THE UNIVERSITY OF TEXAS AT AUSTIN
CENTER FOR TRANSPORTATION RESEARCH

TECHNICAL REPORT 0-6878-2
TXDOT PROJECT NUMBER 0-6878

Performance of Preventive Maintenance Treatments for Flexible Pavements in Texas

Pedro A. Serigos
Andre Smit
Jorge A. Prozzi

August 2016; Published March 2017

http://library.ctr.utexas.edu/ctr-publications/0-6878-2.pdf

Technical Report Documentation Page

1. Report No. FHWA/TX-16/0-6878-2	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Performance of Preventive Maintenance Treatments for Flexible Pavements in Texas		5. Report Date August 2016; Published March 2017 6. Performing Organization Code
7. Author(s) Pedro A. Serigos, Andre de Fortier Smit, and Jorge A. Prozzi		8. Performing Organization Report No. 0-6878-2
9. Performing Organization Name and Address Center for Transportation Research The University of Texas at Austin 1616 Guadalupe Street, Suite 4.202 Austin, TX 78701		10. Work Unit No. (TRAIS) 11. Contract or Grant No. 0-6878
12. Sponsoring Agency Name and Address Texas Department of Transportation Research and Technology Implementation Office P.O. Box 5080 Austin, TX 78763-5080		13. Type of Report and Period Covered Technical Progress Report Sept 2015 to Aug 2016 14. Sponsoring Agency Code
15. Supplementary Notes Project performed in cooperation with the Texas Department of Transportation and the Federal Highway Administration.		

16. Abstract

This report documents the work performed in the first year of the Texas Department of TxDOT Project 0-6878. The main objective of this project is to quantify the effectiveness of various popular preventive maintenance (PM) treatments under varying conditions toward optimizing their design and application. The work conducted in the first year is divided into two main parts.

The first part consists of an evaluation of the effectiveness of different PM treatments through a model-based approach using pavement sections included in the Specific Pavement Study (SPS)-3 experiment of the Federal Highway Administration (FHWA) Long-Term Pavement Performance (LTPP) program. For this analysis, the effectiveness of the different PM treatments was assessed and ranked using statistical analysis and modelling of the performance response of a set of treated and non-treated (control) pavement sections. The proposed model aimed to explain the relationship between the loss in serviceability rate as a function of treatment type along with pavement, traffic, climate conditions, and their interaction with the PM treatment effectiveness.

The second part estimates the effective life of PM treatments of in-service flexible pavements located throughout Texas through the statistical analysis and modelling of TxDOT databases that include more than twenty years of relevant design, construction, and performance data of maintenance and rehabilitation (M&R) works. The preliminary analysis focused on the three most popular PM treatment types: chip seals, microsurfacing, and thin overlays. The effective life of these treatments is estimated using survival analysis techniques as a function of the underlying pavement characteristics and external influences with regard to traffic and climate.

17. Key Words Preventive Maintenance; Chip Seal; Thin Overlay; Microsurface;	18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161; www.ntis.gov.

19. Security Classif. (of report)	20. Security Classif. (of this page)	21. No. of pages	22. Price
Unclassified	Unclassified	TBD	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

Performance of Preventive Maintenance Treatments for Flexible Pavements in Texas

Pedro A. Serigos
Andre Smit
Jorge A. Prozzi

CTR Technical Report:	0-6878-2
Report Date:	August 2016; Published March 2017
Project:	0-6878
Project Title:	Accelerating Innovation in Partnered Pavement Preservation
Sponsoring Agency:	Texas Department of Transportation
Performing Agency:	Center for Transportation Research at The University of Texas at Austin

Project performed in cooperation with the Texas Department of Transportation and the Federal Highway Administration.

Center for Transportation Research
The University of Texas at Austin
1616 Guadalupe, Suite 4.202
Austin, TX 78701

http://ctr.utexas.edu/

Disclaimers

Author's Disclaimer: The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the Federal Highway Administration or the Texas Department of Transportation (TxDOT). This report does not constitute a standard, specification, or regulation.

Patent Disclaimer: There was no invention or discovery conceived or first actually reduced to practice in the course of or under this contract, including any art, method, process, machine manufacture, design or composition of matter, or any new useful improvement thereof, or any variety of plant, which is or may be patentable under the patent laws of the United States of America or any foreign country.

Engineering Disclaimer

NOT INTENDED FOR CONSTRUCTION, BIDDING, OR PERMIT PURPOSES.

Project Engineer: Jorge A. Prozzi

Acknowledgments

The authors express appreciation to all personnel from the Texas Department of Transportation that contributed to this research project and provided the research team with useful guidance and continuous support. In particular, we would like to thank Wade Odell from the Research and Technology Implementation Office. In addition, the following people are acknowledged for their technical contribution and advice: Doug Eichorst II (DE Lubbock District), Magdy Mikhail, Robin Huang (Maintenance Division), and Gisel Carrasco (Construction Division).

Table of Contents

List of Figures

List of Tables

Chapter 1. Introduction

This report documents the work performed in the first full year of the Texas Department of Transportation (TxDOT) Research Project 0-6878. The main objective of this project is to quantify the effectiveness of various popular preventive maintenance (PM) treatments under varying conditions toward optimizing their design and application. The work conducted in the first year is divided into two main parts. The first part analyzes the field performance of different PM treatments using a nationwide database, whereas the second part estimates the effective life of PM treatments using TxDOT data.

The report is organized in three chapters. The first chapter provides a brief introduction to and the motivation for this study. The second and third chapters describe the analyses of PM treatments' performance and duration conducted using both national and Texas data, along with a description of the future work planned for meeting the goals of the study.

1.1 Preventive Maintenance of Flexible Pavements

The condition of a pavement decreases over time due to the combined effect of traffic and climate until it reaches the limit of its serviceability levels; at this point a maintenance and rehabilitation (M&R) treatment is applied, suddenly increasing the serviceability level back to a high value (Figure 1.1). Theoretically, the rate at which a pavement surface deteriorates increases with time as the structure weