvenating fog seal, respectively.

Table 4-10 Analysis results for the light preservation applications category

Effect	β estimate	95% Confidence Limits		Chi-square	P-Value
Pretreatment condition (Good)					
Fair	1.1758	0.4944	1.8572	11.44	0.0007
Poor	1.6627	1.0343	2.2911	26.89	<.0001

For the chip seal results shown in Table 4-11, all the three variables were found to be influential in defining the deterioration path. Note that in creating the models and interpreting the risks, care should be taken on high p-values. For instance, while the ‘section’ effect is significant in influencing the survival rates, some levels inside this effect may not be. Take the scrub seal as a case in point. The large p-value does not mean that the scrub seal is not a good treatment, in fact, it is so good that creates a straight line in the survival plot with close to 100% survivability. This near zero slope line results in a high p-value, similar to what happens for an insignificant variable in a linear regression. This explanation is in line with field observations, as the scrub seal performance was shown to be much better than the baseline section.

Table 4-11 Analysis results for the chip seal category

Effect	β estimate	95% Confidence Limits		Chi-square	P-Value
Section (single layer chip seal)					
FiberMat® chip seal	-0.324	-1.071	0.421	0.73	0.3937
Single layer chip seal with crack sealing	-1.449	-2.530	-0.367	6.89	0.0087
Triple layer chip seal	-3.078	-5.136	-1.021	8.60	0.0034
Double layer chip seal	-2.206	-3.707	-0.705	8.31	0.0040
Scrub seal	-16.958	-2093	2059.8	0.00	0.9872
Pretreatment condition (Good)					
Fair	0.9745	0.1989	1.7502	6.06	0.0138
Poor	0.9517	0.1533	1.7502	5.46	0.0195
Traffic level (Lower bound)					
Outbound	0.4009	-0.1779	0.9797	1.84	0.1746

Regarding the Traffic level, it seems there is minor evidence that the risk of failure is higher for the upper traffic bound of 1 million ESALs. The p-value is equal to 0.17 and it means in every 100 pavements, 83 of them experience said risk. Yet, the evidence is not strong enough from a statistical standpoint to draw definitive conclusions.

Statistical analysis results for the micro surfacing group is presented in Table 4-12. There are section effects and pretreatment condition effects, meaning that at least two micro surfacing types have different deterioration paths. The deterioration risk for 'poor' pretreatment condition is higher than the risk for 'fair' and 'good' conditions, respectively, as it has been observed time and again in this experiment.

Table 4-12 Analysis results for the micro surfacing category

Effect	β estimate	95% Confidence Limits		Chi-square	P-Value
Section (single layer micro surfacing)					
Single layer micro surfacing with crack sealing	-0.2438	-0.8064	0.3188	0.72	0.3956
Double layer micro surfacing	-3.0398	-4.1316	-1.9480	29.78	<.0001
Pretreatment condition (Good)					
Fair	0.4888	-0.1151	1.0927	2.52	0.1127
Poor	1.0296	0.3828	1.6764	9.73	0.0018

For the thin overlays, results are shown in Table 4-13. As shown, there are treatment and pretreatment condition effects. RAP and RAS sections have the lowest p-value meaning that they conclusively follow a different deterioration path than the baseline treatment.

Table 4-13 Analysis results for the thin overlay category

Effect	β estimate	95% Confidence Limits		Chi-square	P-Value
Section (virgin thin overlay with PG 67-22)					
HMA thin overlay over FiberMat® chip seal	-14.6540	-2328.66	2299.351	0.00	0.9901
Virgin thinlay with PG67-22 on 100% foamed recycle base	-0.5255	-2.9322	1.8813	0.18	0.6687
A 4.75 NMAS thin virgin mix with PG76-22 binder applied on pavement surface	0.7188	-1.3087	2.7463	0.48	0.4871
Ultra-thin bonded surface course	1.8661	0.2622	3.4700	5.20	0.0226
50% RAP thinlay	2.8420	1.3047	4.3793	13.13	0.0003
5% RAS Thinlay	2.9308	1.3609	4.5007	13.39	0.0003
HiMA Thinlay	-14.4254	-1324.3	1297.89	0.00	0.9842
Pretreatment condition (Good)					
Fair	-0.4255	-1.3754	0.5245	0.77	0.3800
Poor	1.2121	0.3952	2.0291	8.46	0.0036

The results from the above analyses can be used to generate survival curves showing the survival probability over time, and from that, life-extending benefits can be estimated. As explained before, in the Cox model the first part of the equation, $h_0(t)$, is the baseline hazard rate which is estimated using the KM methodology. The second part, $exp(\beta^t Z)$, takes the effects of different variables. For the cape seal category, none of the variables were significant, thus, the estimated cumulative hazard rate was only dependent on the baseline hazard rate, $h_0(t)$. The survival function can be derived from the cumulative hazard rate using Equation 4.1:

$$S(t) = \exp\big(-H(t)\big) \qquad 4.1$$

Where *S(t)* is survival rate at time *t*, and $H(t)$ is the cumulative hazard rate at time t for different covariate levels which can be calculated using Equation 4.2:

$$H(t) = H_0(t) \times \exp(\beta^t Z) \qquad 4.2$$

Where $H_0(t)$ is the cumulative hazard rate at the baseline condition, $\beta^t = (\beta_1, \dots, \beta_p)$ is a coefficient vector and *Z* is a vector of covariate values. β estimates are model coefficients and are estimated by maximizing the full likelihood function. $H_0(t)$ estimations were readily available in SAS® which are reported in Table 4-14 for all the six general treatment categories.

Table 4-14 Baseline cumulative hazard rates for the six treatment categories

Untreated sections

Time, year	Cumulative hazard rate
0	0.000
1	0.070
2	0.285
3	0.467
4	0.587
5	0.674
6	0.744
7	0.808
8	0.868
9	0.925
10	0.975

Light application category

Time, year	Cumulative hazard rate
0	0.000
1	0.006
2	0.044
3	0.100
4	0.137
5	0.158
6	0.172
7	0.184
8	0.198
9	0.211
10	0.225

Chip seal category

Time, year	Cumulative hazard rate
0	0.000
1	0.001
2	0.006
3	0.021
4	0.049
5	0.098
6	0.178
7	0.297
8	0.465
9	0.689
10	0.981

Micro surfacing category

Time, year	Cumulative hazard rate
0	0.000
1	0.033
2	0.160
3	0.360
4	0.582
5	0.804
6	1.025
7	1.249
8	1.482
9	1.722
10	1.970

Cape seal category

Time, year	Cumulative hazard rate
0	0.000
1	0.001
2	0.059
3	0.076
4	0.086
5	0.094
6	0.102
7	0.109
8	0.115
9	0.121
10	0.127

Thin overlay category

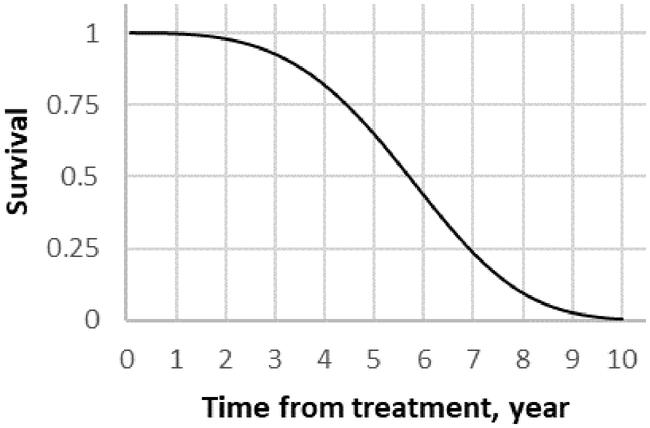
Time, year	Cumulative hazard rate
0	0.000
1	0.000
2	0.000
3	0.001
4	0.004
5	0.008
6	0.016
7	0.027
8	0.044
9	0.068
10	0.099

Other pieces of information are needed to obtain survival probabilities. For different covariate effects, βs and the class level information that were used in SAS® should be known. βs were previously reported in Tables 4-9 through 4-13. The class level information are reported in Table 4-15. An example solution is provided herein to facilitate survival curve generation from the raw SAS® output. The survival rate at 5 years is calculated for section 23, the 50% RAP thin overlay with poor pretreatment condition. From Table 4-13, β^t = (-0.51, 0.59, 2.15, 2.82, 2.89, -13.25, -0.03, 1.15). From Table 4-14, $H_0(t = 5)$ is equal to 0.008.

Table 4-15 defines the covariate levels for *Z1* through *Z8* as (0, 0, 0, 1, 0, 0, 0, 1). Substituting Equation 4.2 into Equation 4.1 and using the relevant values, the survival probability can be obtained:

$$S(t = 5\, years) = \exp\,(-0.008\, \times \exp\big((-0.51)(0) + (0.59)(0) + (2.15)(0) + (2.82)(1) + (-13.25)(0) + (-0.03)(0) + (1.15)(1)\big) = 0.65$$

Similar calculations were performed for other times, and consequently, the survival curve was generated. For the above example, the survival curve is shown in Figure 4-7.



Note: Median treatment life is 5.8 years

Figure 4-7 Survival curve for section 23, thin overlay with 50% RAP in poor pretreatment condition

The median survival time is 5.8 years, meaning that half of the subsections failed by this time. Complete failure of the section when 100% of subsections reach 20% cracking will occur at the 10-year mark.

Table 4-15 Class level information for the treatment categories in the semi-parametric survival regression

Class	Value	Design Variables →						Relevant Z
Untreated category								
Section number	3	0						Z1
	4	1						
Pretreatment condition	Good	0	0					Z2, Z3
	Fair	1	0					
	Poor	0	1					
Light preservation category								
Pretreatment condition	Good	0	0					Z1, Z2
	Fair	1	0					
	Poor	0	1					
Chip seal category								
Section number	2	1	0	0	0	0		Z1, Z2, Z3, Z4, Z5
	6	0	0	0	0	0		
	7	0	1	0	0	0		
	8	0	0	1	0	0		
	9	0	0	0	1	0		
	16	0	0	0	0	1		
Pretreatment condition	Good	0	0					Z6, Z7
	Fair	1	0					
	Poor	0	1					
Traffic level	Lower bound	0						Z8
	Upper bound	1						
Micro surfacing category								
Section number	11	0	0					Z1, Z2
	12	1	0					
	13	0	1					
Pretreatment condition	Good	0	0					Z3, Z4
	Fair	1	0					
	Poor	0	1					
Thin overlay category								
Section number	19	0	0	0	0	0	0	Z1, Z2, Z3, Z4, Z5, Z6
	20	1	0	0	0	0	0	
	21	0	1	0	0	0	0	
	22	0	0	1	0	0	0	
	23	0	0	0	1	0	0	
	24	0	0	0	0	1	0	
	25	0	0	0	0	0	1	
Pretreatment condition	Good	0	0					Z7, Z8
	Fair	1	0					
	Poor	0	1					

Similar analyses were conducted for the rest of the treatment categories. Median life expectancy for all of the sections is reported in Tables 4-16 through 4-20. In addition to the median lives, survival curves for all of the treatments were generated and are presented in APPENDIX A.

Table 4-16 Median treatment lives for the untreated category, years

Section no.	Treatment	Pretreatment condition		
		Good	***Fair***	***Poor***
3 & 4	Untreated category	4.0	1.2	0.0

Table 4-17 Median treatment lives for the light application category, years

Section no.	Treatment	Pretreatment condition		
		Good	***Fair***	***Poor***
1	Rejuvenating fog seal	5.8	2.3	1.9
5	Crack sealing only	5.8	2.3	1.9

Table 4-18 Median treatment lives for the chip seal category, years

Section no.	Treatment	Pretreatment condition		
		Good	***Fair***	***Poor***
2	FiberMat® chip seal	(7.5, 10.0)	(5.6, 7.5)	(6.7, 8.8)
6	Single layer chip seal	(6.8, 9.1)	(5.1, 6.8)	(6.0, 8.0)
7	Single layer chip seal with crack sealing	>10	(7.8, >10)	(9.3, >10)
8	Triple layer chip seal	>10	>10	>10
9	Double layer chip seal	>10	(9.8, >10)	>10
16	Scrub seal	>10	>10	>10

Note: for sections that lives are reported in ranges (a, b), *a* is the median life for the upper traffic bound level and *b* is the median life for the lower traffic bound level.

Table 4-19 Median treatment lives for the micro surfacing category, years

Section no.	Treatment	Pretreatment condition		
		Good	***Fair***	***Poor***
11	Single layer micro surfacing	4.5	3.3	2.5
12	Single layer micro surfacing with crack sealing	5.4	3.8	2.8
13	Double layer micro surfacing	>10	>10	>10

Table 4-20 Median treatment lives for thin overlay category, years

Section no.	Treatment	Pretreatment condition		
		Good	***Fair***	***Poor***
18	HMA thin overlay over a FiberMat® chip seal	>10	>10	>10
19	Virgin thin overlay with PG67-22	>10	>10	>10
20	Virgin thin overlay with PG67-22 on 100% foamed recycle base	>10	>10	>10
21	Virgin thin overlay with PG76-22	>10	>10	>10
22	Ultra-thin bonded surface course	9.5	9.5	6.9
23	50% RAP thin overlay	7.9	7.9	5.8
24	5% RAS Thin overlay	7.8	7.8	5.7
25	HiMA Thin overlay	>10	>10	>10

Based on the quantified lives, untreated sections showed a median life, from 0 to 4 years, depending on the pretreatment condition. Note that at the start of this study, the untreated sections were already 13 years old, thus aged and prone to cracking. A newly paved road will survive much longer than the numbers derived for the untreated category.

In the light application group, both sections showed similar performance with median lives from 1.9 to 5.8 years depending on their pretreatment conditions.

For the chip seal group, double and triple layer chip seals and the scrub seal are showing excellent survival lives beyond 10 years, while the performance of other sections are also highly desirable. It can be seen that the FiberMat® chip seal does a better job than a single layer chip seal. Also, comparing sections 6 and 7 gives the indication that crack sealing prior to chip seal further enhances the survival life. The life-extension benefits of crack sealing in section 7 is more pronounced in subsections with worse pretreatment conditions. The performances seen here also well aligns with the hierarchical clustering results shown in Chapter 3.

For the micro surfacing category, double layer micro surfacing is showing exemplary performance. Yet, the survival rates for sections 11 and 12 are somewhat unexpected. The reason for the underperformance is mostly related to how failure threshold was defined in this study. Also, the survival methodology is partly to blame, as discussed previously in this chapter.

For all of the cape seal sections, median survival lives are more than 10 years, regardless of the specific treatment type, pretreatment conditions, and traffic level. Cape seals are performing extremely well in this experiment.

In the thin overlay group, median lives range from 5.8 to more than 10 years. The highest performance belongs to the sections with only virgin materials, and also the highly polymer-modified section. The RAP and RAS incorporated sections are performing almost identical, and when applied in the right timeframe where pavement condition is still good, the benefits are substantial. The values shown in Tables 4-16 through 4-20 are treatment lives, and not life-extending benefits. To obtain these benefits, pairwise comparisons with the untreated category were conducted, and the results are shown in Tables 4-21 through 4-24.

Many of the sections are shown to have higher life-extending benefits when treatments are applied in ‘poor’ pretreatment condition which is unrealistic. It is because it was assumed that life-extension benefit for the untreated category in ‘poor’ condition is equal to 0, whereas in reality failure for said pretreatment level happened some unknown time prior to the start of the experiment in 2012. For the untreated sections, the average cracking levels were 0.2%, 16.9%, and 34.3% for the good, fair, and poor pretreatment condition categories, respectively. Hence, it is reasonable to assume that the majority of subsections in ‘poor’ category were already failed at the time of the treatments application. However, the exact time cannot be known. Survival curves presented in Figure A. 1 – APPENDIX A may give an indication of the approximate failure time for the ‘poor’ pretreatment condition level.

Light preservation applications can extend the life of the pavements by up to 1.8 years, when are applied in ‘good’ initial condition.

Table 4-21 Median life-extending benefits for the light application category, years

Section no.	**Treatment**	**Pretreatment condition**		
		Good	***Fair***	***Poor***
1	Rejuvenating fog seal	1.8	1.1	1.9
5	Crack sealing only	1.8	1.1	1.9

Table 4-22 Median life-extending benefits for the chip seal category, years

Section no.	Treatment	Pretreatment condition		
		Good	*Fair*	*Poor*
2	FiberMat® chip seal	(3.5, 6.0)	(4.4, 6.3)	(6.7, 8.8)
6	Single layer chip seal	(2.8, 5.1)	(3.9, 5.6)	(6.0, 8.0)
7	Single layer chip seal with crack sealing	>6	(6.6, >8.8)	(9.3, >10)
8	Triple layer chip seal	>6	>8.8	>10
9	Double layer chip seal	>6	(8.6, >8.8)	>10
16	Scrub seal	>6	>8.8	>10

Note: for sections that lives are reported in ranges (a, b), *a* is the median life for the upper traffic bound level and *b* is the median life for the lower traffic bound level.

Table 4-23 Median life-extending benefits for the micro surfacing category, years

Section no.	Treatment	Pretreatment condition		
		Good	*Fair*	*Poor*
11	Single layer micro surfacing	0.5	2.1	2.5
12	Single layer micro surfacing with crack sealing	1.4	2.6	2.8
13	Double layer micro surfacing	>6	>8.8	>10

Table 4-24 Median life-extending benefits for thin overlay category, years

Section no.	Treatment	Pretreatment condition		
		Good	*Fair*	*Poor*
18	HMA thin overlay over a FiberMat® chip seal	>6	>8.8	>10
19	Virgin thin overlay with PG67-22	>6	>8.8	>10
20	Virgin thin overlay with PG67-22 on 100% foamed recycle base	>6	>8.8	>10
21	Virgin thin overlay with PG76-22	>6	>8.8	>10
22	Ultra-thin bonded surface course	5.5	8.3	6.9
23	50% RAP thin overlay	3.9	6.7	5.8
24	5% RAS Thin overlay	3.8	6.6	5.7
25	HiMA Thin overlay	>6	>8.8	>10

In the chip seal category, life-extensions beyond 10 years are reported. Note that the values for ‘poor’ condition should be adjusted as explained before. For several sections, ‘fair’ condition is reported to provide more benefits than the ‘good’ condition. This is basically a result of mathematical subtraction. Note that for these sections, raw treatment lives are reported to be more than 10 years for both ‘good’ and ‘fair’ levels, but expectedly, the extension beyond 10 years would be larger for the ‘good’ pretreatment condition compared to the extension for the ‘fair’ pretreatment condition. Yet, at this point in time these information are not available and the tables are reported in the way described. Reader should be cognizant that the values reported in Tables

4-21 through Table 4-24 are unadjusted and for almost all cases, life-extending benefits should be higher for ‘good’ initial conditions compared to lower conditions.

In this section the life-extending benefits of preservation treatments were quantified using a semi-parametric survival methodology. Regression estimates and the corresponding class level information are provided to facilitate survival probability calculations. Moreover, using said information, survival plots for the untreated category and all the rest of preservation treatments are provided in APPENDIX A. In the next section, a full-parametric methodology was used to better understand failure behavior of different treatments.

4.1.3 Full-parametric Survival Results

In practice, various predictors can affect treatment survival experience. Practitioners are usually interested in the effect of different predictors on a treatment for comparison, prediction, and better decision making. A parametric analysis was conducted on each treatment group to better understand the effect of different covariates on the survivorship of the treatments. In a full parametric model, in addition to covariate parameter estimation, distributions are to be fitted to the data, and in the process, distribution parameters are estimated. This estimation is performed by maximum likelihood estimation (MLE) through solving the Newton–Raphson algorithm.

Note that the effects of special cases, such as crack sealing or recycled material application were investigated before using the non-parametric and semi-parametric methodologies. The focus in this section is to understand the failure behavior of different treatment categories, develop parametric survival curves, and derive survival times for all of the treatments. Life-extending benefits can then be estimated by comparisons with the untreated category.

Similar to the procedure followed for the Cox model, three main covariates, namely treatment effect, pretreatment condition, and traffic level were entered into the models and checked for significance. The basic idea of a probability plot is to take a "nonparametric" estimate of fraction failing as a function of time and plot it on a distribution-specific scale. This nonparametric estimation is then assessed by comparing with a known probability distribution. This assessment is made to examine if a particular distribution can adequately describe the data.

JMP® contains several life distributions such as Weibull, lognormal, exponential, Frechet, and loglogistic. For each preservation category, all of the distributions were fitted to the data, and the one with the lowest AICc or BIC was selected. Significant covariates were then selected based on a 5% significance level. Wald's test statistic was used to determine the covariates significance, as shown in Table 4-25.

Table 4-25 Significant variables and distribution selection information

Untreated category

Model Significance
Degrees of freedom = *2*
ChiSquare = *79.77*
Prob>ChiSq = *<0.0001*

Significant Covariates
Pretreatment condition, *p-value: <0.0001*

Distribution	Model Selection Measures		
	AICc	**BIC**	
Weibull	314.92243	323.43208	
Lognormal	309.77075	318.2804	
Exponential	313.88384	320.3609	
Frechet	***306.17789***	***314.68754***	***Best***
Loglogistic	312.83058	321.34023	

Light preservation category

Model Significance
Degrees of freedom = 4
ChiSquare = *24.34*
Prob>ChiSq = *<0.0001*

Significant Covariates
Traffic level, *p-value*: 0.0025
Pretreatment condition, *p-value: 0.0055*
Treatment effect, *p-value: 0.0175*

Distribution	Model Selection Measures		
	AICc	**BIC**	
Weibull	411.07756	424.21904	
Lognormal	393.80633	406.9478	
Exponential	427.36374	438.46306	
Frechet	***382.64386***	***395.78534***	***Best***
Loglogistic	392.73856	405.88004	

Table 4-25 Continued. Significant variables and distribution selection information

Chip seal category

Model Significance
Degrees of freedom = *7*
ChiSquare = 47.17
Prob>ChiSq = <*0.0001*

Significant Covariates
Treatment effect, *p-value: 0.0000*
Pretreatment condition, *p-value: 0.0019*

Distribution	Model Selection Measures		
	AICc	BIC	
Weibull	***377.48756***	***408.81369***	***Best***
Lognormal	379.93447	411.26061	
Exponential	416.49473	444.40647	
Frechet	384.5943	415.92044	
Loglogistic	377.57493	408.90107	

Micro surfacing category

Model Significance
Degrees of freedom = *4*
ChiSquare = 72.55
Prob>ChiSq = <*0.0001*

Significant Covariates
Treatment effect, *p-value: 0.0000*
Pretreatment condition, *p-value: 0.0059*

Distribution	Model Selection Measures		
	AICc	BIC	
Weibull	498.50099	514.07286	
Lognormal	490.26268	505.83456	
Exponential	517.48264	530.55883	
Frechet	***487.71339***	***503.28526***	***Best***
Loglogistic	495.62637	511.19825	

Cape seal category

Model Significance
Not relevant

Significant Covariates
None

Distribution	Model Selection Measures		
	AICc	BIC	
Weibull	37.051378	42.523798	
Lognormal	36.81441	42.286829	
Exponential	***35.116625***	***37.870218***	***Best***
Frechet	36.628946	42.101366	
Loglogistic	37.042837	42.515257	

Thin overlay category

Model Significance
Degrees of freedom = *9*
ChiSquare = 79.36
Prob>ChiSq = <*0.0001*

Significant Covariates
Treatment effect, *p-value: 0.0001*
Pretreatment condition, *p-value: 0.0119*

Distribution	Model Selection Measures		
	AICc	BIC	
Weibull	***414.98724***	***455.35639***	***Best***
Lognormal	415.82074	456.18989	
Exponential	463.20296	499.97082	
Frechet	420.32187	460.69102	
Loglogistic	415.09334	455.46249	

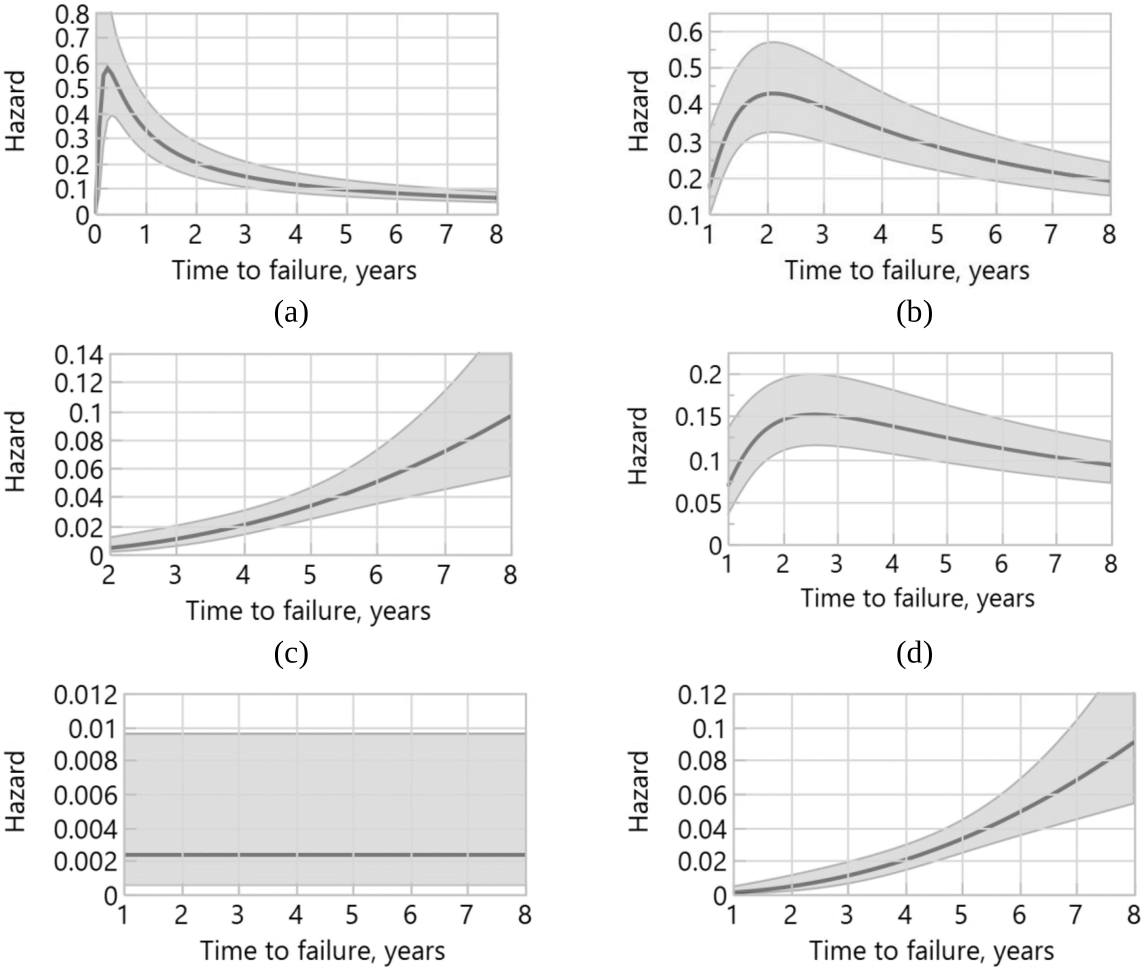
For each of the treatment categories, a particular distribution was the best fit. Fitting distributions allows for better understanding of the data in question, and as a result, gives more confidence for extrapolation. In model assessments, it became apparent that the full-parametric survival has a higher predictive power compared to the semi-parametric. Results of the model assessments are shown at the end of this chapter. As such, a 12-year prediction time was selected for the full-parametric analysis. This helped resolve some of the issues that were seen previously for life-extending benefit calculation in the semi-parametric methodology.

Distribution fitting is even more important in the context of life data. As explained before, probability, survival, and hazard functions are different forms of each other. In distribution fitting, although the shape of the probability function may look similar for several distributions, the hazard function shape would be so different. For instance, an exponential distribution results in a constant hazard rate, whereas a Weibull distribution can have increasing, constant, or decreasing hazard rates. The hazard probabilities contain important information on deterioration behavior of the subjects.

Figure 4-8 shows the hazard curves with the 95% confidence bands for different treatment categories. It should be noted that the *Y-axes* scale were not equalized across plots purposefully to better show the shape of the curves, regardless of the hazard magnitudes.

It can be seen that the untreated, light applications and micro surfacing categories follow a similar hazard trend. First, increasing to a peak and then declining over time. It means that if a subsection survives up to the peak of the curve, the risk of failure will decrease thereafter. Note how the magnitude of the hazard rates are becoming less and less for the light application and micro surfacing categories, compared to the untreated sections. For the untreated category, hazard reaches its peak of 0.6 at roughly 4 months into the study. This hazard rate means that out of 100 tentative pavement sections, 60 were to be failed in the following month.

By applying the chip seal and micro surfacing categories, the starting hazard probability decreased to zero and gradually increased to 0.1 after 8 years of service. For the cape seal category, hazard rates follow an exponential distribution with a constant hazard rate bordering zero. This means that application of cape seals almost brought the cracking phenomenon to a standstill. The exemplary performance of cape seals can also be inferred from the event plots shown in Figure 3-13. The wide confidence band is due to few subsections experiencing failure in the cape seal category.



(a) (b)

(c) (d)

(e) (f)

Figure 4-8 Hazard rate plots for (a) untreated category, (b) light applications, (c) chip seal category, (d) micro surfacing category, (e) cape seal category, and (f) thin overlay category.

Tables 4-26 through 4-31 show the estimates for the fitted models. The reference levels are cited in parenthesis. In each table, β subscript should be numbered in the order shown in the table from 1 to *n* subscript. For instance, for the chip seal category β_1 is 3.69 and β_9 is 0.29. The intercept and shape (σ) are distribution parameters, not covariates.

Table 4-26 Parameter Estimates for the untreated category and Frechet distribution

Term	β estimate	Std Error	Lower 95%	Upper 95%
Intercept	-7.63	19777.52	-38770.86	38755.61
Pretreatment condition (Poor)				
Good	8.75	19777.52	-38754.48	38771.99
Fair	7.20	19777.52	-38756.04	38770.43
σ	0.93	0.13	0.68	1.17

Table 4-27 Parameter Estimates for the light preservation category and Frechet distribution

Term	β estimate	Std Error	Lower 95%	Upper 95%
Intercept	0.80	0.06	0.67	0.93
Traffic level (Upper bound)				
Lower bound	0.22	0.07	0.08	0.35
Section (Stand-alone crack sealing)				
Rejuvenating fog seal	0.18	0.07	0.03	0.32
Pretreatment condition (Poor)				
Good	0.29	0.09	0.12	0.47
Fair	-0.24	0.11	-0.45	-0.03
σ	0.53	0.06	0.42	0.64

Table 4-28 Parameter Estimates for the chip seal category and Weibull distribution

Term	β estimate	Std Error	Lower 95%	Upper 95%
Intercept	3.69	6346.84	-12435.89	12443.28
Section (Scrub seal)				
FiberMat® chip seal	-1.39	6346.84	-12440.97	12438.20
Single layer chip seal	-1.73	6346.84	-12441.32	12437.85
Single layer chip seal with crack sealing	-1.17	6346.84	-12440.75	12438.42
Triple layer chip seal	-0.75	6346.84	-12440.33	12438.84
Double layer chip seal	-1.06	6346.84	-12440.65	12438.52
Pretreatment condition (Poor)				
Good	0.29	0.10	0.10	0.48
Fair	-0.08	0.08	-0.23	0.08
δ	0.29	0.05	0.20	0.38

Table 4-29 Parameter Estimates for the micro surfacing category and Frechet distribution

Term	β estimate	Std Error	Lower 95%	Upper 95%
Intercept	1.55	0.09	1.37	1.73
Pretreatment condition (Poor)				
Good	0.23	0.10	0.03	0.43
Fair	0.09	0.12	-0.14	0.32
Section (Double layer micro surfacing)				
Single layer micro surfacing	-0.67	0.11	-0.89	-0.46
Single layer micro surfacing with crack sealing	-0.51	0.10	-0.71	-0.31
σ	0.68	0.07	0.55	0.81

Table 4-30 Parameter Estimates for the cape seal category and Exponential distribution

Term	β estimate	Std Error	Lower 95%	Upper 95%
Intercept	6.03	0.71	4.64	7.41
δ	1.00	0.00	1.00	1.00

Table 4-31 Parameter Estimates for the thin overlay category and Weibull distribution

Term	β estimate	Std Error	Lower 95%	Upper 95%
Intercept	4.44	10969.62	-21495.62	21504.49
Pretreatment condition (Poor)				
Good	0.08	0.07	-0.06	0.21
Fair	0.20	0.10	0.01	0.39
Section (HiMA Thinlay)				
HMA thin overlay over FiberMat® chip seal	5.74	54041.59	-105913.80	105925.30
Virgin thinlay with PG67-22	-1.52	10969.62	-21501.58	21498.53
Virgin thinlay with PG67-22 on 100% foamed recycle base	-1.37	10969.62	-21501.42	21498.68
Virgin thinlay with PG76-22	-1.73	10969.62	-21501.78	21498.32
Ultra-thin bonded surface course	-2.06	10969.62	-21502.12	21497.99
50% RAP thinlay	-2.35	10969.62	-21502.40	21497.71
5% RAS Thinlay	-2.37	10969.62	-21502.42	21497.68
δ	0.29	0.04	0.21	0.37

The coding scheme in JMP® is a bit different than what was seen for SAS® in the way that reference levels are defined as -1 vector instead of 0 vector. Table 4-32 shows class level information used to generate survival curves in the full-parametric method. Survival functions for Weibull and Freshet distributions are shown in Equations 4.3 and 4.4, respectively. Note that exponential distribution is a special case of Weibull with shape parameter equal to 1.

$$S(x|z) = \exp\left[-e^{-\mu/\sigma}\,(xe^{-\beta^t z})^{\frac{1}{\sigma}}\right] \qquad 4.3$$

$$S(x|z) = 1 - \exp\left[-e^{\frac{-(\log x-(\mu+e^{\beta^t z})}{\sigma}}\right] \qquad 4.4$$

Where x is time to failure, μ is the location parameter, σ is the scale parameter, β^t is the vector of covariates, and z is the covariate values coded in Table 4-32. An example solution is provided to show how equations and Z values can be used to generate survival probabilities. The survival rate at 5 years is calculated for section 23, the 50% RAP thin overlay in poor pretreatment condition.

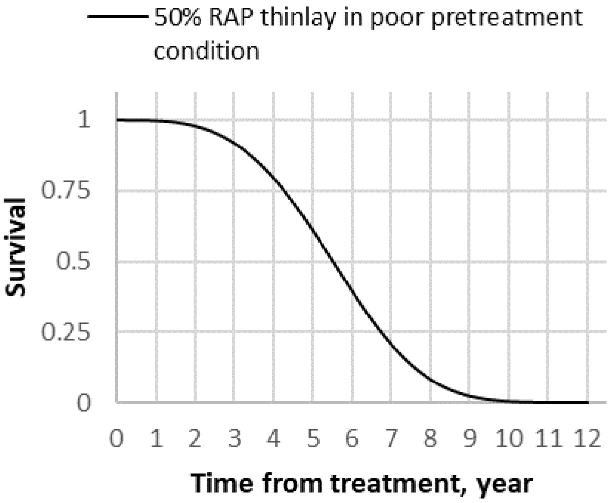
Table 4-32 Class level information for the treatment categories in the full-parametric survival regression

Class	Value	Design Variables						→	Relevant Z
Untreated category									
Pretreatment condition	Good	1	0						Z2, Z3
	Fair	0	1						
	Poor	-1	-1						
Light preservation category									
Traffic level	Inbound	0							Z2
	Outbound	-1							
Section	1	0							Z3
	5	-1							
Pretreatment condition	Good	1	0						Z4, Z5
	Fair	0	1						
	Poor	-1	-1						
Chip seal category									
Section	2	1	0	0	0	0			Z2, Z3, Z4, Z5, Z6
	6	0	1	0	0	0			
	7	0	0	1	0	0			
	8	0	0	0	1	0			
	9	0	0	0	0	1			
	16	-1	-1	-1	-1	-1			
Pretreatment condition	Good	1	0						Z7, Z8
	Fair	0	1						
	Poor	-1	-1						
Micro surfacing category									
Pretreatment condition	Good	1	0						Z2, Z3
	Fair	0	1						
	Poor	-1	-1						
Section	11	1	0						Z4, Z5
	12	0	1						
	13	-1	-1						
Thin overlay category									
Pretreatment condition	Good	1	0						Z2, Z3
	Fair	0	1						
	Poor	-1	-1						
Section	18	1	0	0	0	0	0	0	Z4, Z5, Z6, Z7, Z8, Z9, Z10
	19	0	1	0	0	0	0	0	
	20	0	0	1	0	0	0	0	
	21	0	0	0	1	0	0	0	
	22	0	0	0	0	1	0	0	
	23	0	0	0	0	0	1	0	
	24	0	0	0	0	0	0	1	
	25	-1	-1	-1	-1	-1	-1	-1	

From Table 4-31, covariate estimates are β_2 to β_{10} . Therefore, the vector of β^t is (0.08, 0.20, 5.74, -1.52, -1.37, -1.73, -2.06, -2.35, -2.37). From Table 4-32, the corresponding Z values for 50% RAP in poor pretreatment condition is (-1, -1, 0, 0, 0, 0, 0, 1, 0). Substituting values in Equation 4.3 results in:

$$S(5 = years|z) = \exp\left[-e^{-4.44}/_{0.29}.\left(5e^{-(-0.08-0.20-2.35)}\right)^{\frac{1}{0.29}}\right] = 0.61$$

This analysis is repeated for different times, and the survival curve is generated, as shown in Figure 4-9. Same process was repeated for all of the treatments, and full-parametric survival curves were generated and are presented in APPENDIX B. In addition, median treatment lives were extracted from the survival curves are provided in Tables 4-33 to 4-37 for all preservation treatments.



Note: Median treatment life is 5.6 years

Figure 4-9 Survival curve for section 23, thin overlay with 50% RAP in poor pretreatment condition

Table 4-33 Median treatment lives for the untreated category, years

Section no.	Treatment	Pretreatment condition		
		Good	*Fair*	*Poor*
3 & 4	Untreated category	4.0	1.0	0.0

Table 4-34 Median treatment lives for the light application category

Section no.	Treatment	Pretreatment condition		
		Good	*Fair*	*Poor*
1	Rejuvenating fog seal	(3.5, 5.4)	(2.1, 3.2)	(2.5, 3.9)
5	Stand-alone crack sealing	(2.5, 3.8)	(1.5, 2.3)	(1.8, 2.7)

Note: for this category lives are reported in ranges (a, b). *a* is the median life for the upper traffic bound level and *b* is the median life for the lower traffic bound level.

Table 4-35 Median treatment lives for the chip seal category, years

Section no.	Treatment	Pretreatment condition		
		Good	*Fair*	*Poor*
2	FiberMat® chip seal	12	8.4	7.3
6	Single layer chip seal	8.5	6.0	5.2
7	Single layer chip seal with crack sealing	>12	10.4	9.1
8	Triple layer chip seal	>12	>12	>12
9	Double layer chip seal	>12	11.6	10.1
16	Scrub seal	>12	>12	>12

Table 4-36 Median treatment lives for the micro surfacing category, years

Section no.	Treatment	Pretreatment condition		
		Good	*Fair*	*Poor*
11	Single layer micro surfacing	3.9	3.4	2.3
12	Single layer micro surfacing with crack sealing	4.6	4.0	2.7
13	Double layer micro surfacing	>12	>12	>12

Table 4-37 Median treatment lives for thin overlay category, years

Section no.	Treatment	Pretreatment condition		
		Good	*Fair*	*Poor*
18	HMA thin overlay over a FiberMat® chip seal	>12	>12	>12
19	Virgin thinlay with PG67-22	>12	>12	>12
20	Virgin thinlay with PG67-22 on 100% foamed recycle base	>12	>12	>12
21	Virgin thinlay with PG76-22	>12	>12	10.2
22	Ultra-thin bonded surface course	10.4	11.8	7.4
23	50% RAP thinlay	7.9	8.9	5.6
24	5% RAS Thinlay	7.7	8.7	5.4
25	HiMA Thinlay	>12	>12	>12

As mentioned earlier, the prediction window was extended to 12 years for the full-parametric models. Still, many of the treatments are showing lives in excess of 12 years. The raw treatment life information is needed to calculate life-extending benefits by comparing to the untreated category. Table 4-38 through Table 4-41 show the life-extending benefits for different preservation treatments. For the light application category results, shown in Table 4-38, rejuvenating fog seals can extend the life of the pavement by up to 3.9 years. The stand-alone crack sealing extends the life of the pavement by up to 2.7 years when the pretreatment condition is poor. Lower benefits are obtained in the outbound direction where more traffic is present.

Table 4-38 Median life-extending benefits for the light application category, years

Section no.	**Treatment**	**Pretreatment condition**		
		Good	***Fair***	***Poor***
1	Rejuvenating fog seal	(0, 1.4)	(1.1, 2.2)	(2.5, 3.9)
5	Stand-alone crack sealing	(0, 0)	(0.5, 1.3)	(1.8, 2.7)

Note: for this category lives are reported in ranges (a, b). *a* is the median life for the upper traffic bound level and *b* is the median life for the lower traffic bound level.

It can be seen that the life-extending benefits are larger for worse conditions. For the stand-alone crack sealing, it was previously discussed that in ‘good’ condition, the sealing was not applied to the section at all, and as such, there is no generated benefit. The benefits can be seen in the ‘fair’ and ‘poor’ conditions where sealing was actually applied.

In the chip seal category, shown in Table 4-39, life-extending benefits range from 4.5 to more than 12 years. Note that the larger life-extending benefits for ‘poor’ condition is a result of the imposed limitation on the prediction window. For some sections such as scrub seals, raw treatment lives are reported to be more than 12 years for all pretreatment condition levels, but expectedly, the extension beyond 12 years would be larger for the ‘good’ pretreatment condition compared to the extension for the ‘fair’ pretreatment condition. Yet, this information is not currently available and the tables are reported in the way described.

Table 4-39 Median life-extending benefits for the chip seal category, years

Section no.	**Treatment**	**Pretreatment condition**		
		Good	***Fair***	***Poor***
2	FiberMat® chip seal	8.0	7.4	7.3
6	Single layer chip seal	4.5	5.0	5.2
7	Single layer chip seal with crack sealing	>8	9.4	9.1
8	Triple layer chip seal	>8	>11	>12
9	Double layer chip seal	>8	10.6	10.1
16	Scrub seal	>8	>11	>12

Multi-layered systems are showing superior performance in this group. Also, crack sealing in combination with the treatment can double the life-extending benefits. The different construction technique used in the scrub seal can greatly influence the performance, when compared to a regular chip seal section.

For the micro surfacing group shown in Table 4-40, benefits range from 0 to more than 12 years. In this group, double layer micro surfacing is showing exemplary performance.

Table 4-40 Median life-extending benefits for the micro surfacing category, years

Section no.	**Treatment**	**Pretreatment condition**		
		Good	***Fair***	***Poor***
11	Single layer micro surfacing	0.0	2.4	2.3
12	Single layer micro surfacing with crack sealing	0.6	3.0	2.7
13	Double layer micro surfacing	>8	>11	>12

For the thin overlays, those with virgin materials are providing more than 8 years of cracking performance, in all of the pretreatment conditions. The use of recycled materials decreases the performance to some degree. Another observation was that for some of the treatments, such as RAP and RAS thin overlays, the optimum benefits are gained when pretreatment condition has passed the ‘good’ level and before reaching ‘poor’ levels. Benefits are more pronounced when cracks are to a level to be treated effectively, but not too much to decrease the treatment performance.

Table 4-41 Median life-extending benefits for thin overlay category, years

Section no.	Treatment	Pretreatment condition		
		Good	*Fair*	*Poor*
18	HMA thin overlay over a FiberMat® chip seal	>8	>11	>12
19	Virgin thinlay with PG67-22	>8	>11	>12
20	Virgin thinlay with PG67-22 on 100% foamed recycle base	>8	>11	>12
21	Virgin thinlay with PG76-22	>8	>11	10.2
22	Ultra-thin bonded surface course	6.4	10.8	7.4
23	50% RAP thinlay	3.9	7.9	5.6
24	5% RAS Thinlay	3.7	7.7	5.4
25	HiMA Thinlay	>8	>11	>12

In this section, full-parametric survival methodology was used to better understand the deterioration behavior of various preservation treatments. In this methodology, life distributions are fitted to the data which gives higher statistical confidence for a broader extrapolation. As such, the prediction window was extended to 12 years. Results of semi-parametric and full-parametric survival methodologies slightly differ. For the performance comparison purposes, a semi-parametric method can be used since it offers risk analysis. For life-extending benefit analysis, a full-parametric analysis should be preferred since data are better represented by fitting distributions. In the next section, results of another probabilistic methodology, Markov chain, are presented.

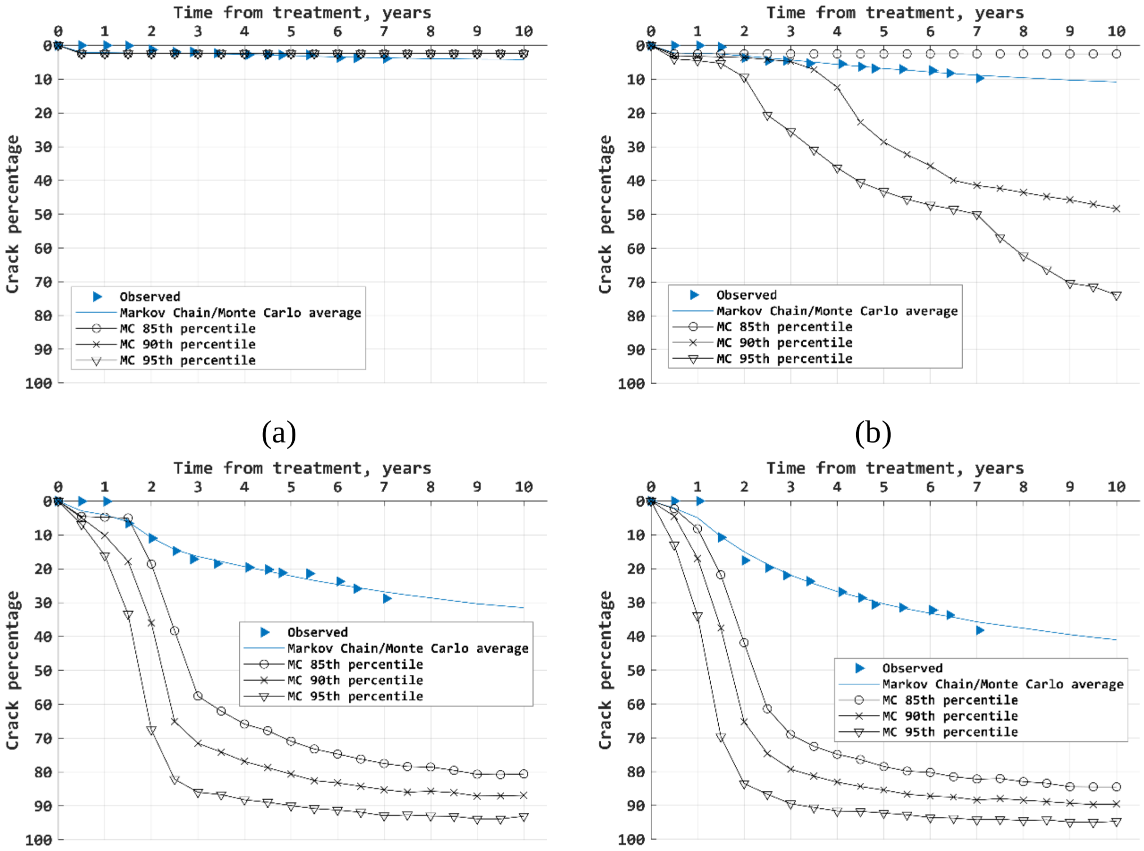
4.2 Markov Process & Monte Carlo Simulation Approach

It was mentioned earlier that for Markov modeling pavement treatments were put into subcategories based on a hierarchical agglomerative clustering method, and life-extending benefits were derived using an MC technique. Here, first, the results for example cases are illustrated and the implications are subsequently discussed. Second, performance curves for each treatment category are shown and discussions provided. The developed TPMs for each of the clusters can be found in APPENDIX C. Tables of treatment lives are provided for different treatment categories and subcategories, and discussions are ensued. Finally, an example of deterioration progression is shown using density curves to better understand the undergoing degradation process.

4.2.1 Model Flexibility

TPMs and the resulting Markov models should be capable of producing a wide range of performance behaviors observed in different treatments. Some of the treatments are more robust in which their performance curve is almost flat after 7 years, while some others are showing steep deterioration curves. Micro surfacing with its different clusters and pretreatment conditions is a group that is showing all these variety of performances, as shown in Figure 4-10.

Thus, micro surfacing was a good candidate to examine if the model can accommodate different performance behaviors. Figure 4-10(a and d) represent sections with low and high predicted cracking, respectively. As can be seen, the Markov model is adequately capable of capturing the shape of the deterioration curve for different scenarios. This was true for other treatments as well, however, such graphs are not presented for the sake of brevity. Later in the section, it is shown that the model can predict cracking levels adequately with high r-squares for different types of treatments. Moreover, percentile curves resulting from the MC simulations are graphed.



(a) (b)

(c) (d)

Figure 4-10 Crack performance prediction curves for micro surfacing group (a) cluster 1 and 'good' pretreatment condition, and (b) cluster 1 and 'poor' pretreatment condition, (c) cluster 2 and 'good' pretreatment condition and (d) cluster 2 and 'poor' pretreatment condition

4.2.2 Reliability in Treatment Selection

The Markov chain solution using Equation 3.16, and the MC numerical solution described in previous sections produce the same results, as they should, and both are depicted in the blue curves in Figure 4-10. However, results from the MC method are instrumental in creating percentile curves. The stochasticity of treatment performance behavior can be understood with the MC results in the form of percentile curves.

For illustration, cracks on a pavement with single layer micro surfacing (cluster 2) and 'poor' pretreatment condition (Figure 4-10b) will not reach the 20% cracking failure threshold for average and 85th percentile curves during the 10-year analysis period. However, it fails in 4.4 and

2.5 years if 90th and 95th percentile reliability are considered. Hence, if the goal is to keep the road in a good or fair condition as defined by MAP-21, depending on the considered reliability, different life-extending benefits will be achieved.

The argument would be that the 'average' predicted values should not trick someone into believing that cracks will not exceed the average values shown in Figure 4-10. Even more interestingly, in cases such as Figure 4-10b, the average cracking value is not necessarily representing values near 50th percentile due to nonsymmetrical crack distributions. In fact, for Figure 4-10b, average values are somewhere between 85th and 90th percentiles. That explains why in real world scenarios better or worse expected performances are often observed.

A higher reliability value can ensure a higher performance for the pavement. If a desired treatment cannot provide the required performance at the required reliability percentile, a more robust treatment should be selected.

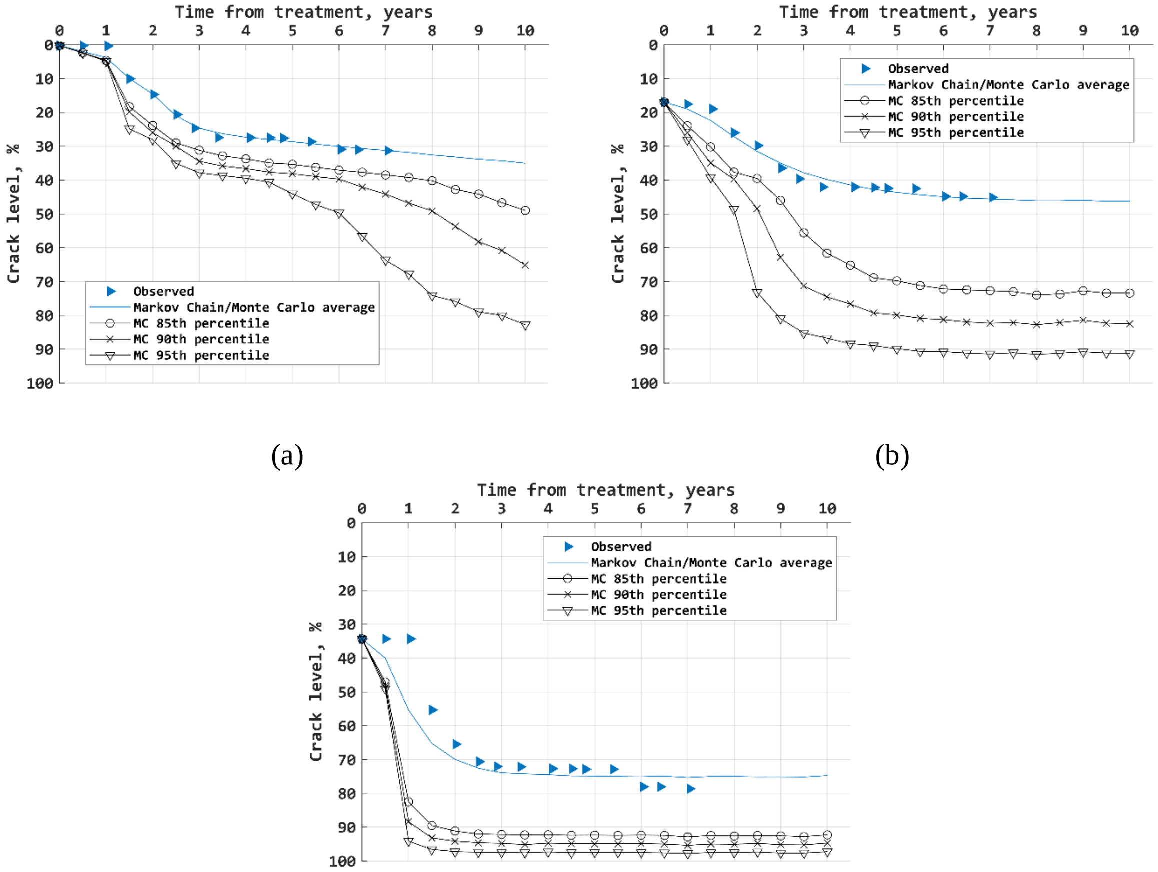
4.2.3 Life Extension Benefits

The average and percentile lives were calculated by developing Markov models and implementing the MC simulation technique for all 12 subclasses and for different pretreatment conditions. This was done because pretreatment condition is known to have a major impact on posttreatment deterioration. Providing the service lives for different pretreatment conditions, and inclusion of reliability analysis in the form of percentile values provides a broader picture of life-extending benefits. Other percentiles may be interpolated to acquire rough life estimates for other scenarios.

Note that the above mentioned estimation only provides time to failure information in years of service from the last treatment, which was in August 2012, and hence, by definition, it is different than life extension. To calculate life-extending benefits, pairwise comparisons should be made with a baseline treatment such as the untreated category at the relevant covariate level and the percentile values. For instance, time to failure of a chip seal section at ‘fair’ pretreatment condition should be compared with the untreated category in the same ‘fair’ pretreatment condition. Also, similar analyses can be conducted for percentile cracking values in addition to the commonly reported average values. In the following section, Markov generated deterioration curves and subsequent discussions are provided.

4.2.3.1 Untreated Sections

Figure 4-11 shows performance curves for the untreated category. Data collection started right after LR-159 was treated in the summer of 2012. Figure 4-11 shows that for the untreated section with ‘good’ pretreatment condition, the average life would be 2.4 years.



(a)

(b)

(c)

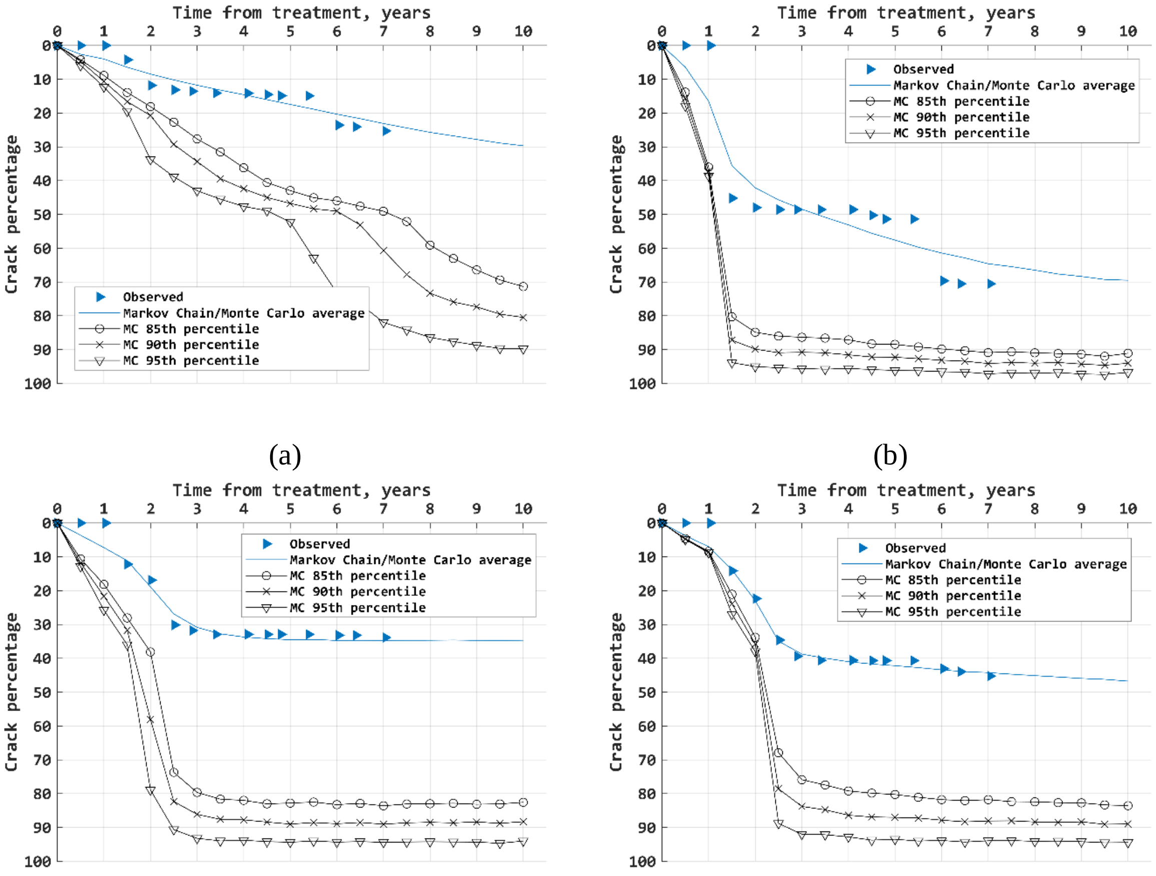
Figure 4-11 Markov crack prediction curves for untreated section with (a) ‘good’, (b) ’fair’ and (c) ‘poor’ pretreatment condition

The existing pavement surface was constructed in 1999. So, in total, it took 15.4 years for the newly constructed pavement to fail. Hence, this was the right time for preventive treatment application when pavement was still in ‘good’ to ‘fair’ conditions. As can be seen in Figure 4-11, untreated sections had already failed or were at the cusp of failure at the start of the study for ‘fair’ and ‘poor’ pretreatment conditions. They only survived by as much as 2.4 and 0.7 year in the case of ‘good’ and ‘fair’ pretreatment conditions, respectively.

For the untreated section with ‘poor’ pretreatment condition, deterioration is rapid and the section actually started from a failed state. For this case, the developed Markov structure was not able to adequately predict life of the pavement prior to year 3. Nonetheless, deterioration beyond the failure threshold should not be a matter of concern as the model can predict well for the rest of the treatments, as will be demonstrated later.

4.2.3.2 Light Preservation Application

Light preservation treatment performances are shown in Figure 4-12. Comparing with the baseline condition shown in Figure 4-11, light applications can only provide moderate benefits. For instance, for fog seal the average life extensions can be as much as 3.5 (=5.9-2.4) and 2.5 (=3.2-0.7) years in ‘good’ and ‘fair’ pretreatment conditions, respectively. However, their true potential is when they are used in combination with other preventive treatments such as a chip seal treatment with crack sealing in advance (133). Note that at higher reliability levels, lower performance (i.e. higher cracking) is predicted.

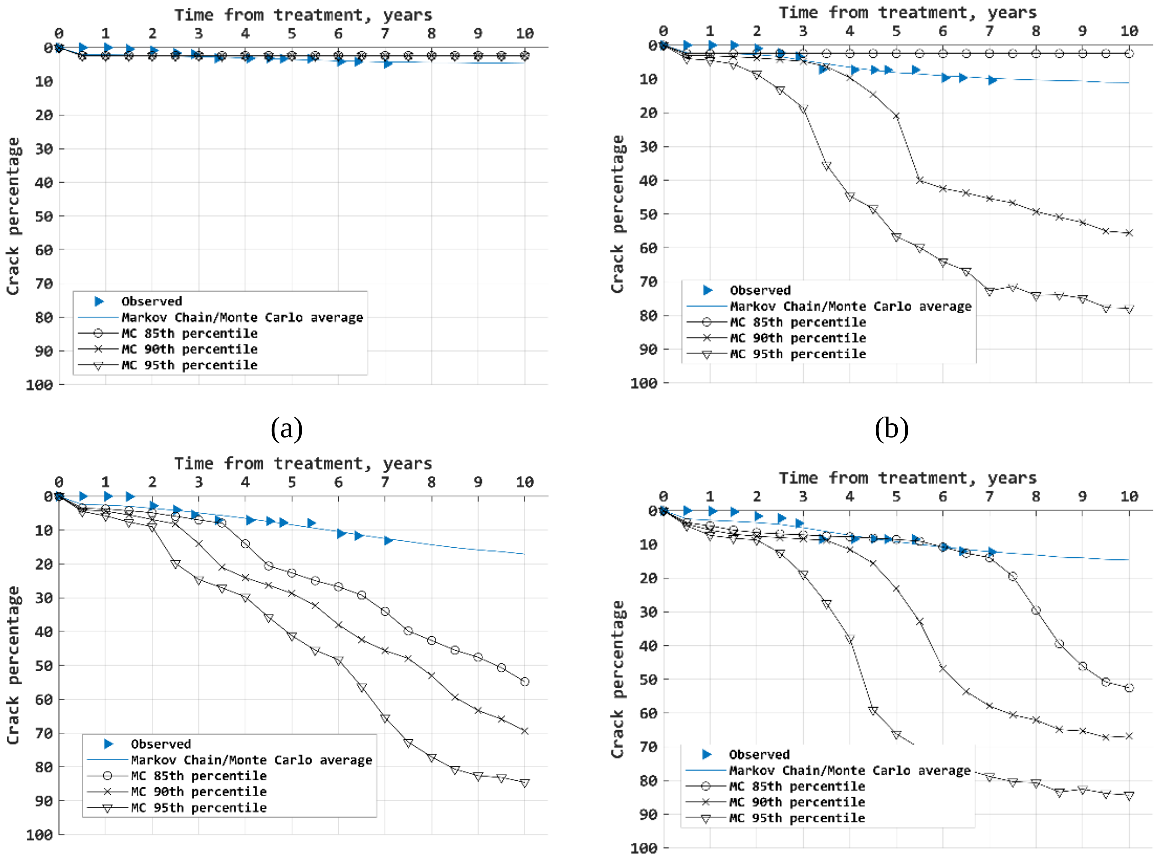


(a) (b) (c) (d)

Figure 4-12 Markov crack prediction curves for light preservation treatments for cluster 1 for (a) 'good' and b) 'poor pretreatment condition and for cluster 2 for (c) 'good', (d) 'poor' pretreatment conditions

4.2.3.3 Chip Seals

Chip seals perform substantially better than the 'do-nothing' scenarios. It is shown in Figure 4-13 that for cluster 1 – the higher performing cluster in Table 3-7 – consisting of scrub seal, double and triple layer chip seals, the average pavement life extension is more than 10 years for all pretreatment conditions. For this cluster, even subsections with 'poor' pretreatment condition exhibit excellent performance. The second cluster also provides substantial life-extending benefits of at least 7.6 (=10-2.4) years when section is in 'good' pretreatment condition. Also, higher reliability translates into lower life-extensions for the chip seal group.



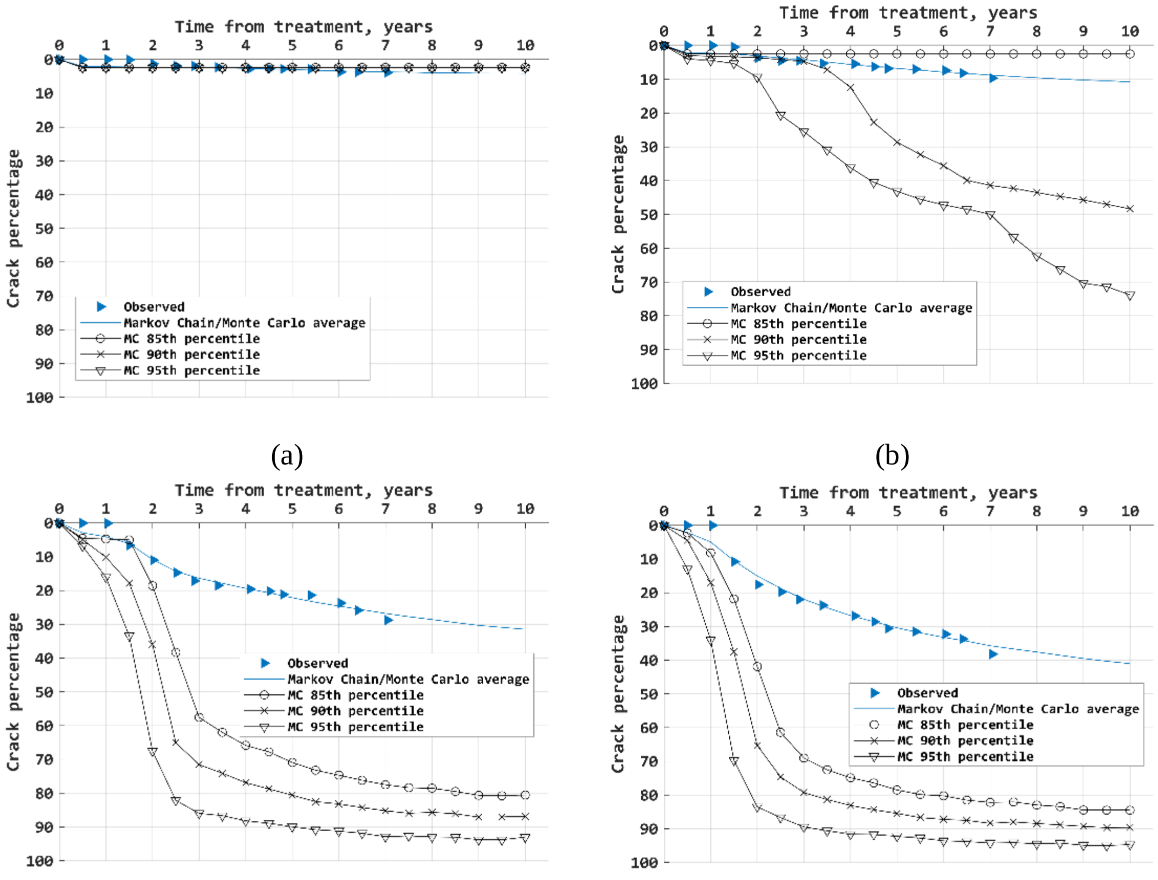
(a) (b)

(c) (d)

Figure 4-13 Markov crack prediction curves for chip seal treatments cluster 1 for (a) 'good' and (b) 'poor'pretreatment condition and for cluster 2 for (c) 'good' and (d) 'poor' pretreatment conditions.

4.2.3.4 Micro Surfacing

As shown in Figure 4-14, in the micro surfacing group, double layer micro surfacing is showing superior performance comparable to that of cape seals and thin overlays, and on average, life extensions in excess of 10 years can be expected. Substantial benefits can be achieved even for pavements with 'poor' pretreatment condition. For the second cluster, however, a lower performance is observed. This can be attributed to relatively high pretreatment crack levels of 12.2% (Table 3-7), and lack of a uniformly applied protective layer like the one with double-layer micro surfacing.



(a) (b)

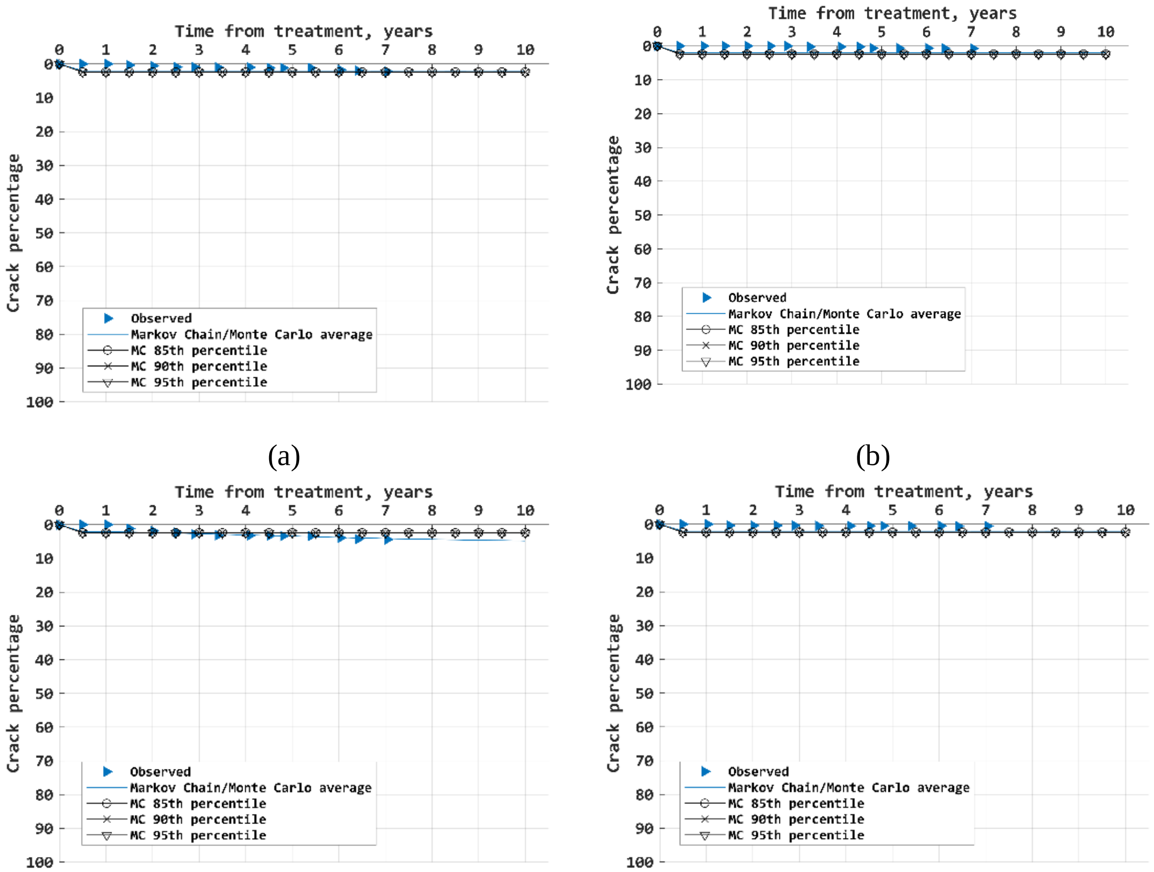
(c) (d)

Figure 4-14 Markov crack prediction curves for micro surfacing treatments cluster 1 for (a) ‘good’ and (b) ‘poor’ pretreatment condition and for cluster 2 for (c) ‘good’ and (d) ‘poor’ pretreatment conditions.

An interesting observation is that for some of the graphs, the average performance lies somewhere near or above 85th percentile curves. The takeaway would be that in a population of pavements that are treated, cracking data throughout the time follows a nonsymmetrical distribution, and for many situations, the average cracking predictions are closer to higher percentiles. Hence, a lot of treatments that have been selected so far and laid out on roads may actually be performing better than their ‘average’ life that would have been expected at the time of treatment selection.

4.2.3.5 Cape Seals

Both clusters of cape seals have shown exemplary performance of beyond 10 years based on average and percentile predictions, comparable and even better than thin overlays. It is noteworthy that pretreatment condition has not influenced cape seal performance for the analysis period. More years of data collection may influence the predictions in the future.



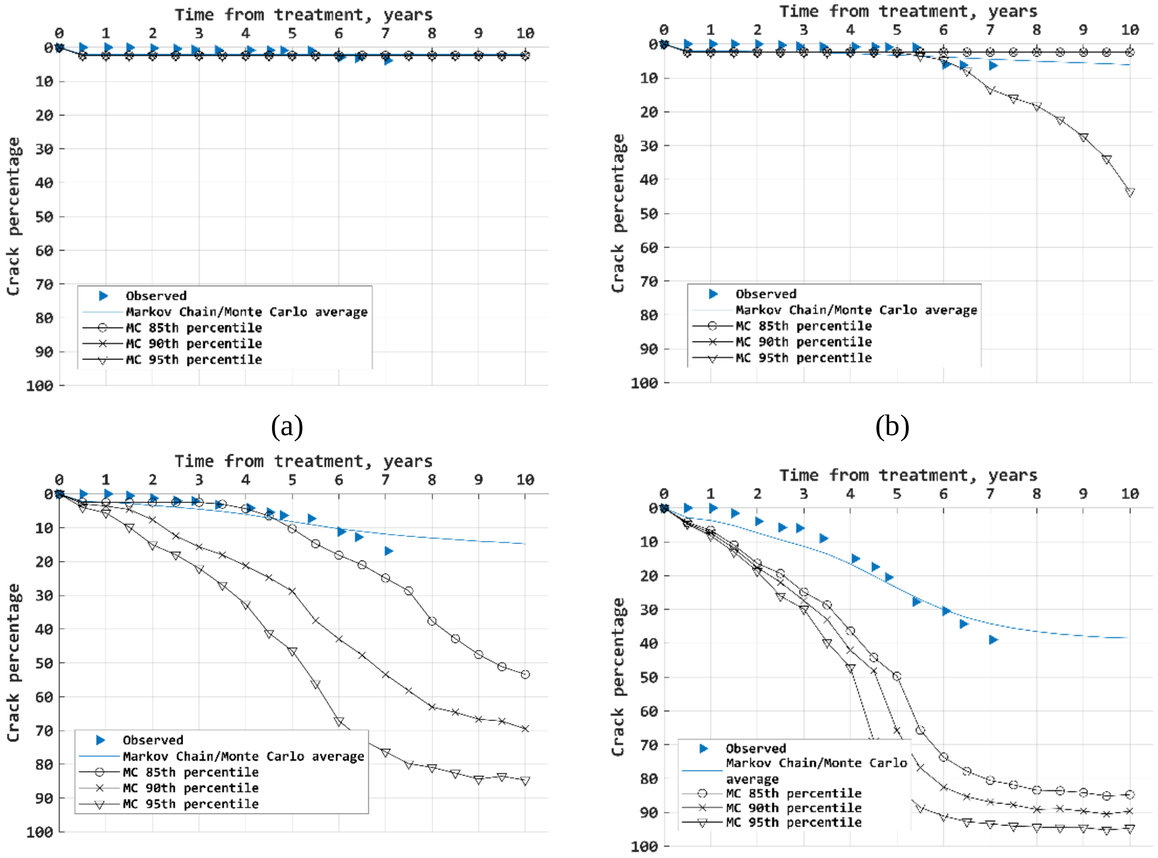
(a) (b)

(c) (d)

Figure 4-15 Markov crack prediction curves for cape seal treatments cluster 1 for (a) ‘good’ and (b) ‘poor’ pretreatment condition and for cluster 2 for (c) ‘good’ and (d) ‘poor’ pretreatment conditions.

4.2.3.6 Thin Overlays

Thin overlays with virgin binder, and the one with highly polymer-modified binder showed exemplary performance with more than 10 years of expected service life even in ‘fair’ and ‘poor’ pretreatment conditions. With high reliability at 95th percentile and ‘poor’ pretreatment condition, the service life reduces to 8.2 years, which is still substantial. In the second cluster, the use of RAP and RAS reduced the performance to some degree. Nevertheless, it still provides substantial life extension when compared with a ‘do-nothing’ scenario. It is also to be noted that binder replacement for these recycled sections were very high and not typical of common road applications.



(a) (b)

(c) (d)

Figure 4-16 Markov crack performance prediction curves for thin overlays cluster 1 for (a) ‘good’ and (b) ’poor’ pretreatment condition and for cluster 2 for (c) ‘good’ , (d) ’poor’ pretreatment conditions.

Table 4-42 summarizes life estimates for different treatment categories and clusters and in different pretreatment conditions. Moreover, percentile lives of treatments is provided with the typically reported average lives to provide a broader picture of life-extension benefits.

Table 4-42 Treatment life of the baseline (untreated) and preservation treatments at different pretreatment condition levels and percentiles (years)

Treatment Category	Cluster Number	Treatments	Pretreatment Condition	Average	85th percentile	90th percentile	95th percentile
Untreated	-	Untreated section 3 & 4	Good	2.4	1.7	1.5	1.4
			Fair	0.7	0.2	0.2	0.1
			Poor	[1] N/A	N/A	N/A	N/A
Light preservation application	1	Rejuvenating fog seal	*Good*	5.9	2.2	1.9	1.5
			Fair	3.2	1.4	1.4	1.3
			Poor	1.1	0.6	0.6	0.6
	2	Crack sealing only	*Good*	2.1	1.1	0.9	0.8
			Fair	2.1	1.8	1.7	1.7
			Poor	1.8	1.5	1.4	1.3
Chip seals	1	Double layer, triple layer chip seal and Scrub seal	*Good*	>10	>10	>10	>10
			Fair	>10	>10	>10	7.6
			Poor	>10	>10	4.9	3.0
	2	FiberMat® chip seal, single layer chip seal and single layer chip seal with crack sealing	*Good*	>10	4.5	3.4	2.5
			Fair	8.9	3.5	2.7	2.0
			Poor	>10	7.5	4.8	3.1
Micro surfacing	1	Double layer micro surfacing	*Good*	>10	>10	>10	>10
			Fair	>10	>10	>10	>10
			Poor	>10	>10	4.4	2.5
	2	Single layer micro surfacing, Single layer micro surfacing with crack sealing	*Good*	4.2	2.0	1.6	1.1
			Fair	2.9	2.1	2.0	2.0
			Poor	2.7	1.4	1.1	0.7
Cape seals	1	FiberMat® cape seal	*Good*	>10	>10	>10	>10
			Fair	>10	>10	>10	>10
			Poor	>10	>10	>10	>10
	2	Cape seal and Scrub cape seal	*Good*	>10	>10	>10	>10
			Fair	>10	>10	>10	>10
			Poor	>10	>10	>10	>10
Thin overlays	1	Thin overlay over FiberMat® chip seal, Virgin thinlay with PG67-22, Virgin thinlay with PG76-22, Virgin thinlay with PG67-22 on 100% foamed recycled base, HiMa thinlay	*Good*	>10	>10	>10	>10
			Fair	>10	>10	>10	>10
			Poor	>10	>10	>10	8.2
	2	Ultra-thin bonded surface course, 5% RAS thin overlay, and 50% RAP thin overlay	*Good*	>10	6.3	3.8	2.7
			Fair	>10	>10	6.2	3.3
			Poor	4.5	2.6	2.3	2.1

[1] N/A: Not applicable; pavement already failed at the defined threshold value.

As already mentioned, life-extension benefits can be calculated by comparing the performance of treated sections with that of the untreated category. For example, the section with 50% RAP thin overlay application and ‘good’ pretreatment condition will survive for more than 10 years on average. This translates into more than 7.6 (=10.0-2.4) years of life extension when compared with the base treatment at the same pretreatment condition level. Such analyses were conducted for all of the clusters and results are presented in Table 4-43.

The average life extending benefit for all preservation treatments was more than 6.6 years. Specifically, more than 7.6 years for the thin overlays, cape seals and chip seals, more than 1.6 years for light applications, and more than 4.7 years for micro surfacing. It should be emphasized that the derived life-extending benefits are subjected to change, likely in an upward direction, as the study is continuing. So far, results have been promising.

Table 4-43 Life-extending benefits of preservation treatment in different pretreatment condition levels and different percentile values (years)

Treatment Category	Cluster Number	Treatments	Pretreatment Condition	Average	85th percentile	90th percentile	95th percentile
Light preservation application	1	Rejuvenating fog seal	*Good*	3.5	0.6	0.4	0.1
			Fair	2.6	1.2	1.2	1.2
			Poor	1.1	0.6	0.6	0.6
	2	Crack sealing only	*Good*	–	–	–	–
			Fair	1.4	1.5	1.6	1.6
			Poor	1.8	1.5	1.4	1.3
Chip seals	1	Double layer, triple layer chip seal and Scrub seal	*Good*	>7.6	>8.3	>8.5	>8.6
			Fair	>9.3	>9.8	>9.8	7.5
			Poor	>10	>10	4.9	3.0
	2	FiberMat® chip seal, single layer chip seal and single layer chip seal with crack sealing	*Good*	>7.6	2.8	1.9	1.1
			Fair	8.2	3.3	2.5	1.9
			Poor	>10	7.5	4.8	3.1
Micro surfacing	1	Double layer micro surfacing	*Good*	>7.6	>8.3	>8.5	>8.6
			Fair	>9.3	>9.8	>9.8	>9.9
			Poor	>10	>10	4.4	2.5
	2	Single layer micro surfacing, Single layer micro surfacing with crack sealing	*Good*	1.8	0.4	0.1	-0.3
			Fair	2.2	1.8	1.9	1.9
			Poor	2.7	1.4	1.1	0.7
Cape seals	1	FiberMat® cape seal	*Good*	>7.6	>8.3	>8.5	>8.6
			Fair	>9.3	>9.8	>9.8	>9.9
			Poor	>10	>10	>10	>10
	2	Cape seal and Scrub cape seal	*Good*	>7.6	>8.3	>8.5	>8.6
			Fair	>9.3	>9.8	>9.8	>9.9
			Poor	>10	>10	>10	>10
Thin overlays	1	Thin overlay over FiberMat® chip seal, Virgin thinlay with PG67-22, Virgin thinlay with PG76-22, Virgin thinlay with PG67-22 on 100% foamed recycled base, HiMa thinlay	*Good*	>7.6	>8.3	>8.5	>8.6
			Fair	>9.3	>9.8	>9.8	>9.9
			Poor	>10	>10	>10	8.2
	2	Ultra-thin bonded surface course, 5% RAS thin overlay, and 50% RAP thin overlay	*Good*	>7.6	4.7	2.3	1.4
			Fair	>9.3	>9.8	6.0	3.2
			Poor	4.5	2.6	2.3	2.1

In Table 4-43, life-extending benefits expectedly decrease as reliability increases. However, a seemingly contradictory observation is that for several treatments, larger life-extending benefits are reported for ‘poor’ pretreatment condition compared to better conditions.

This is due to a mathematical simplification and not due to real physical evidence. For many sections, treatment lives were reported as more than *n* years. However, the extent of it is not known yet with the current data. For example, cape seals are estimated to survive for more than 10 years in all pretreatment conditions. It is more likely that subsections in ‘good’ condition far outlive the ones in ‘poor’ pretreatment condition. However, for the time being, all are reported as ‘more than 10’ years, which leads to said issue. Hence, the results are intently reported as such in Table 4-43 to reflect the longer term uncertainty that still has not been resolved. More years of data collection will reveal more deterioration trends and will provide more conclusive evidence.

The number of subsections in different initial conditions are listed in Table 4-44. Larger number of subsections results in a more accurate estimation for the cracking distribution when the MCS technique is used. Red shaded cells show subsections in which their results should be more carefully interpreted. For these instances, the derived benefits can be checked comparatively with that of the better or worse pretreatment conditions for acceptability – for the same treatment.

Table 4-44 Number of subsections in each cluster and pretreatment condition

Treatment Category	Cluster Number	Pretreatment Condition		
		Good	Fair	Poor
Untreated	–	46	13	13
Light preservation application	1	27	10	3
	2	5	9	26
Chip seals	1	87	24	9
	2	81	26	33
Micro surfacing	1	19	6	13
	2	39	18	18
Cape seals	1	30	6	4
	2	52	19	9
Thin overlays	1	122	36	40
	2	86	18	12

For the stand-alone crack sealing section in ‘good’ condition, the life-extending benefits could not be estimated reasonably. Small negative life-extension values were derived which can be attributed to simulation imperfections where there were few subsections for analysis (Table 4-44). Therefore, the treatments are reported as not having a life-extending benefit. Again, such simulation results should be treated cautiously. For this treatment, only 5 subsections were in ‘good’ initial condition. However, it was already discussed that there is no life-extending benefit for ‘good’ pretreatment condition since in effect almost no sealing was applied to subsections with ‘good’ condition for this section.

All in all, preventive treatments provide some degree of life extension. From the curves, treatment combinations, such as cape seals, or multi-layer treatments, such as a double-layer micro surfacing, provide the greatest life-extending benefits and are not influenced much by the pretreatment condition. Also, for many of the more robust treatments, the model predicts more than 10 years of cracking performance. Therefore, for these sections, the exact benefits cannot be quantified at this moment. More years of observations are needed to fully capture the longer-term deterioration trends.

4.2.4 Further Discussion

Figure 4-17 exhibits crack progression in the time domain for the micro surfacing cluster 2 with ‘poor’ pretreatment condition. The graphs resulted from 10,000 MC simulations and is a testament to stochasticity and non-linearity of deterioration phenomenon. The pretreatment crack level was 27.3% for this condition. Immediately after treatment application, it improved to 0.0% cracking. A year after treatment, crack levels increased to 4.9% and all subsections had about the same cracking level judging by the tight distribution. At year 3, the average cracking is 21.9% yet many subsections are still in ‘good’ condition. From year 3 to 6, a buildup of cracks can be observed in the curves where the proportion of subsections with ‘poor’ condition is gradually increasing. The most successful preservation action should therefore take place in this timeframe, before a rapid deterioration begins. Up to year 6, the distribution looks unimodal meaning that many subsections are still in better than ‘poor’ condition. As time advances, from years 7 to 9, deterioration increases to a point where a second peak in ‘poor’ condition region is born and a substantial portion of subsections are showing crack levels higher than 40%. It is to be noted that after year 9, the distributions will not change much because of the Markov model limitations where the last interval in TPM is defined as 50-100. The model will gradually reach the asymptote of 75%, which is the midpoint of this range. Nonetheless, this should not be a concern with the MAP-21 criterion.

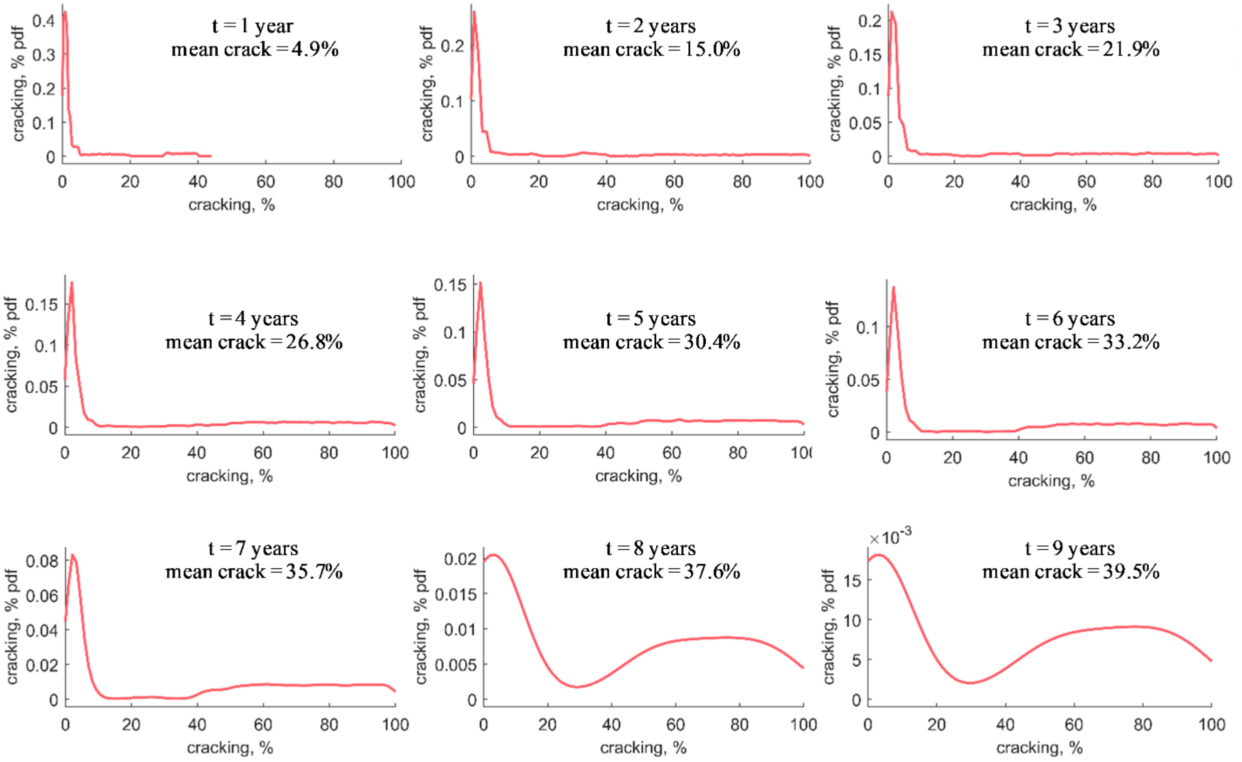


Figure 4-17 Crack percentage probability density function for micro surfacing cluster 2 with ‘poor’ pretreatment condition

4.2.5 Model Performances and Evaluation

Survival methodologies and Markov chain work on completely different mathematical principles. In survival analysis, survival probabilities are calculated from the portion of the subjects that have experienced the failure relative to those that are at risk. In this study, the 20% cracking level was used to define failure and subsections at risk. On the other hand, in the Markov chain, the crack percentages were used directly in predictions, and failure was defined where the average, or a percentile of the cracking reaches 20% cracking level.

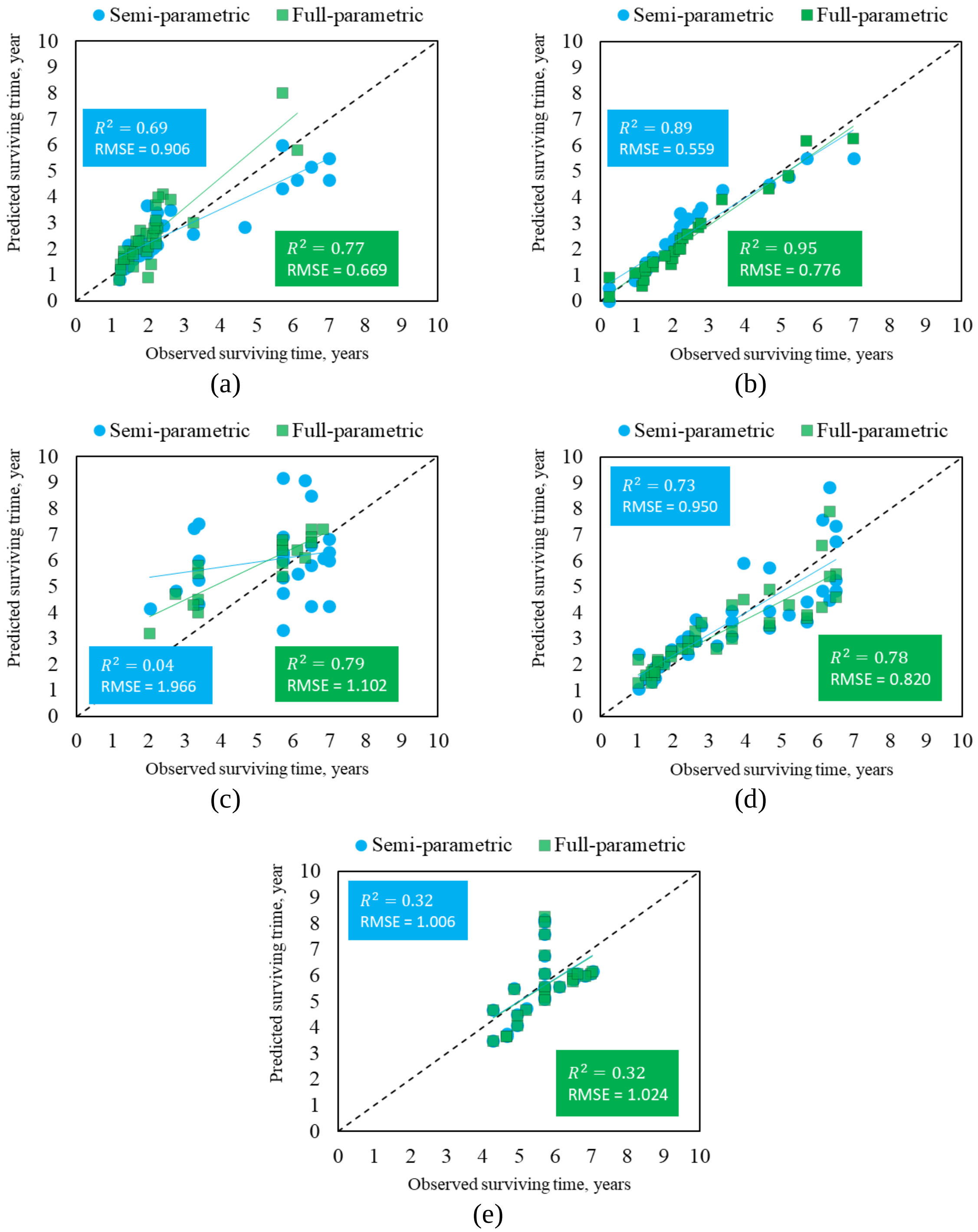
A direct comparison between survival and Markov models was not feasible since different approaches and measures were used in these methodologies. For the survival methodologies, observed and predicted survival times across survival probabilities were compared, whereas for the Markov model, the observed and predicted crack levels were compared.

The goodness-of-fit measure (*R^2*), and Root Mean Square Error (RMSE) measures, as are defined in Equations 4.5 and 4.6 were used to assess goodness of fit and also for comparative purposes.

$$R^2 = 1 - \left[\sum \frac{(O_i - P_i)^2}{\left(O_i - O_{avg}\right)^2}\right] \qquad 4.5$$

$$\mathrm{RMSE} = \sqrt{\frac{\sum (O_i - P_i)^{\,2}}{n}} \qquad 4.6$$

Where n = number of observations, O_i= field crack observations i, P_i = predicted value of observation i, O_{avg}= average of actual values. The observed and predicted survival times across survival probabilities were derived for both semi-parametric and full-parametric models. Note that the observed survival probabilities were obtained using the KM non-parametric methodology, where information of failed and at-risk subsections are used to estimate survival rates. Results are shown for different treatment categories in Figure 4-18.



(a) (b) (c) (d) (e)

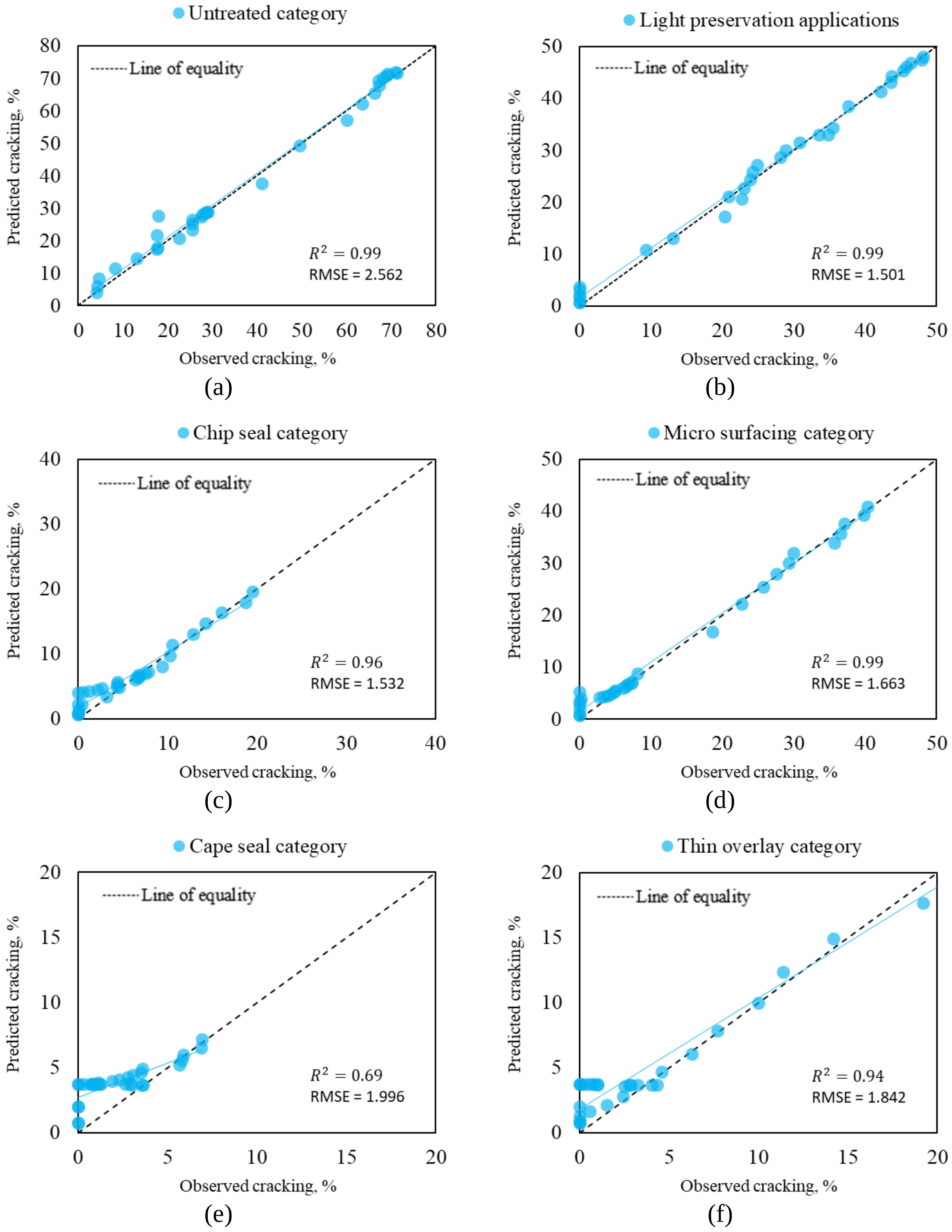
Figure 4-18 Observed versus predicted survival times for (a) untreated, (b) light preservation applications, (c) chip seal category, (d) micro surfacing category, and (e) thin overlay category

For the untreated sections, the full-parametric model provides a higher R^2 and lower RMSE. For the light applications, full-parametric survival can better explain the variability in data. Note that RMSE is dependent on the number of subjects n, and a higher R^2 does not necessarily guarantee a lower RMSE.

For the chip seal category, full-parametric gives a much higher prediction power. For micro surfacing, R^2 and RMSE values indicate to a better fit for the full-parametric model. For the thin overlays, both models are performing similarly. The low R^2 of 0.32 is attributed to higher variability in predictions.

Note that such analysis could not be done for the cape seals, where few subsections experienced failure for all of the sections in the group. As was seen before, the performance curve for this group more resembles a straight line. This was also true for treatments with very high survival rates such as scrub seals and HiMa thin overlay. For such treatments, more years of data is needed for subsections to fail for the deterioration trend to become explainable. The higher R^2 values makes the full-parametric model more reliable for predictions. In this study, crack values were predicted for up to 10 years in the semi-parametric analysis, and up to 12 years in the full-parametric analysis.

For the Markov model, predictions were compared with the observed crack percentages for the average pretreatment conditions. Figure 4-19 shows the goodness of fit plots for all of the treatment categories. The coefficient of determination (R^2) is high for most of the treatment categories, and data are scattered evenly around the line of equality. Lower prediction power occurs for subsections with less than 5% cracking, which should not be a concern when dealing with 20% criterion in MAP-21. Markov model predictions are close to observed values in higher cracking levels.



(a) (b)

(c) (d)

(e) (f)

Figure 4-19 Predicted versus observed crack percentages for all treatment groups in 7 years

4.2.6 Summary

In this section, different probabilistic methodologies were used to investigate deterioration behavior of preservation treatments. The effects of several variables on cracking performance of these treatments were then assessed. Moreover, life-extending benefits of these treatments were quantified using different methodologies. It was shown that preservation treatments are effective maintenance strategies with life-extending benefits that mostly depend on pretreatment conditions.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary

This dissertation aimed to develop probabilistic performance models for innovative preservation treatments. Performance models enable prediction of pavement deterioration behavior and are indispensable to pavement management systems. In pursuit of the objective, first a literature review consisting of two parts was conducted. In the first part, preservation life estimates were reviewed. It was shown that the reported life-extending benefits are highly variable, and the life-extension depends on the research methodology and several other factors such as traffic loading, pavement, and climatic conditions. In the second part, deterministic and probabilistic models that have been used previously along with their advantages and disadvantages were reviewed.

The body of this study started with the introduction of the preservation study on Lee 159 county road in Auburn, AL, and followed by the description of its special traffic loading conditions, treatment types, and data collection and filtration methods. It was explained that the only distress measure that exhibited an upward trend was cracking, and as such, it was used to define the distress index. MAP-21 cracking criterion was used in this study to define failure. Afterwards, the methodology that cracks were measured in this study was explained and contrasted against MAP-21. The body then continued by investigating the structural health of the sections using FWD testing and by assessing the deflection basin parameters against the defined thresholds from the literature.

Two main probabilistic performance modeling methodologies – namely survival analysis and Markov Chain – were used in the study. Included in the body of the research is the mathematical explanation of said methodologies. For the methodology section, first, survival analysis section was expanded. Survival analysis was divided into non-, semi-, and full-parametric sections and the related formulations were elaborated. Three main statistical terms – namely failure probability, survival probability, and hazard rate – were explained in the context of pavement preservation modeling. As a reminder, failure was defined where a subsection has more than 20% cracking of its area. Survival probability at time *t* was defined as the probability of a subsection surviving (i.e. not failing) beyond time *t,* and hazard rate was defined as a conditional probability that gives instantaneous failure rate of subsections in instances of time. Afterwards, model selection based on AIC and BIC statistics was explained. Second, Markov Chain Monte Carlo methodology and its several concepts such as duty cycles, TPM form, condition state vectors and its matrix formulation were explained. In this study, a novel algorithm was introduced to numerically solve the Markov process using Monte Carlo simulation. Methodology section ended by checking the stability of the Markov chain Monte Carlo model.

Throughout this research, it was emphasized that the value of pavement preventive maintenance is anchored to the performance of the treatments — the key is not how long the treatments last, but the life-extending value imparted to the pavement. The quantification of the treatment life-extending benefits and understanding their variabilities could only be realized in a highly controlled study where the possible effects of confounding factors are minimized. The lack of information on life-extending benefits was the main drive to conduct the present study. In the following sections, conclusions from each of the methodologies are being discussed.

5.2 Conclusions

All methodologies arrived at similar conclusions. It is also true that each methodology is more suitable to unearth a particular aspect of treatment performance. The non-parametric analysis is suitable to explore different behaviors before conducting any more rigorous analysis. The semi-parametric Cox model is more useful for assessing risk factors and performing comparisons, and Markov chain is particularly useful when dealing with the design reliability. PMS systems in use today might be utilizing any of these models. Offering all these models will facilitate their incorporation into those frameworks. In the following sections, conclusions from each of these methodologies are presented.

5.2.1 Non-parametric Survival Analysis

- Survival curves stratified by the pretreatment conditions were generated for the whole dataset. It was shown that sections with ‘poor’ initial condition have a significantly lower survival chance compared to sections with ‘good’ initial condition. Hence, the timing of the treatment application plays a critical role in preservation practices.
- In another analysis, deterioration data were stratified over treatment categories. Survival curves clearly indicate that preservation treatments engender significant benefits when compared to that of untreated sections, regardless of other factors. These benefits are higher for more robust treatments such as cape seals and thin overlays.
- For light applications, the median survival life was about 2 years and almost equal to that of the untreated sections. This finding was not consistent with the expectation that some benefits should be gained. Reasons for this inconsistency is rooted in the way that survival methodology estimates failure probabilities. In fact, sections with more than 20% cracking by total area are all treated as ‘failed,’ regardless of the cracking percentages beyond the failure threshold. For the light application group, despite the similarity of median survival lives, the average cracking level at failure was much lower compared to that of untreated

sections. Therefore, there were some benefits that were unaccounted in the survival methodology.

- Stand-alone crack sealing has effectively prevented water and incompressible material intrusion into the pavement structure. It is shown to be beneficial when the section is in ‘fair’ and ‘poor’ conditions. For the ‘good’ pretreatment condition level, the benefits are small, because dataset had a very low percentage of cracks (near zero) and therefore, the percentage of cracks that were sealed was also very low. Therefore, both sections ended up performing in a very similar way. Therefore, crack sealing benefits are optimum when surface condition is moderately cracked. Comparisons with the untreated category shows that in the ‘fair’ pretreatment condition, the median life due to crack sealing increases by 2.6 years while for the ‘poor’ condition, the median benefit is 2.2 years.
- An idea that forged during the experimental design was to see if crack sealing in advance of other treatments can provide additional benefits. Having a crack sealing/filing treatment that specifically addresses cracking prior to application of the main treatment was shown to be beneficial with the chip seal and micro surfacing sections having higher survival rates, when crack sealing is applied in advance. At year 7, the survival rate for the chip seal section with priorly applied crack sealing was 15% higher compared to the standalone chip sealed section. The micro surfacing sections with and without crack sealing in advance exhibited similar median times to failure. However, this can be attributed to the limitations of the survival analysis where sections with crack percentages beyond the failure threshold are all treated same as ‘failed.’ The average pretreatment cracking percentage was 21.4% for the micro surfacing section and 41.9% for the micro surfacing with crack seal/fill, yet

both showing similar median times to failure. This suggests there is a benefit that is unaccounted for in this dataset.

- Several thin overlays had incorporated recycled materials to assess their performances. The survival rates were slightly lower for the RAP and RAS sections compared to the virgin thin overlays. The lower survival rates are still highly desirable considering that the recycled sections had a very high binder replacement, which is not typical of overlays currently being used in the States.

5.2.2 Semi-Parametric Survival Analysis

- Semi-parametric survival analysis is primarily useful to assess different risks related to different strategies, time of treatment, etc. Although semi-parametric models can also be used to generate survival curves, a full-parametric methodology is usually recommended since goodness of fit tests were in favor of the full-parametric methods.
- Risk analyses confirmed the findings of the non-parametric method that regardless of the family of the treatments, all preservation categories provide some level of life-extending benefit when compared to "do-nothing" scenarios. Cape seals, thin overlays, chip seals and micro surfacing can decrease the risk of failure by more than 75%. The light applications decreased the risk of failure by as much as 46%.
- The pretreatment condition risk was quantified as part of the semi-parametric analysis. The risk of failure for 'poor' and 'fair' pretreatment condition levels were 3.3 and 2.4 time higher than that of the 'good' condition, respectively. The traffic level effect was not significant when including all of the sections in the analysis.
- For the thin overlays, recycled sections were shown to face higher risk of failure, 4.8 times higher, than that of virgin thin overlays. Also, deterioration was more pronounced in the

outbound direction. The pretreatment condition was not significant for thin overlays. Also, the risk of failure for RAP and RAS sections were determined to be almost equal. Note that for thin overlays, the pretreatment condition and traffic level effects were found to have some correlation, and it might be that the effects were confounded for this category. Regardless of the included variable, it is certain that higher traffic levels accelerate deterioration.

- For two of the sections, crack sealing was applied prior to treatment application. These sections included chip sealing and micro surfacing. It is shown that crack sealing reduces the risk of pavement failure by 15% and 60% for the micro surfacing and chip seal sections, respectively.
- Life-extending benefits of all treatments were estimated by comparing treatment lives to the untreated sections life. Generally, treatments with highest life-extending benefits were cape seals, virgin thin overlays, and multi-layer treatment applications. Chip seal with crack sealing in advance and scrub seal were the only examples of a single-layer treatment that were comparable to virgin thin overlays, with more than 6 years of life-extending benefits.
- In the semi-parametric methodology, chip seals were the only category that traffic level was determined to be significant in addition to the initial condition effect. Lower treatment lives were predicted for the outbound direction where higher cumulative ESALs occurred.

5.2.3 Full-parametric Survival Analysis

- In the full-parametric methodology, several distributions were fitted to the treatment categories. It is shown that each category is following a different distribution, and hence, different deterioration behaviors are expected. Chip seals and thin overlays followed a

Weibull distribution. The untreated, light applications and micro surfacing followed a Frechet distribution, and cape seals followed an exponential distribution. The hazard rates are different for each of these distributions which is indicative of different deterioration behavior. The hazard rate, or instantaneous rate of failure, can define the proportion of subsections that are at risk of crossing the target failure threshold in any instance in time.

- Full-parametric methods are more suitable for prediction purposes. Comparison of semi-parametric and full-parametric results showed that in the full-parametric method, higher R^2 values are obtained when comparing the observed and predicted survival times. Hence, for the full-parametric method, a longer prediction window was selected.
- Full-parametric survival methodology is in essence a regression type solution which incorporates probabilistic nature of deterioration. Similar to any regression model, coefficient estimates, class level information and parameterized equations are needed to generate the dependent variable which is failure/survival probability. These information are provided in Chapter Four. Survival curves that were generated using said information were also provided in APPENDIX B. The life-extending benefits were calculated similar to the procedure explained for the semi-parametric model.

Generally, a very good agreement can be seen among different survival methodologies, aside from the differences that are due to the unequal prediction window.

5.2.4 Markov Chain & Monte Carlo Simulation Approach

- Markov chain model was used in conjunction with the Monte Carlo simulation to realistically estimate the life of the treatments and to develop percentile curves to incorporate reliability.

- All preventive treatments showed life-extension benefits to some degree. Type of the treatment and condition of the pavement prior to treatment application significantly affect life-extending benefits.
- Light preservation applications were mostly efficient when the pavement was in ‘good’ pretreatment condition. Also, maximum crack sealing benefit was obtained when it was used in combination with another treatment, such as chip seal with crack sealing application.
- In the chip seal group, the performance of scrub seal equaled those of double and triple layer chip seals. Scrub seal is a good example of a case when application technique produces comparable performance while using less materials.
- All cape seal sections exhibited excellent performance with life-extension benefits of at least 7.6 years on average reliability levels. Cape sealed sections have been very effective preventive treatments and have remained crack-free after 10 years of service for both lower and upper traffic bound levels.
- Thin overlays performances were not equal between clusters. Cluster 1 consisting of thin overlays with virgin binder and with highly modified polymer (HiMA) binder showed excellent performance with life-extending benefits in excess of 7.6 years. The second cluster consisting of ultra-thin bonded surface course and thin overlays with recycled materials showed great performance when pretreatment conditions were ‘good’ and ‘fair.’ Their performance decreased significantly in ‘poor’ pretreatment condition. Note that the recycled thin overlays had very high binder replacement percentage, which expectedly affects cracking performance.

- Monte Carlo simulation has added another dimension to the Markov chain analysis – the reliability concept. It was confirmed that the average results of Monte Carlo match the Markov chain results. In fact, Monte Carlo solves the Markov chain process numerically instead of following matrix multiplication. Hence, the numerical simulation presents the ability to unearth the reliability concept, since it provides results not just for the average values, but also for other cracking percentiles. Through this analysis, it was realized that distress data for each section can be nonsymmetrical in each date. As such, treatment selection based on the average predicted values cannot guarantee performance when higher percentile designs are needed. Also, the nonsymmetrical deterioration data can partly explain the wide range of treatment performances reported by other researchers.

5.3 Recommendations

Deterioration measurements are showing that after 7 years of data collection, cracking is the only distress that is showing an increasing trend. While the increase was enough to allow for model development, several sections are still showing little to no cracking. The proportion of subsections with cracking below the 20% failure threshold after 7 years from the treatment application is 86%, 45%, 95%, and 86% for chip seals, micro surfacing, cape seals and thin overlays, respectively. It is recommended that data collection be continued for years to come, until more subsections register cracking levels beyond the target failure threshold. This will help to minimize variability in the context of survival analysis.

This study sought to develop a methodology that can predict cracking performance from historical data. The statistical principles explained throughout this research can be easily applied to other distress measures, and other test locations. When enough data are gathered, it is recommended that a broader model be developed to quantify life-extending benefits under different climatic regions, traffic levels, and pretreatment conditions. Note that implementation of such a model cannot happen without calibration and validation for local or regional data.

Distresses will continue to be monitored for possible changes. If increasing trends are observed for distresses other than cracking, it is recommended that first, the distresses be unified into a composite index such as PCI, and then a model be developed in a similar way that described in this study. Alternatively, performance models can be developed for individual distress indexes, separately.

For some of the treatments, the number of subsections was low in specific conditions at the time of the treatment application. In the context of statistical inference, more samples lead to lower variability. For this reason, it is recommended that distress data contain a wider distribution of pretreatment conditions in similar studies to make sure enough samples are available when data are stratified over covariate levels – in this case, pretreatment condition levels. The results presented in this study correspond to a portion of a larger research scope that covers additional test locations subjected to different climate and traffic. These additional locations were treated more recently, but as they continue to remain in service and their performance to be monitored, the data generated may be used to create a more robust dataset.

A PMS can potentially use any of the models described in this study. Based on the results on model performances, Markov chain and full-parametric survival analysis are the two models that are mostly recommended for use. Either of the models have their own pitfalls and merits. Markov chain works with raw distress values whereas survival methodology uses the proportion of subjects that are failed relative to those that are at risk. As such, results of the Markov chain model comes in units of distress which can be better communicated among experts. On the other hand, survival analysis, as opposed to Markov chain, is a parametric model which can better address the influence of various explanatory variables on the survival probability of pavement sections. Selection of either methods depends on data availability and the level of sophistication that is required.

The takeaways of this study are several. First, it is confirmed that the surface pre-treatment conditions are crucial in determination of future treatment performance. Second, it should be reminded that preventive treatments should be applied on pavements with good structural conditions. For a convenient analysis of structural condition, it is recommended that FWD testing be conducted and deflection basin parameters be checked against the defined thresholds prior to application of any preventive treatments. Third, it is confirmed that reliability is an important aspect in preservation treatment selection which has been overlooked in most studies. Thus, it is recommended that reliability aspect be incorporated in PMS because the choice for reliability may alter the decision tree and subsequently the workplans. Basically, higher reliability requires stronger treatments. Fourth, the use of recycled-incorporated thin overlays shown promising performance and thus this study advocates their use to achieve higher sustainability. Finally, it is very likely that the life-extending benefits provided in the tables and figures would be different for other climates and traffic levels. However, performances can be assessed comparatively. It should be that thin overlays outperform chip seals, and likewise chip seals outperform fog seal. Here, once again it is emphasized that the reported life-extending benefits are strictly subjected to the conditions (traffic and climate) and limitations (seven years of performance) that were exclusive to this experiment.

It is recommended that the proposed models and subsequent results be used as a starting point for a PMS that manages road networks in the same climatic and traffic conditions. Over time, a highway agency can use its own data to further refine the models.

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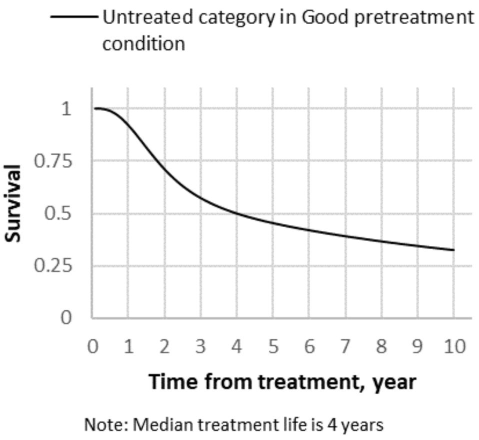
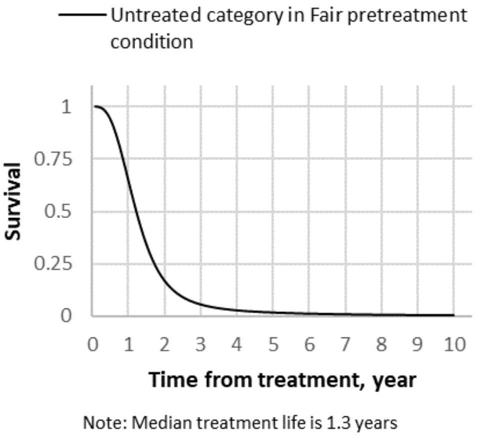
APPENDIX A

Semi-parametric survival plots for preservation treatments



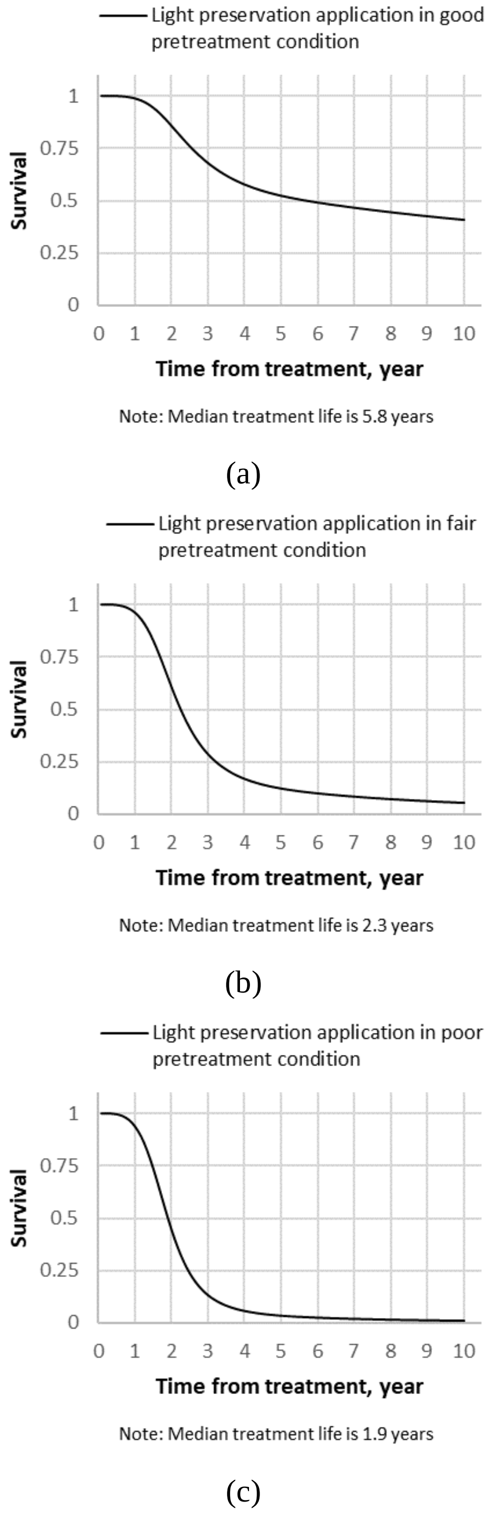
(a)



(b)

Note: for the ‘poor’ pretreatment condition, the untreated pavement has already reached failure at time 0.

Figure A. 1 Survival curves for untreated category in (a) good and (b) fair poor pretreatment condition.

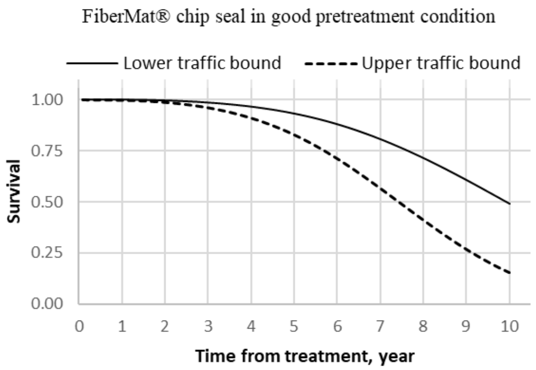


Note: Median treatment life is 5.8 years

Note: Median treatment life is 2.3 years

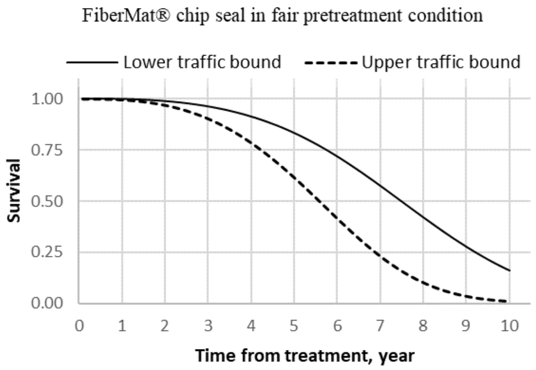
Note: Median treatment life is 1.9 years

Figure A. 2 Survival curves for the light preservation applications in (a) good, (b) fair, and (c) poor pretreatment conditions.


FiberMat® chip seal in good pretreatment condition

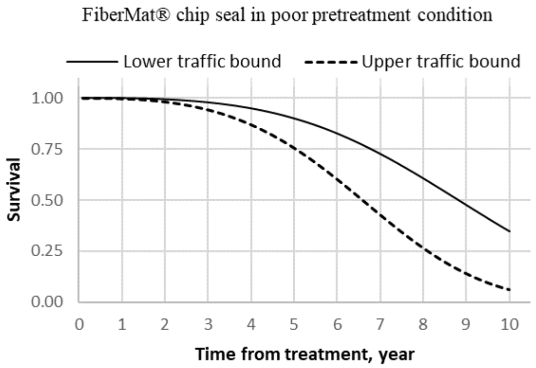
Note: Median treatment life is 10 years for the inbound lane and 7.5 years for the outbound lane.

(a)


FiberMat® chip seal in fair pretreatment condition

Note: Median treatment life is 7.5 years for the inbound lane and 5.6 years for the outbound lane.

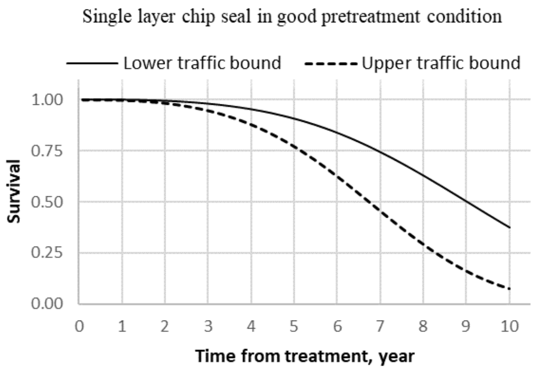
(b)


FiberMat® chip seal in poor pretreatment condition

Note: Median treatment life is 8.8 years for the inbound lane and 6.7 years for the outbound lane.

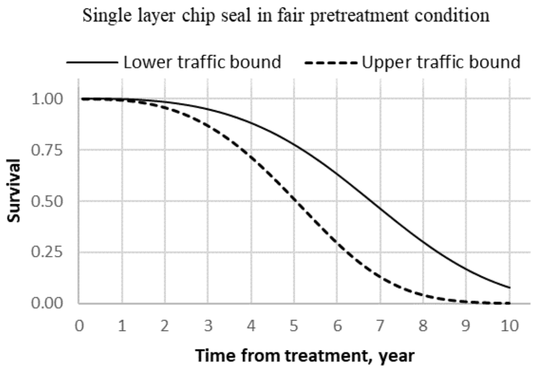
(c)

Figure A. 3 Survival curves for the FiberMat® chip seal in (a) good, (b) fair, and (c) poor pretreatment condition levels and different traffic levels.



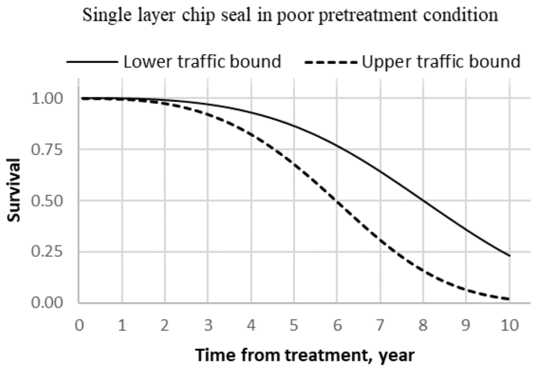
Note: Median treatment life is 9.1 years for the inbound lane and 6.8 years for the outbound lane.

(a)



Note: Median treatment life is 6.8 years for the inbound lane and 5.1 years for the outbound lane.

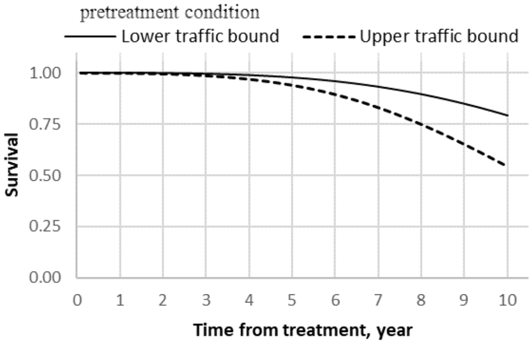
(b)



Note: Median treatment life is 8 years for the inbound lane and 6 years for the outbound lane.

(c)

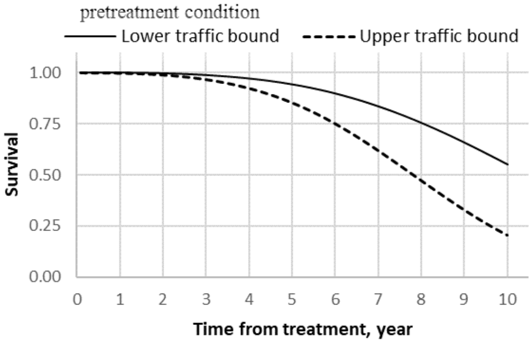
Figure A. 4 Survival curves for the single layer chip seal in (a) good, (b) fair, and (c) poor pretreatment condition levels and different traffic levels.



Single layer chip seal with crack sealing in good pretreatment condition

Note: Median treatment lives are more than 10 years for the inbound and outbound lanes.

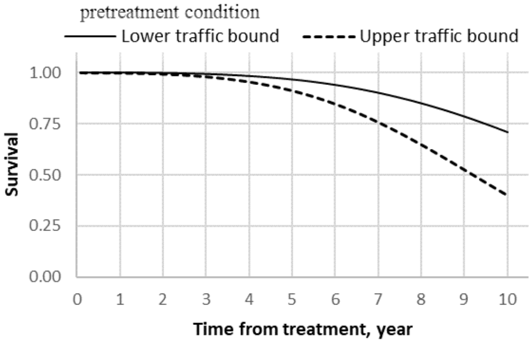
(a)



Single layer chip seal with crack sealing in fair pretreatment condition

Note: Median treatment life is more than 10 years for the inbound lane and 7.8 years for the outbound lane.

(b)

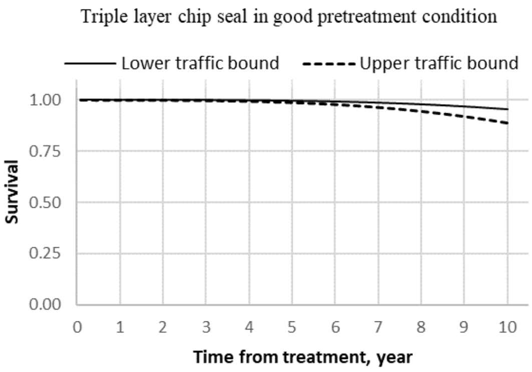


Single layer chip seal with crack sealing in poor pretreatment condition

Note: Median treatment life is more than 10 years for the inbound lane and 9.3 years for the outbound lane.

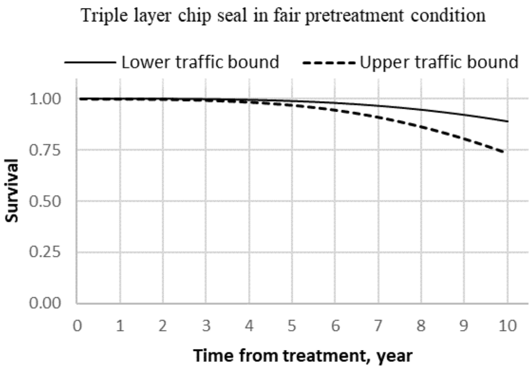
(c)

Figure A. 5 Survival curves for the single layer chip seal with crack sealing in (a) good, (b) fair, and (c) poor pretreatment condition levels and different traffic levels.



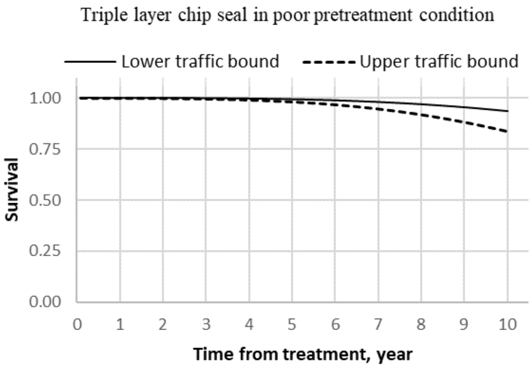
Note: Median treatment lives are more than 10 years for the inbound and outbound lanes.

(a)



Note: Median treatment lives are more than 10 years for the inbound and outbound lanes.

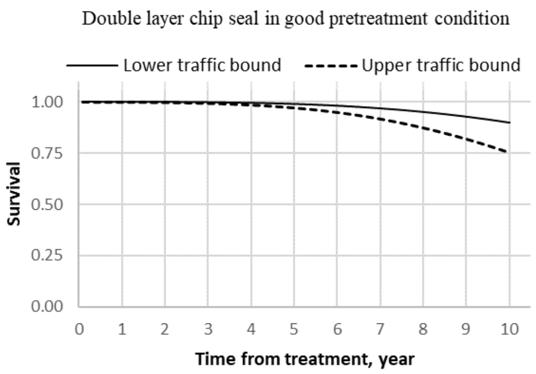
(b)



Note: Median treatment lives are more than 10 years for the inbound and outbound lanes.

(c)

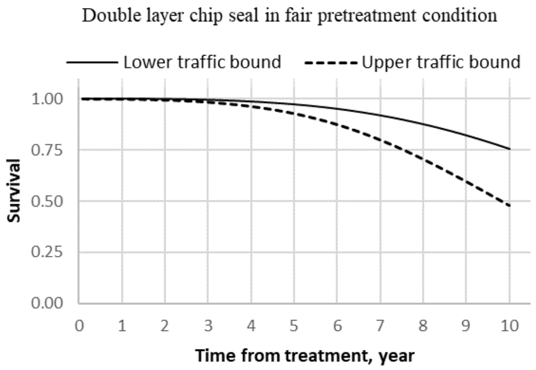
Figure A. 6 Survival curves for the triple layer chip seal in (a) good, (b) fair, and (c) poor pretreatment condition level and different traffic levels.



Double layer chip seal in good pretreatment condition

Note: Median treatment lives are more than 10 years for the inbound and outbound lanes.

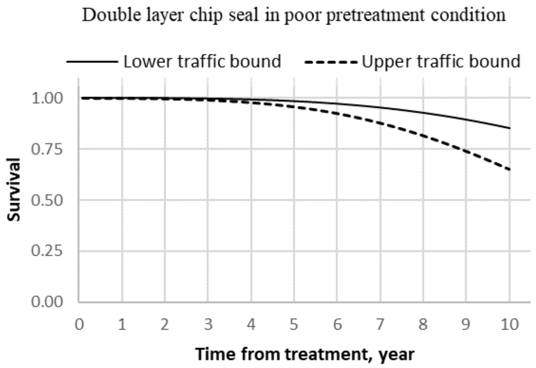
(a)



Double layer chip seal in fair pretreatment condition

Note: Median treatment life is more than 10 years for the inbound lane and 9.8 years for the outbound lane.

(b)

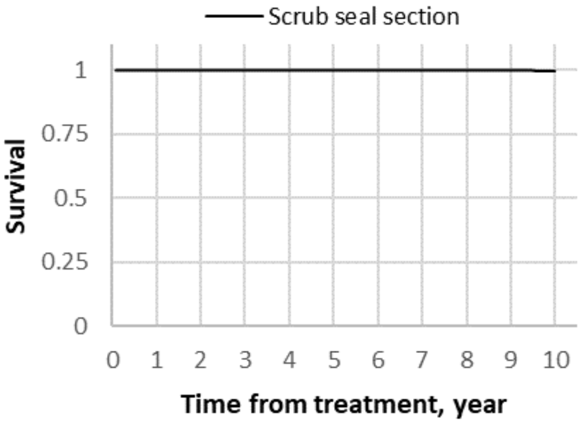


Double layer chip seal in poor pretreatment condition

Note: Median treatment lives are more than 10 years for the inbound and outbound lanes.

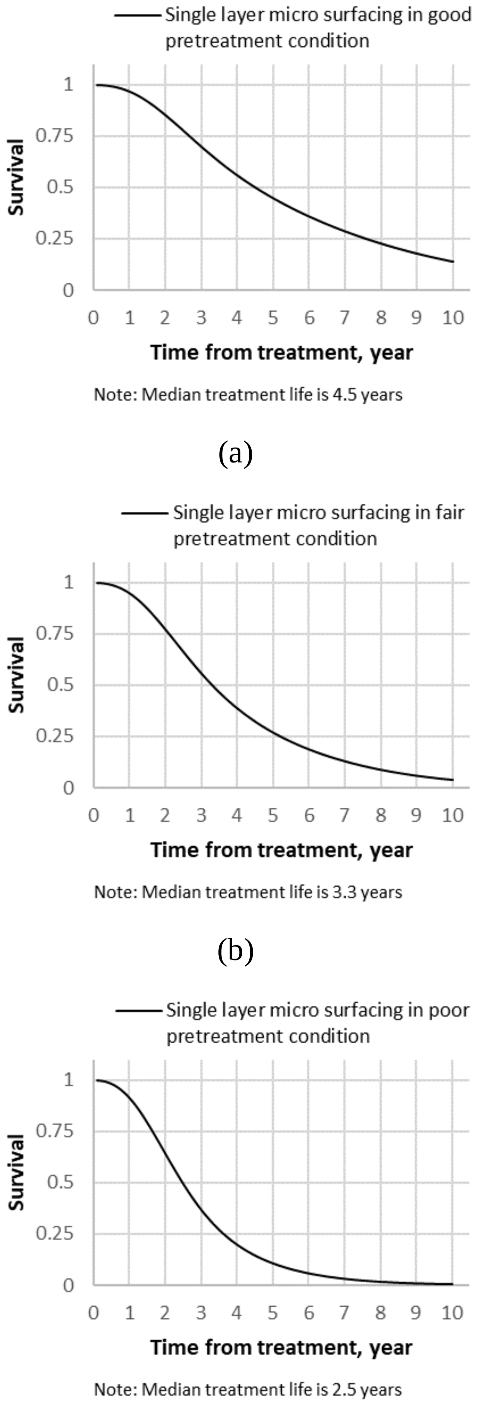
(c)

Figure A. 7 Survival curves for the double layer chip seal in (a) good, (b) fair, and (c) poor pretreatment condition level and different traffic levels.



Note: Median treatment life is more than 10 years and the cracking performance is not influenced by pretreamtment condition or travel direction.

Figure A. 8 Survival curve for the scrub seal sections.



Note: Median treatment life is 4.5 years

(a)

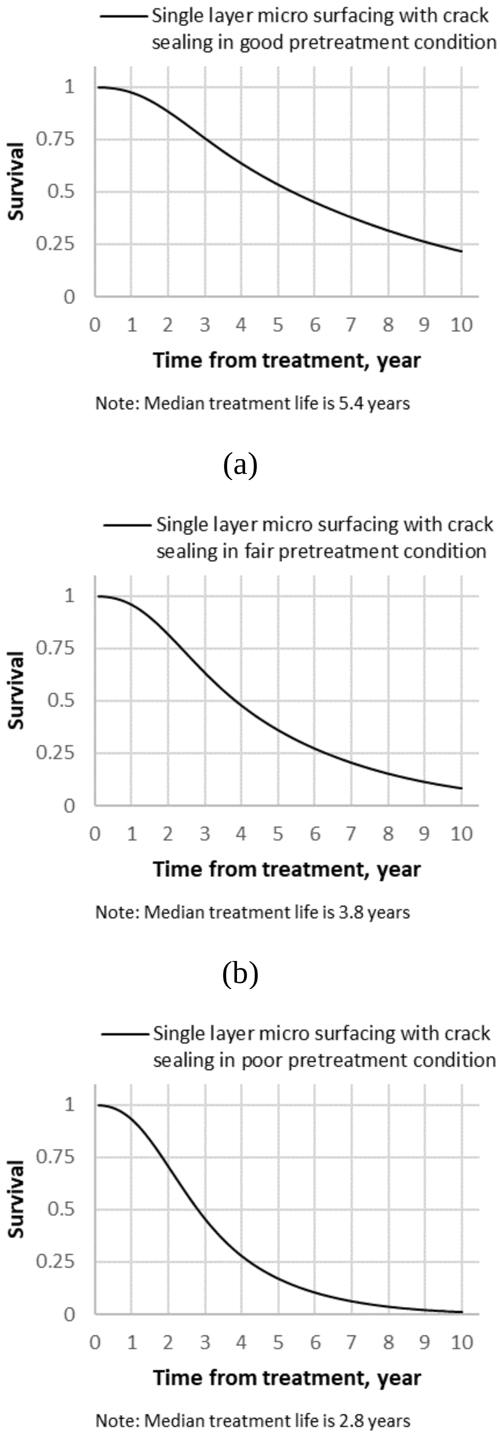
Note: Median treatment life is 3.3 years

(b)

Note: Median treatment life is 2.5 years

(c)

Figure A. 9 Survival curves for the single layer micro surfacing in (a) good, (b) fair, and (c) poor pretreatment condition.



Note: Median treatment life is 5.4 years

(a)

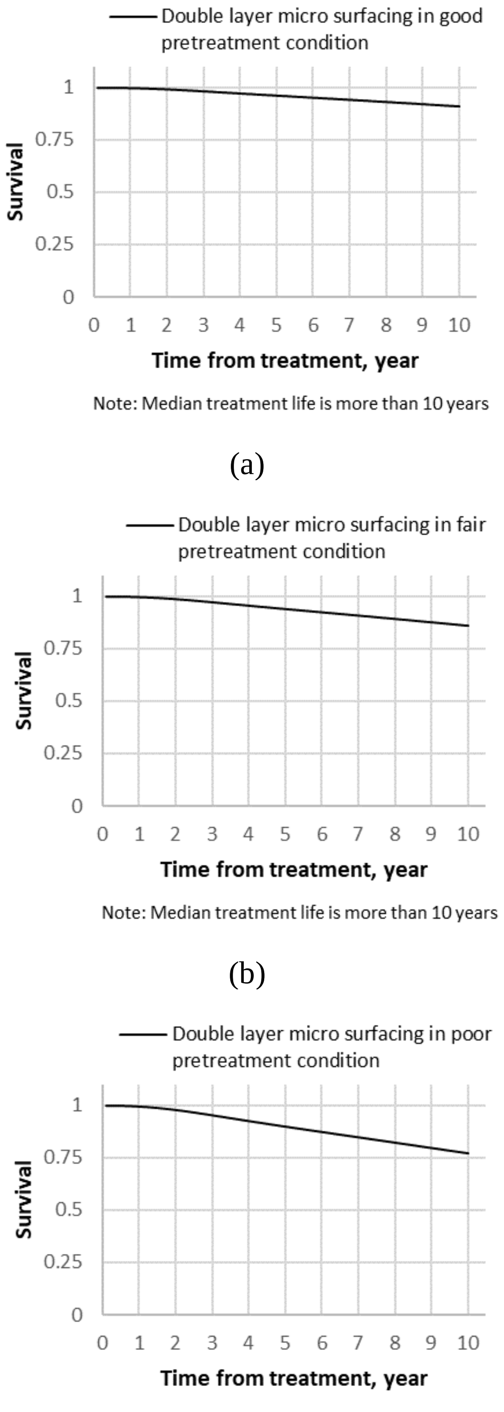
Note: Median treatment life is 3.8 years

(b)

Note: Median treatment life is 2.8 years

(c)

Figure A. 10 Single layer micro surfacing with crack sealing in (a) good, (b) fair, and (c) poor pretreatment condition.



Note: Median treatment life is more than 10 years

(a)

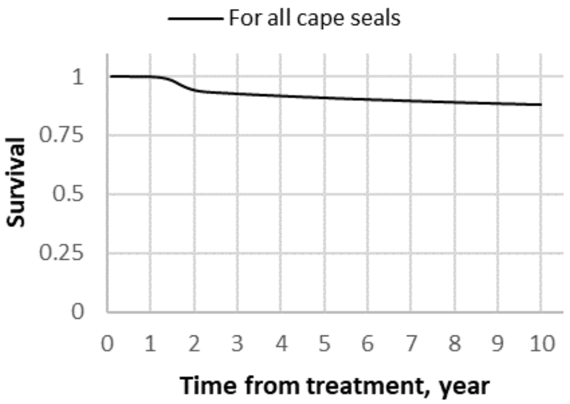
Note: Median treatment life is more than 10 years

(b)

Note: Median treatment life is more than 10 years

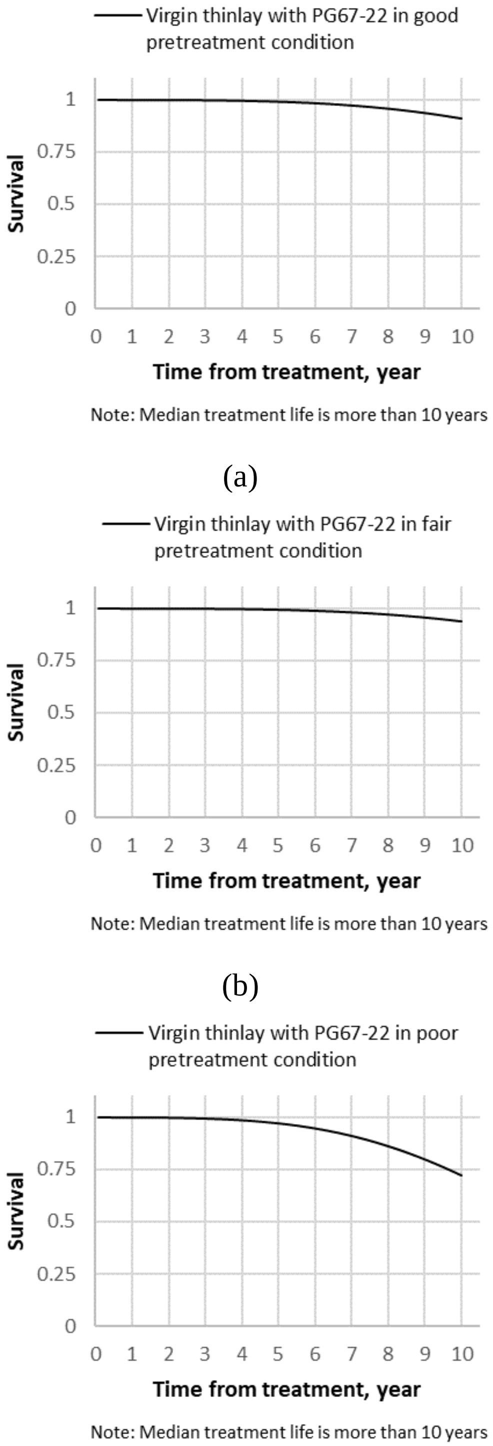
(c)

Figure A. 11 Survival curves for the double layer micro surfacing with (a) good, (b) fair, (c) poor pretreatment condition.



Note: Median treatment life is more than 10 years and the cracking performance is not influenced by the pretreamtment condition or travel direction.

Figure A. 12 Survival curves for the cape seal sections.



Note: Median treatment life is more than 10 years

(a)

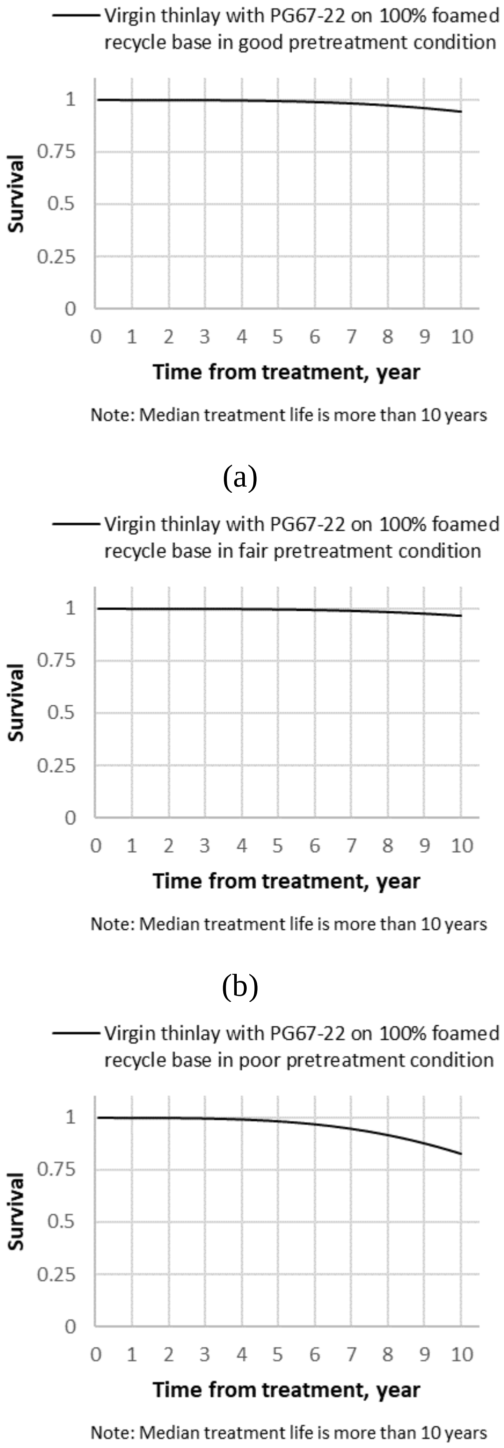
Note: Median treatment life is more than 10 years

(b)

Note: Median treatment life is more than 10 years

(c)

Figure A. 13 Survival curves for the virgin thin overlay with PG67-22 in (a) good, (b) fair, and (c) poor pretreatment condition.



Note: Median treatment life is more than 10 years

(a)

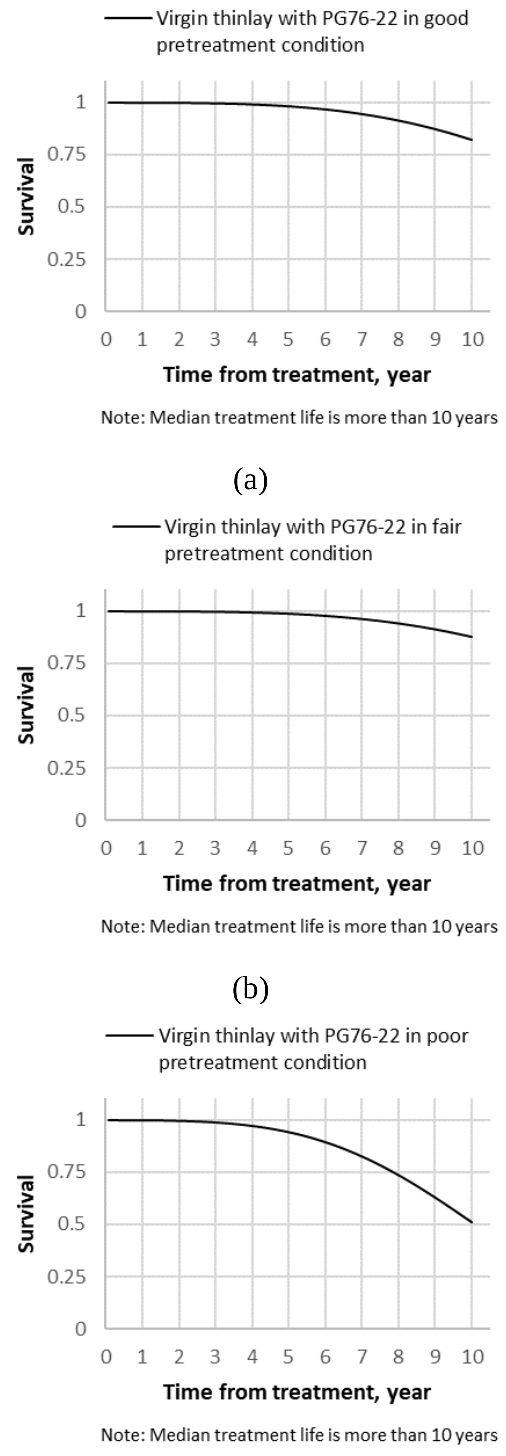
Note: Median treatment life is more than 10 years

(b)

Note: Median treatment life is more than 10 years

(c)

Figure A. 14 Survival curves for the virgin thinlay with PG76-22 on 100% foamed recycle base in (a) good, (b) fair, and (c) poor pretreatment condition.



Note: Median treatment life is more than 10 years

(a)

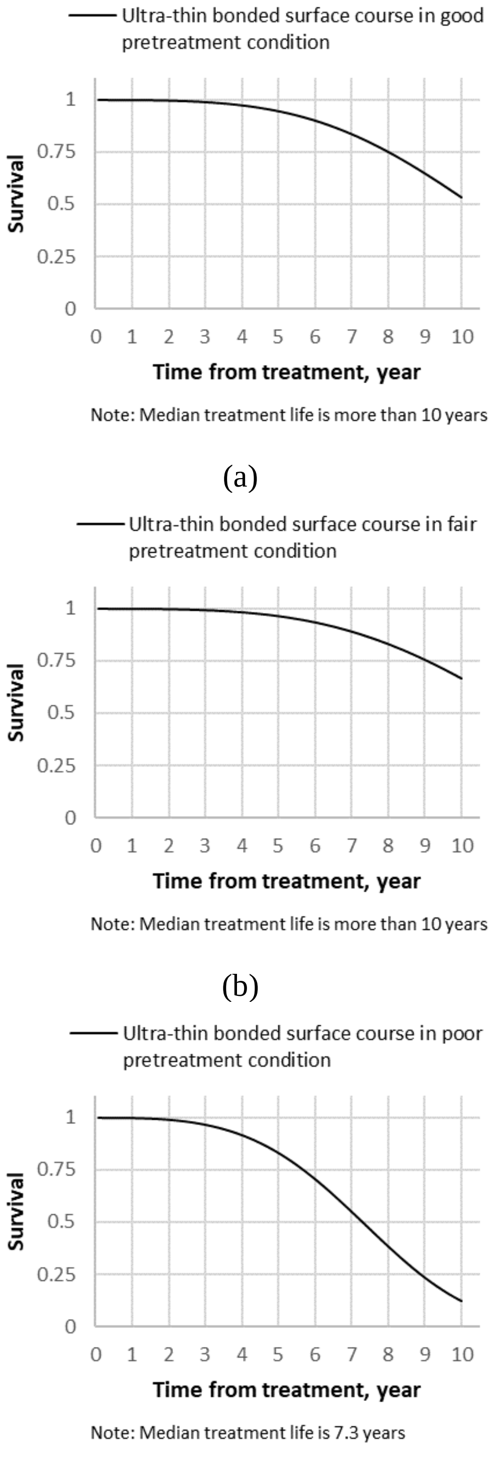
Note: Median treatment life is more than 10 years

(b)

Note: Median treatment life is more than 10 years

(c)

Figure A. 15 Survival curves for the virgin thin overlay with PG76-22 in (a) good, (b) fair, and (c) poor pretreatment condition.



Note: Median treatment life is more than 10 years

(a)

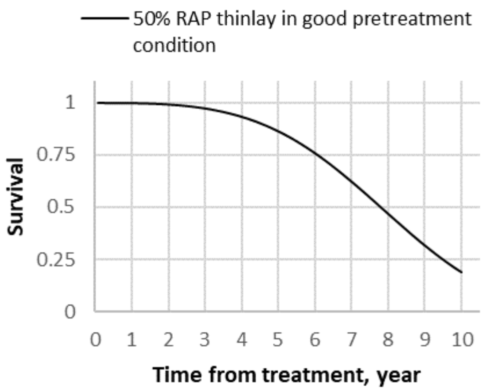
Note: Median treatment life is more than 10 years

(b)

Note: Median treatment life is 7.3 years

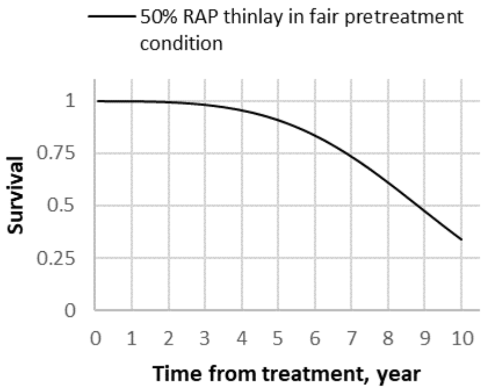
(c)

Figure A. 16 Survival curves for the ultra-thin bonded surface course in (a) good, (b) fair, and (c) poor pretreatment condition.



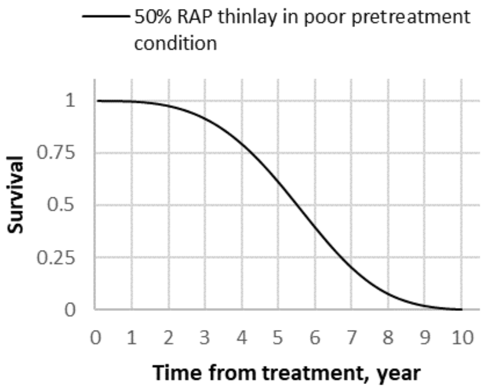
Note: Median treatment life is 7.8 years

(a)



Note: Median treatment life is 8.8 years

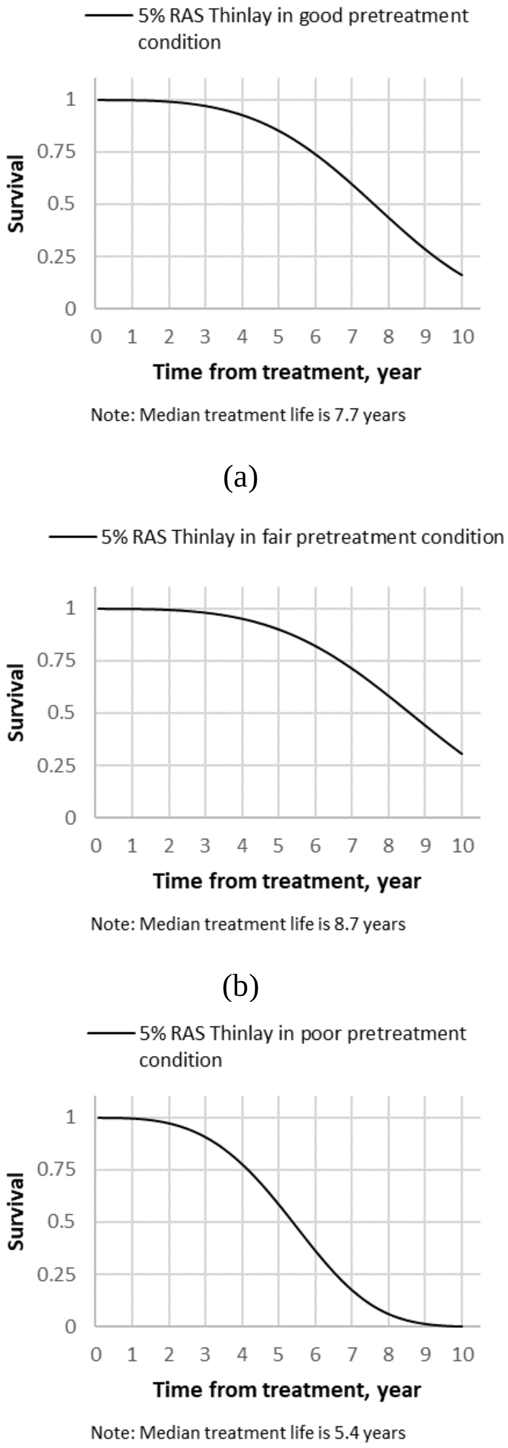
(b)



Note: Median treatment life is 5.6 years

(c)

Figure A. 17 Survival curves for the 50% RAP thin overlay in (a) good, (b) fair, and (c) poor pretreatment condition.



Note: Median treatment life is 7.7 years

(a)

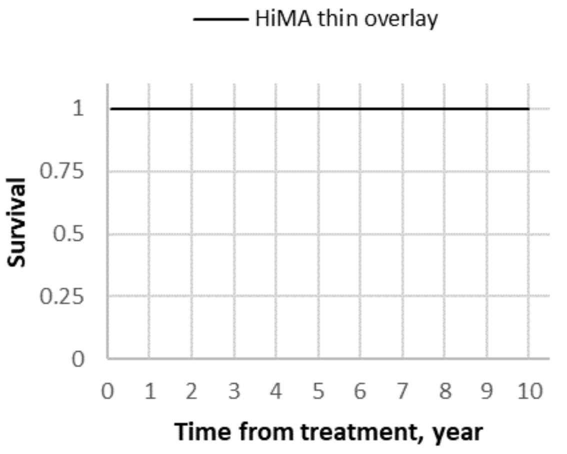
Note: Median treatment life is 8.7 years

(b)

Note: Median treatment life is 5.4 years

(c)

Figure A. 18 Survival curves for the 5% RAS thin overlay in (a) good, (b) fair, and (c) poor pretreatment condition.

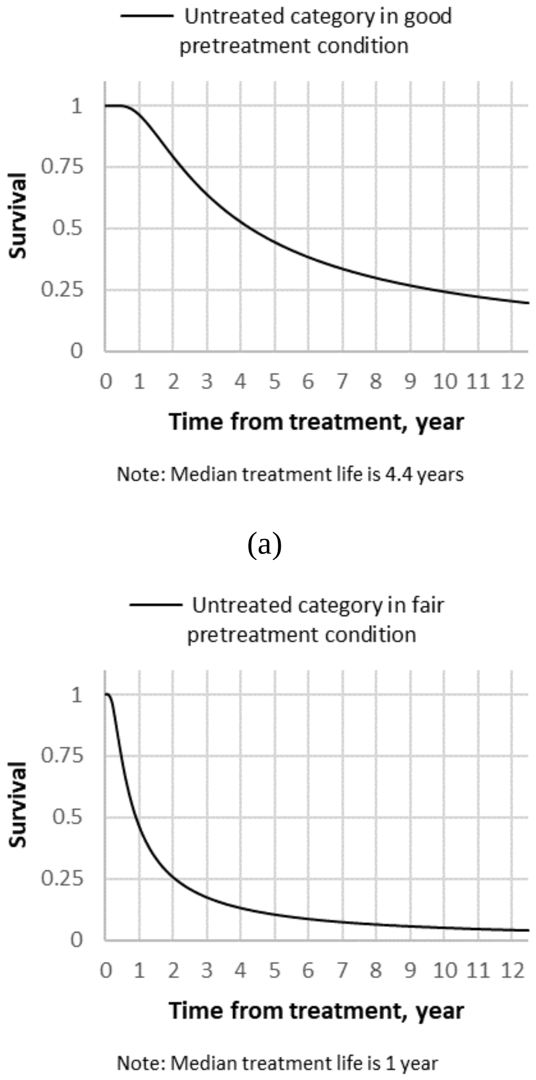


Note: Median treatment life is more than 10 years and the cracking performance is not influenced by the pretreamtment condition or travel direction.

Figure A. 19 Survival curves for the HiMA thin overlay**.**

APPENDIX B

Full-parametric survival plots for preservation treatments



Note: Median treatment life is 4.4 years

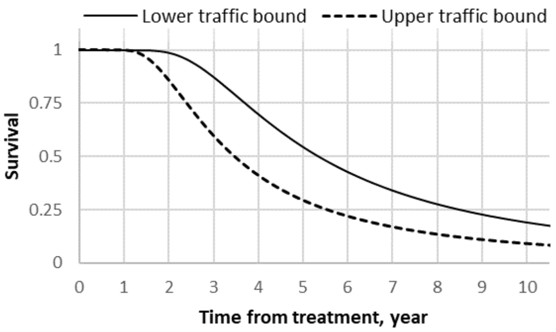
(a)

Note: Median treatment life is 1 year

(b)

Note: for the ‘poor’ pretreatment condition, the untreated pavement has already reached failure at time 0.

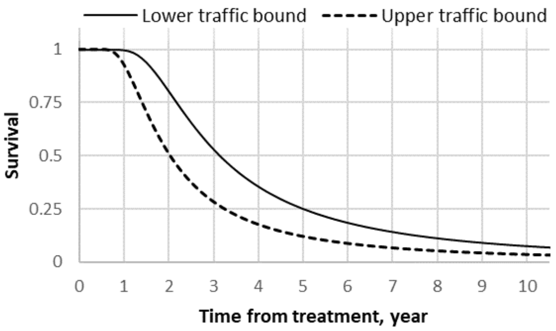
Figure B. 1 Survival curves for untreated category (a) good and (b) fair pretreatment condition.



Rejuvenating fog seal in good pretreatment condition.

Note: Median treatment life is 5.4 years for the inbound lane and 3.5 years for the outbound lane.

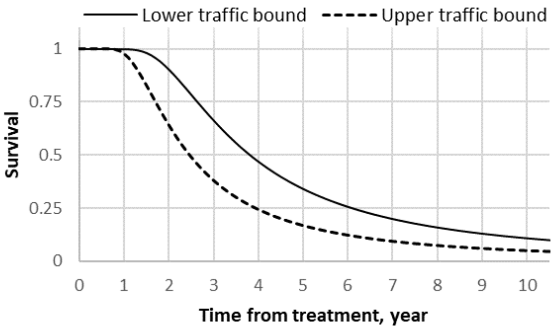
(a)



Rejuvenating fog seal in fair pretreatment condition.

Note: Median treatment life is 3.2 years for the inbound lane and 2.1 years for the outbound lane.

(b)

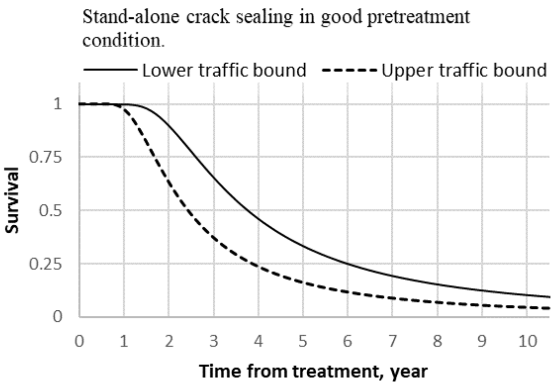


Rejuvenating fog seal in poor pretreatment condition.

Note: Median treatment life is 3.9 years for the inbound lane and 2.5 years for the outbound lane.

(c)

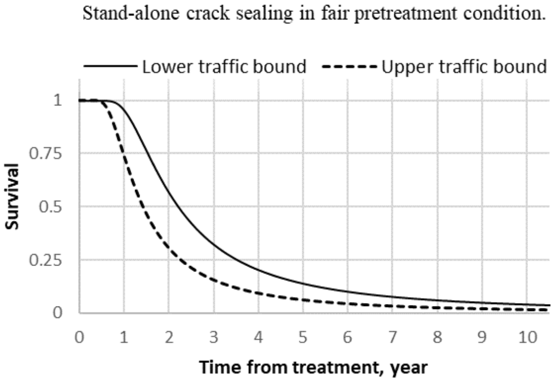
Figure B. 2 Survival curves for the rejuvenating fog seal in (a) good, (b) fair, and (c) poor pretreatment condition and different traffic levels.



Stand-alone crack sealing in good pretreatment condition.

Note: Median treatment life is 3.8 years for the inbound lane and 2.5 years for the outbound lane.

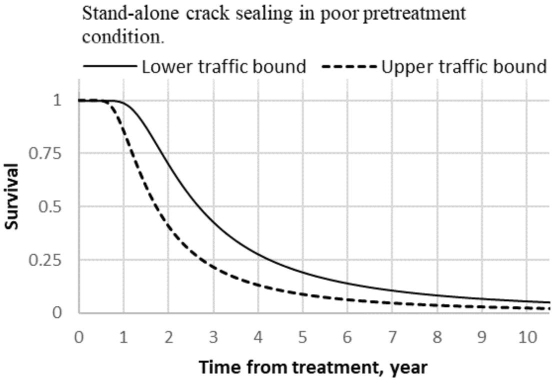
(a)



Stand-alone crack sealing in fair pretreatment condition.

Note: Median treatment life is 2.3 years for the inbound lane and 1.5 years for the outbound lane.

(b)

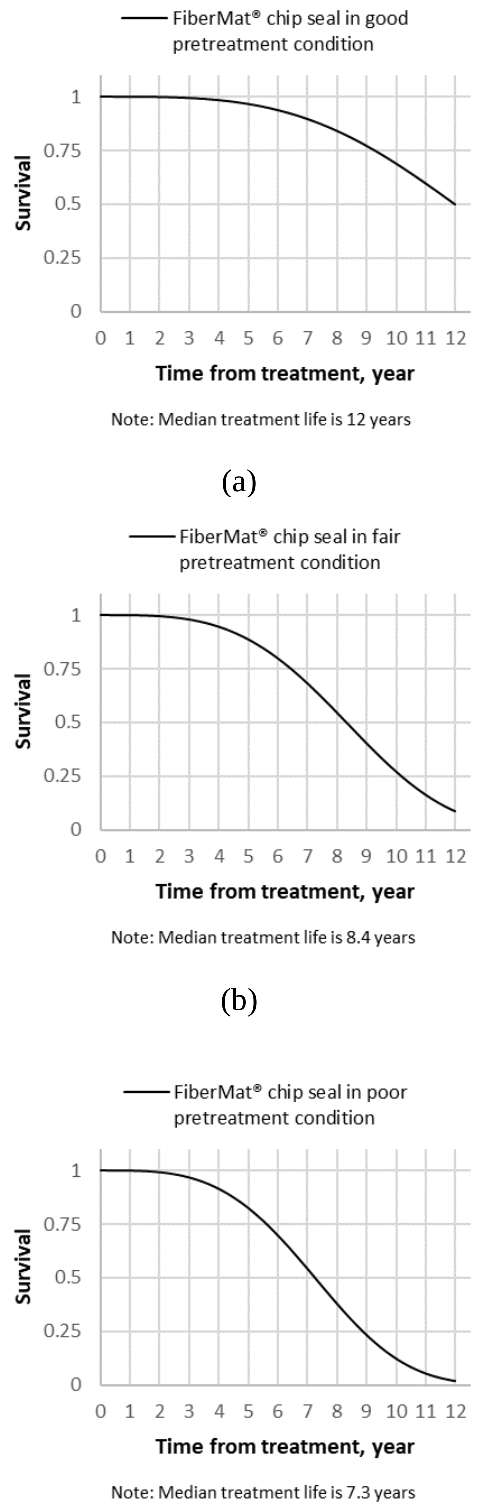


Stand-alone crack sealing in poor pretreatment condition.

Note: Median treatment life is 2.7 years for the inbound lane and 1.8 years for the outbound lane.

(c)

Figure B. 3 Survival curves for the stand-alone crack sealing in (a) good, (b) fair, and (c) poor pretreatment condition and different traffic levels.



Note: Median treatment life is 12 years

(a)

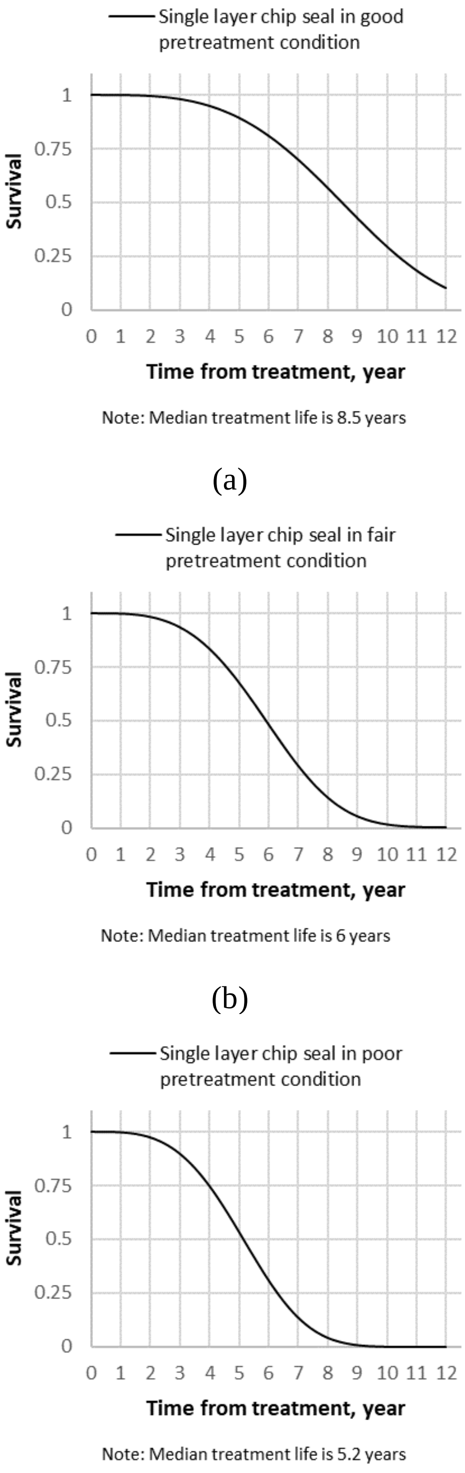
Note: Median treatment life is 8.4 years

(b)

Note: Median treatment life is 7.3 years

(c)

Figure B. 4 Survival curves for the FiberMat® chip seal (a) good (b) fair, and (c) poor pretreatment conditions.



Note: Median treatment life is 8.5 years

(a)

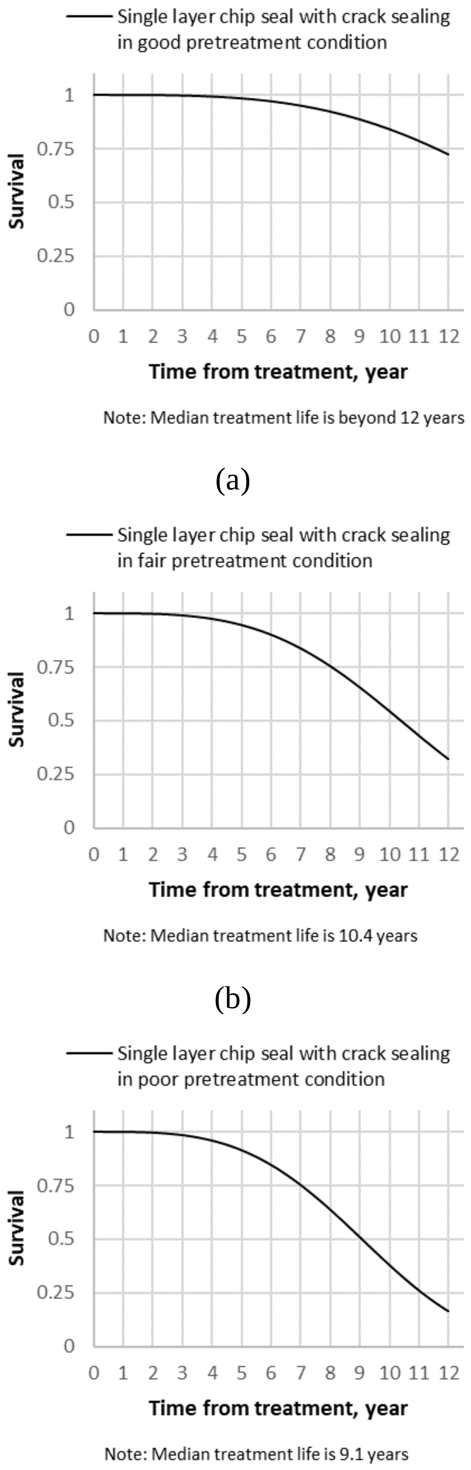
Note: Median treatment life is 6 years

(b)

Note: Median treatment life is 5.2 years

(c)

Figure B. 5 Survival curves for the single layer chip seal in (a) good, (b) fair, and (c) poor pretreatment condition.



Note: Median treatment life is beyond 12 years

(a)

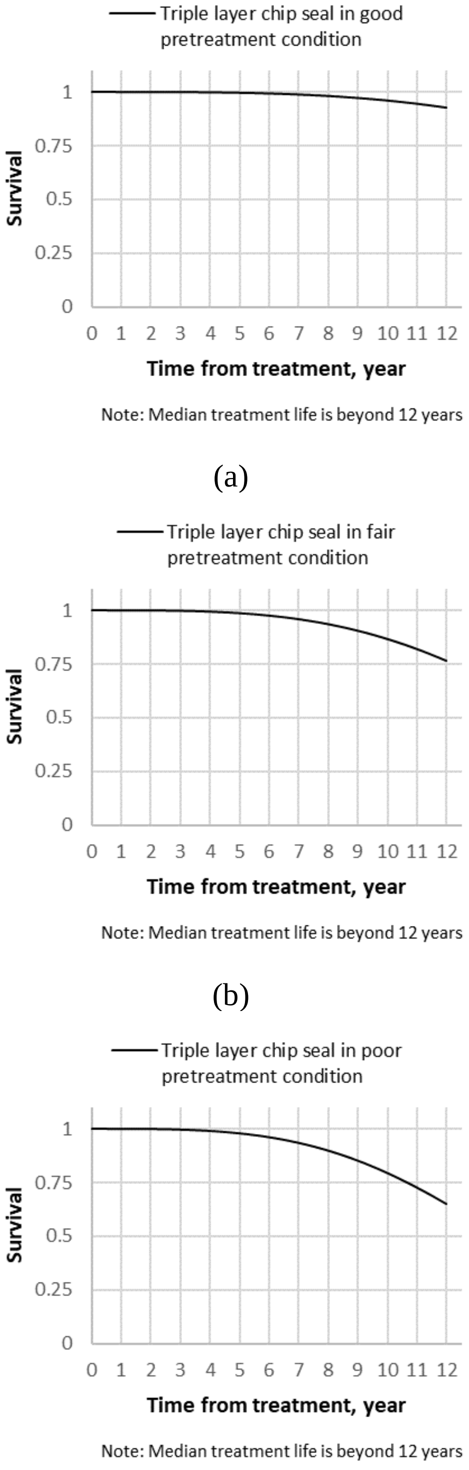
Note: Median treatment life is 10.4 years

(b)

Note: Median treatment life is 9.1 years

(c)

Figure B. 6 Survival curves for the single layer chip seal with crack sealing in (a) good (b) fair, and (c) poor pretreatment condition.

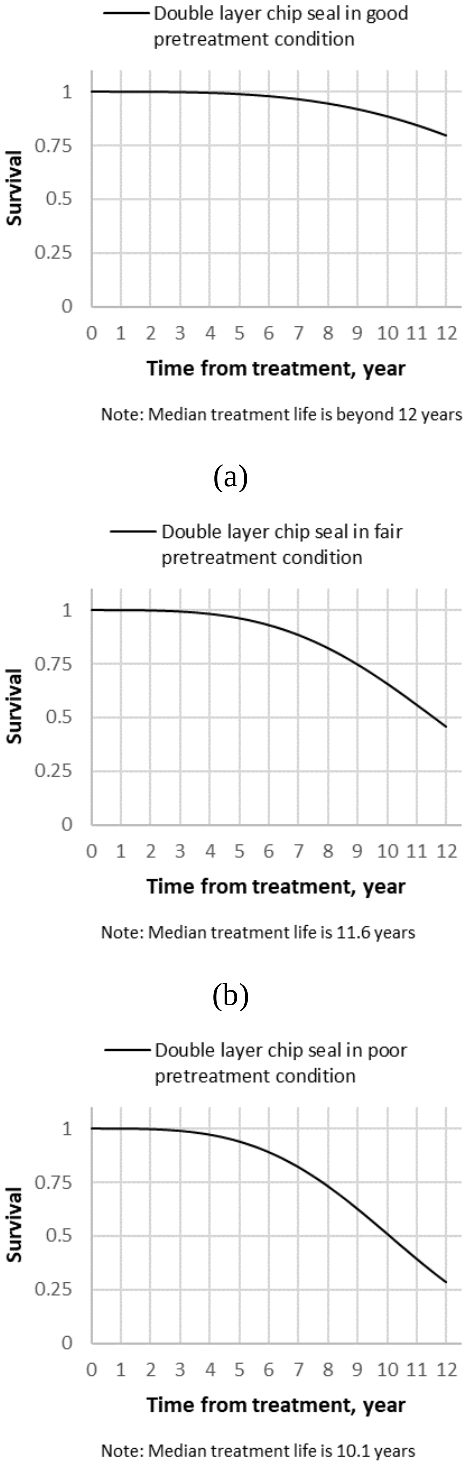


Note: Median treatment life is beyond 12 years

Note: Median treatment life is beyond 12 years

Note: Median treatment life is beyond 12 years

Figure B. 7 Survival curves for the triple layer chip seal in (a) good, (b) fair, and (c) poor pretreatment conditions.



Note: Median treatment life is beyond 12 years

(a)

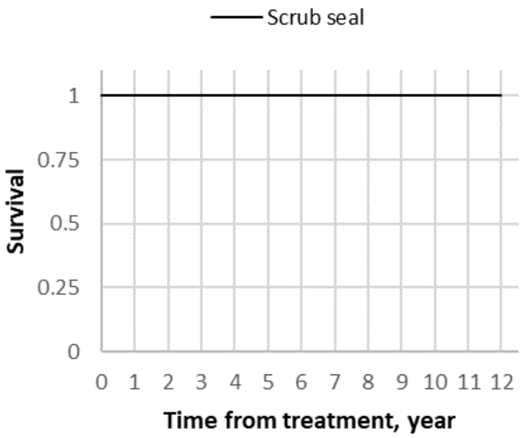
Note: Median treatment life is 11.6 years

(b)

Note: Median treatment life is 10.1 years

(c)

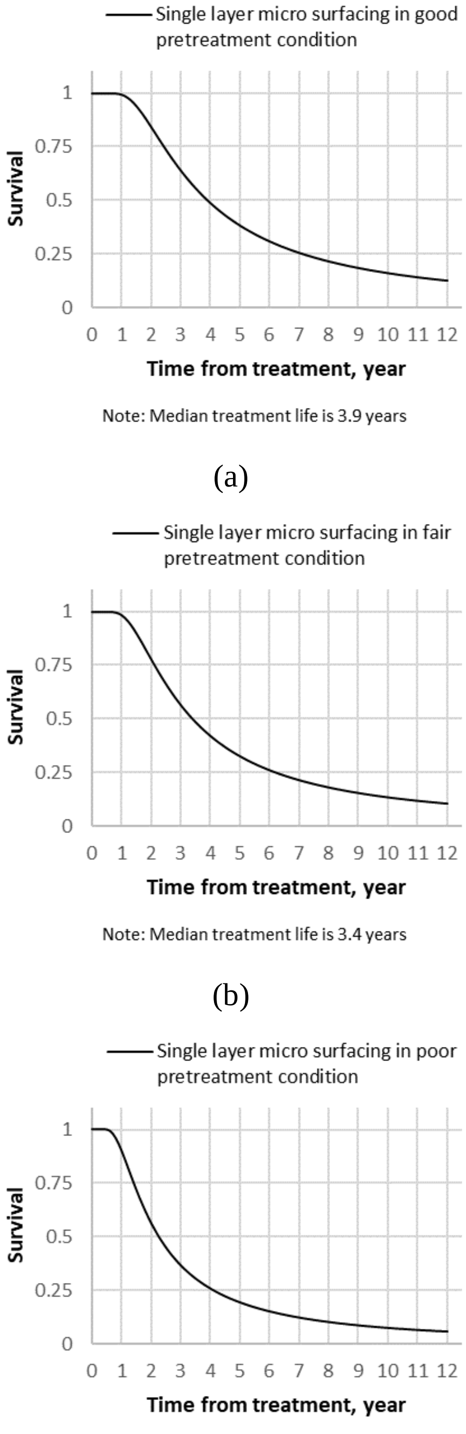
Figure B. 8 Survival curves for the double layer chip seal in (a) good, (b) fair, and (c) poor pretreatment conditions.



Note: Median treatment life is more than 12 years and the cracking performance is not influenced by the pretreatment condition or travel direction

(a)

Figure B. 9 Survival curves for the scrub seal



Note: Median treatment life is 3.9 years

(a)

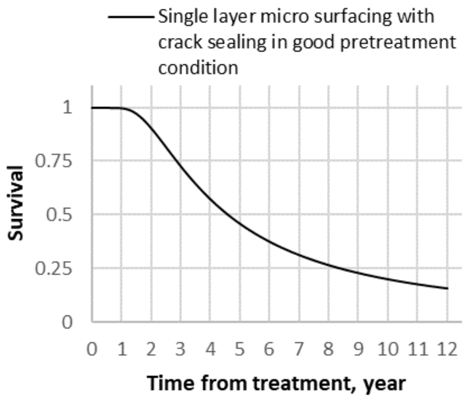
Note: Median treatment life is 3.4 years

(b)

Note: Median treatment life is 2.3 years

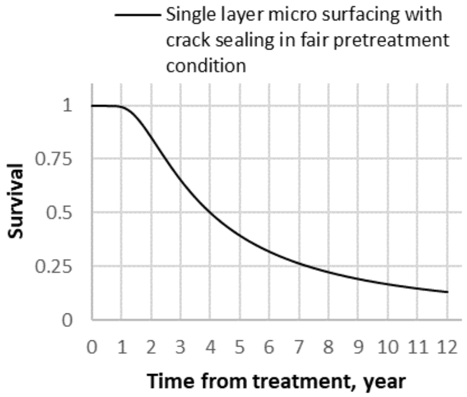
(c)

Figure B. 10 Survival curves for the single layer micro surfacing in (a) good (b) fair, and (c) poor pretreatment condition.



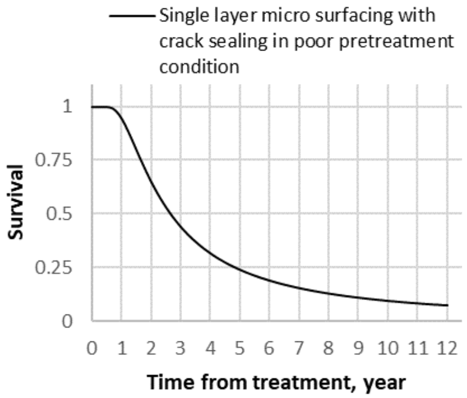
Note: Median treatment life is 4.6 years

(a)



Note: Median treatment life is 4 years

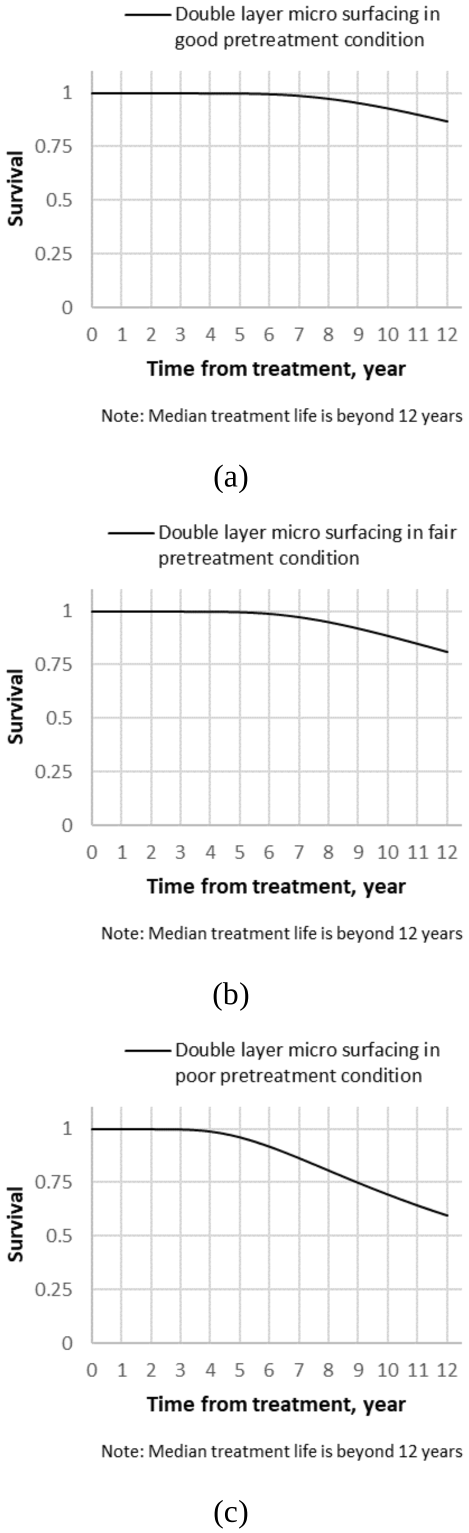
(b)



Note: Median treatment life is 2.7 years

(c)

Figure B. 11 Survival curves for the single layer micro surfacing with crack sealing in (a) good (b) fair, and (c) poor pretreatment condition.

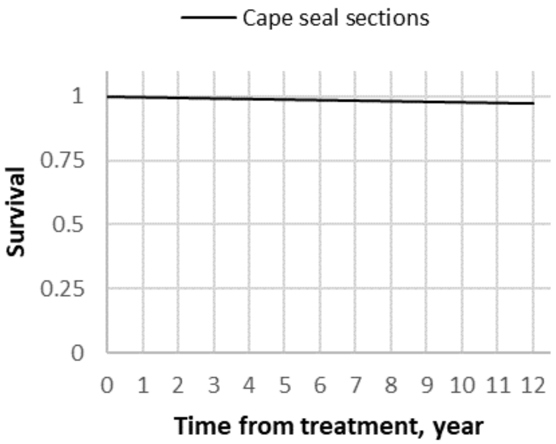


Note: Median treatment life is beyond 12 years

Note: Median treatment life is beyond 12 years

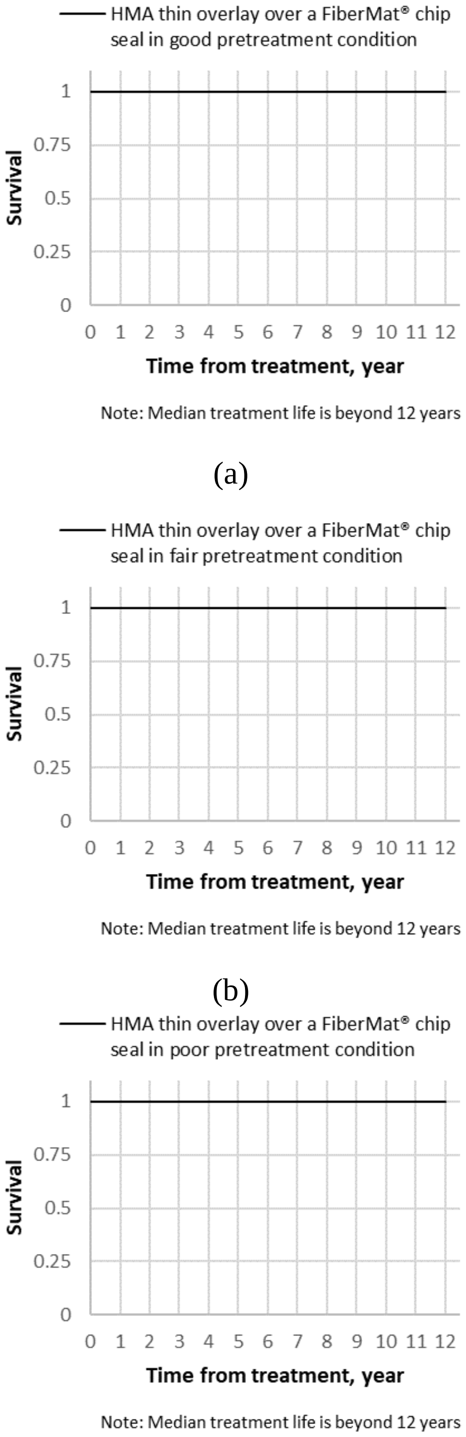
Note: Median treatment life is beyond 12 years

Figure B. 12 Survival curves for the double layer micro surfacing in (a) good (b) fair, and (c) poor pretreatment condition.



Note: Median treatment life is more than 12 years and the cracking performance is not influenced by the pretreatment condition or travel direction

Figure B. 13 Survival curves for the cape seal sections



Note: Median treatment life is beyond 12 years

(a)

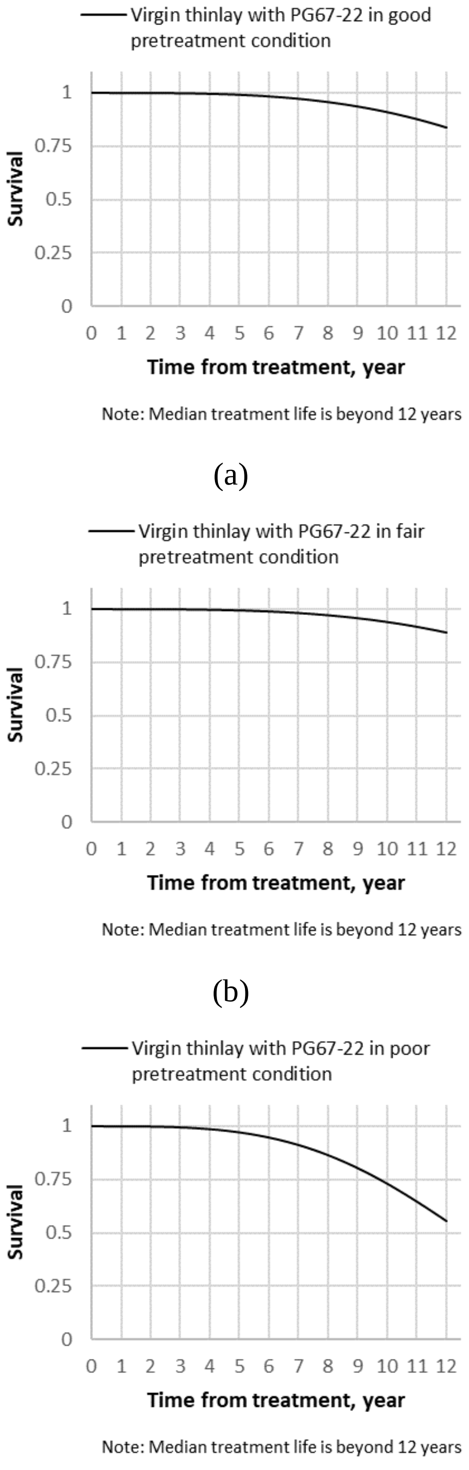
Note: Median treatment life is beyond 12 years

(b)

Note: Median treatment life is beyond 12 years

(c)

Figure B. 14 Survival curves for the thin overlay over a FiberMat® chip seal in (a) good (b) fair, and (c) poor pretreatment condition.



Note: Median treatment life is beyond 12 years

(a)

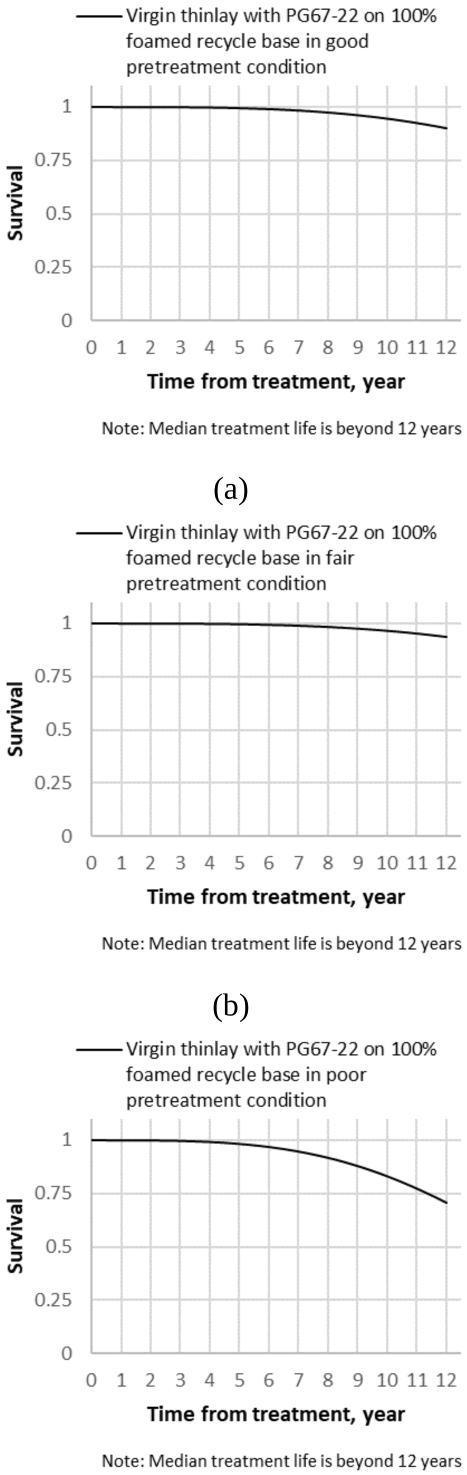
Note: Median treatment life is beyond 12 years

(b)

Note: Median treatment life is beyond 12 years

(c)

Figure B. 15 Survival curves for the virgin thin overlay with PG67-22 in (a) good (b) fair, and (c) poor pretreatment condition.



Note: Median treatment life is beyond 12 years

(a)

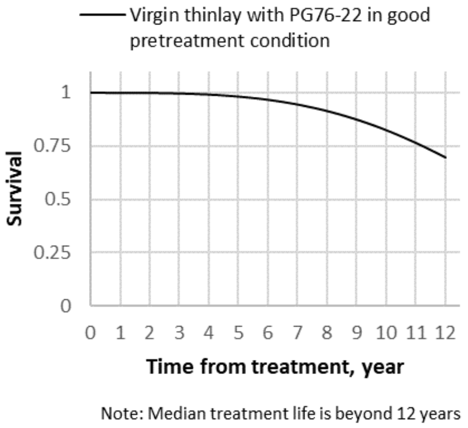
Note: Median treatment life is beyond 12 years

(b)

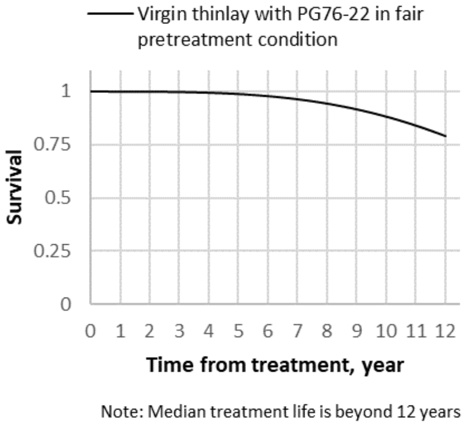
Note: Median treatment life is beyond 12 years

(c)

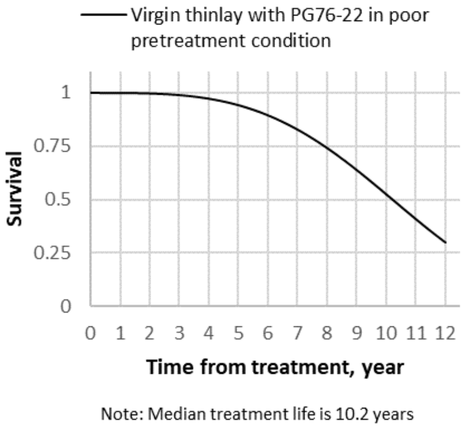
Figure B. 16 Survival curves for the virgin thin overlay over a foam recycled base in (a) good (b) fair, and (c) poor pretreatment condition.



(a)

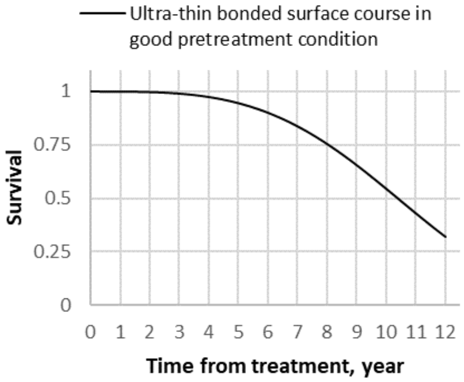


(b)



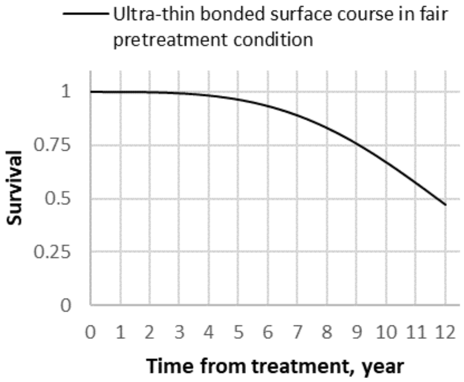
(c)

Figure B. 17 Survival curves for the virgin thin overlay with PG76-22 in (a) good (b) fair, and (c) poor pretreatment condition*.*



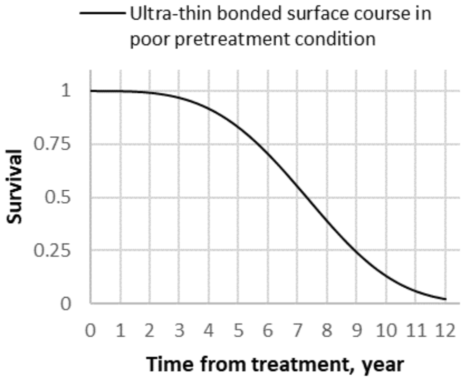
Note: Median treatment life is 10.4 years

(a)



Note: Median treatment life is 11.8 years

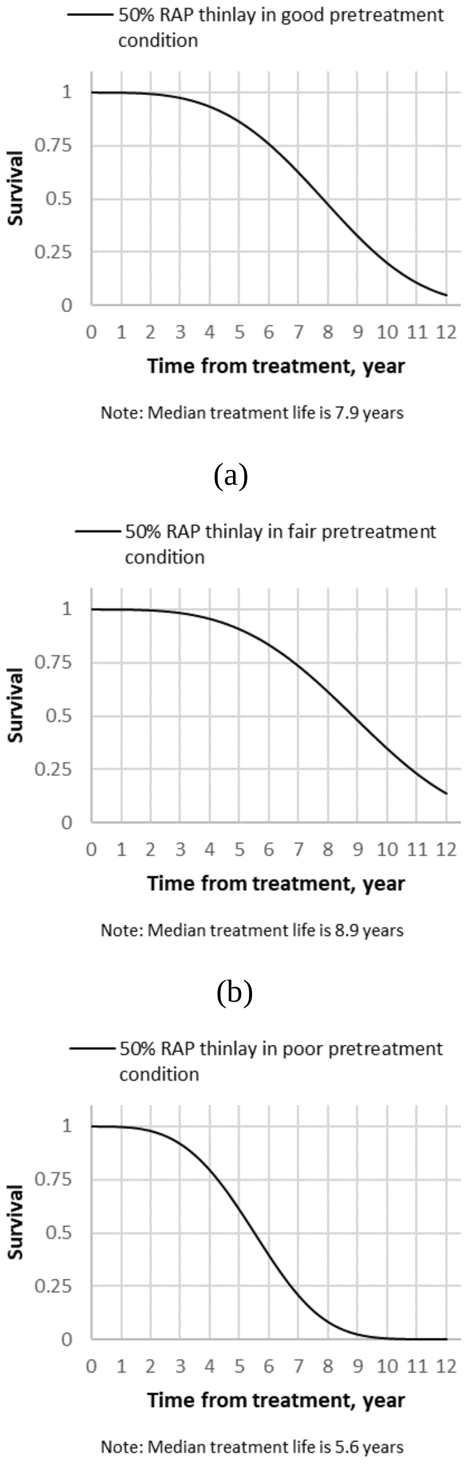
(b)



Note: Median treatment life is 7.4 years

(c)

Figure B. 18 Survival curves for the ultra-thin bonded surface course in (a) good (b) fair, and (c) poor pretreatment condition.



Note: Median treatment life is 7.9 years

(a)

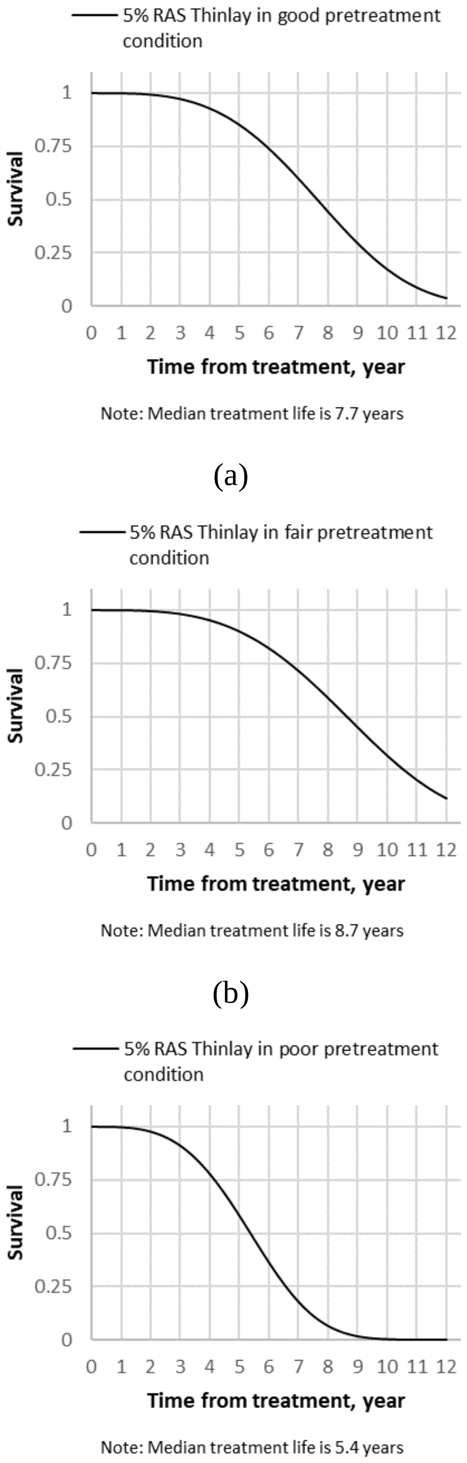
Note: Median treatment life is 8.9 years

(b)

Note: Median treatment life is 5.6 years

(c)

Figure B. 19 Survival curves for the 50% RAP thin overlay in (a) good (b) fair, and (c) poor pretreatment condition.



Note: Median treatment life is 7.7 years

(a)

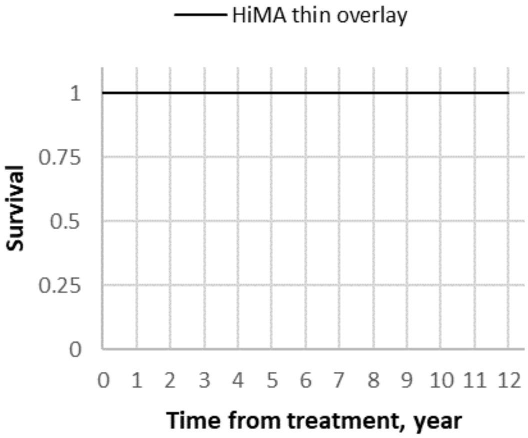
Note: Median treatment life is 8.7 years

(b)

Note: Median treatment life is 5.4 years

(c)

Figure B. 20 Survival curves for the 5% RAS thin overlay in (a) good (b) fair, and (c) poor pretreatment condition.



Note: Median treatment life is more than 12 years and the cracking performance is not influenced by the pretreatment condition or travel direction

Figure B. 21 Survival curves for the HiMA thin overlay section.

APPENDIX C

Markov generated TPMs for preservation treatment clusters in different pretreatment conditions

$$\begin{bmatrix} 0 & 0.999 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.999 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.178 & 0.538 & 0 & 0.182 & 0.102 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.201 & 0.654 & 0 & 0.145 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.208 & 0 & 0.519 & 0.272 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.758 & 0.242 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0.981 & 0 & 0.019 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.995 & 0.005 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.759 & 0.241 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

(a)

$$\begin{bmatrix} 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.104 & 0.104 & 0.229 & 0.104 & 0.354 & 0.104 & 0 & 0 & 0 \\ 0 & 0 & 0.426 & 0.205 & 0.125 & 0.125 & 0.118 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.911 & 0.024 & 0.024 & 0.04 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.773 & 0.023 & 0.179 & 0.025 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.754 & 0.246 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0.373 & 0.447 & 0.18 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.999 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.001 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

(b)

$$\begin{bmatrix} 0.001 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.001 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.5 & 0.5 & 0.001 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.501 & 0.5 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.001 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.252 & 0.749 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.999 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.5 & 0.5 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.128 & 0.872 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

(c)

Figure C. 1 TPMs for the untreated category for (a) ‘good’, (b) ‘fair’ and (c) ‘poor’ pretreatment conditions

$$\begin{bmatrix} 0.156 & 0.5 & 0.281 & 0.063 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.99 & 0.01 & 0.001 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.5 & 0 & 0.5 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.801 & 0.199 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.729 & 0 & 0.272 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.687 & 0.313 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0.712 & 0.288 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.531 & 0.469 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.87 & 0.13 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

(a)

$$\begin{bmatrix} 0.492 & 0.197 & 0.092 & 0 & 0.219 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.999 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.999 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.998 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.446 & 0.555 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0.001 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.999 & 0.002 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.001 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.999 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

(b)

$$\begin{bmatrix} 0.039 & 0.453 & 0.508 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.954 & 0.045 & 0.002 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.001 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.573 & 0.054 & 0.374 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.012 & 0.624 & 0.365 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.001 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0.889 & 0.111 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.5 & 0.5 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.876 & 0.124 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

(c)

$$\begin{bmatrix} 0 & 0.999 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.999 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.032 & 0.218 & 0.751 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.166 & 0.566 & 0 & 0.268 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.181 & 0.295 & 0.524 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.961 & 0 & 0.04 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.016 & 0.984 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.095 & 0.906 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.969 & 0.031 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

(d)

$$\begin{bmatrix} 0.277 & 0.146 & 0.188 & 0 & 0.25 & 0.139 & 0 & 0 & 0 & 0 \\ 0 & 0.75 & 0.001 & 0.25 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.903 & 0.098 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.501 & 0 & 0 & 0.5 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.001 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.001 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0.001 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.001 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.759 & 0.241 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

(e)

$$\begin{bmatrix} 0 & 0 & 0.999 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.017 & 0.908 & 0.009 & 0.001 & 0.001 & 0.064 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.999 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.104 & 0.62 & 0.104 & 0.172 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.172 & 0.21 & 0.247 & 0.371 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.955 & 0 & 0.045 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.001 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.979 & 0.021 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

(f)

Figure C. 2 TPMs for the light treatment applications cluster 1 for (a) ‘good’, (c) ‘fair’ and (e) ‘poor’ pretreatment conditions and for cluster 2 for (b) ‘good’, (d) ‘fair’ and (f) ‘poor’ pretreatment conditions

$$\begin{bmatrix}
0 & 0.969 & 0.031 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0.999 & 0.001 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0.999 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0.5 & 0.5 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0.003 & 0.998 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0.003 & 0.998 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0.568 & 0.433 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.384 & 0.617 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.599 & 0.401 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1
\end{bmatrix}$$

(a)

$$\begin{bmatrix}
0 & 0.75 & 0.25 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0.999 & 0.001 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0.758 & 0.242 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0.675 & 0.077 & 0.249 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0.001 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0.001 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0.764 & 0.236 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.406 & 0.594 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.721 & 0.279 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1
\end{bmatrix}$$

(b)

$$\begin{bmatrix}
0 & 0.938 & 0.063 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0.999 & 0.001 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0.875 & 0.125 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0.5 & 0.5 & 0.001 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0.016 & 0 & 0.985 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0.001 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0.001 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0.001 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.001 & 1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1
\end{bmatrix}$$

(c)

$$\begin{bmatrix}
0 & 0.75 & 0.25 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0.993 & 0.007 & 0.001 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0.797 & 0 & 0.203 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0.126 & 0.875 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0.003 & 0.998 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0.003 & 0.998 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0.684 & 0.317 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.001 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.613 & 0.387 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1
\end{bmatrix}$$

(d)

$$\begin{bmatrix}
0 & 0.875 & 0.125 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0.999 & 0.001 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0.75 & 0.25 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0.25 & 0.75 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0.001 & 0.999 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0.032 & 0.541 & 0.428 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0.001 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.001 & 1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.857 & 0.143 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1
\end{bmatrix}$$

(e)

$$\begin{bmatrix}
0 & 0.75 & 0.25 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0.999 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0.5 & 0.5 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0.889 & 0.019 & 0.092 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0.999 & 0 & 0 & 0.001 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0.998 & 0.002 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.982 & 0.019 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.043 & 0.958 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.999 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1
\end{bmatrix}$$

(f)

Figure C. 3 TPMs for the chip seal category cluster 1 for (a) ‘good’, (c) ‘fair’ and (e) ‘poor’ pretreatment conditions and for cluster 2 for (b) ‘good’, (d) ‘fair’ and (f) ‘poor’ pretreatment conditions

$$\begin{bmatrix} 0 & 0.969 & 0.031 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.999 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.999 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.5 & 0.5 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.75 & 0.25 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.627 & 0.374 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0.001 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.229 & 0.772 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.001 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

(a)

$$\begin{bmatrix} 0.082 & 0.508 & 0.32 & 0.09 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.991 & 0.005 & 0 & 0 & 0.004 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.928 & 0 & 0 & 0.072 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.069 & 0.354 & 0.577 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.001 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.001 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.502 & 0.499 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.001 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.999 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

(b)

$$\begin{bmatrix} 0 & 0.999 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.998 & 0.001 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.835 & 0.078 & 0.088 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.501 & 0 & 0.499 & 0.001 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.751 & 0.25 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.127 & 0.874 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0.127 & 0.874 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.001 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.001 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

(c)

$$\begin{bmatrix} 0.062 & 0.5 & 0.438 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.988 & 0.012 & 0.001 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.999 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.001 & 0.999 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0.001 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0.168 & 0.833 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0.929 & 0.072 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.958 & 0.043 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.952 & 0.048 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

(d)

$$\begin{bmatrix} 0 & 0.875 & 0.125 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.999 & 0.001 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.75 & 0.25 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.001 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.001 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.447 & 0.54 & 0.013 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0.426 & 0.575 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.562 & 0.438 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.853 & 0.147 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

(e)

$$\begin{bmatrix} 0.795 & 0.075 & 0.04 & 0.011 & 0.04 & 0.04 & 0 & 0 & 0 & 0 \\ 0 & 0.97 & 0 & 0 & 0 & 0 & 0.031 & 0 & 0 & 0 \\ 0 & 0 & 0.987 & 0 & 0 & 0 & 0.014 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.983 & 0 & 0 & 0.017 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.001 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.001 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0.006 & 0 & 0.995 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.001 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.852 & 0.148 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

(f)

Figure C. 4 TPMs for the micro surfacing category cluster 1 for (a) ‘good’, (c) ‘fair’ and (e) ‘poor’ pretreatment conditions and for cluster 2 for (b) ‘good’, (d) ‘fair’ and (f) ‘poor’ pretreatment conditions

$$\begin{bmatrix} 0 & 0.999 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.999 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

(a)

$$\begin{bmatrix} 0 & 0.969 & 0.031 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.999 & 0.001 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.5 & 0.5 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.003 & 0.998 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.001 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.151 & 0.801 & 0.048 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0.5 & 0.501 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.549 & 0.452 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.717 & 0.283 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

(b)

$$\begin{bmatrix} 0 & 0.999 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.999 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.906 & 0.031 & 0.031 & 0.031 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

(c)

$$\begin{bmatrix} 0 & 0.969 & 0.031 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.999 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.999 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.5 & 0.5 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.999 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.003 & 0.998 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0.753 & 0.248 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.001 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.633 & 0.367 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

(d)

$$\begin{bmatrix} 0 & 0.999 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.999 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

(e)

$$\begin{bmatrix} 0 & 0.999 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.999 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

(f)

Figure C. 5 TPMs for the cape seal category cluster 1 for (a) ‘good’, (c) ‘fair’ and (e) ‘poor’ pretreatment conditions and for cluster 2 for (b) ‘good’, (d) ‘fair’ and (f) ‘poor’ pretreatment conditions

$$\begin{bmatrix} 0 & 0.999 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.999 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

(a)

$$\begin{bmatrix} 0 & 0.875 & 0.125 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.994 & 0.006 & 0.001 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.5 & 0.5 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.999 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.999 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.5 & 0.5 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0.558 & 0.443 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.001 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.51 & 0.49 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

(b)

$$\begin{bmatrix} 0 & 0.999 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.999 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

(c)

$$\begin{bmatrix} 0 & 0.93 & 0.07 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.994 & 0.006 & 0.001 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.5 & 0.5 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.999 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.999 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.5 & 0.5 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0.627 & 0.374 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.001 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.435 & 0.565 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

(d)

$$\begin{bmatrix} 0 & 0.984 & 0.016 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.996 & 0.004 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.5 & 0.5 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.999 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.003 & 0.998 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.5 & 0.5 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0.525 & 0.476 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.001 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.298 & 0.702 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

(e)

$$\begin{bmatrix} 0 & 0.5 & 0.5 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.998 & 0.003 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.5 & 0.5 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.999 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.999 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.5 & 0.5 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0.627 & 0.374 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.001 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.457 & 0.543 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

(f)

Figure C. 6 TPMs for the thin overlay category cluster 1 for (a) ‘good’, (c) ‘fair’ and (e) ‘poor’ pretreatment conditions and for cluster 2 for (b) ‘good’, (d) ‘fair’ and (f) ‘poor’ pretreatment conditions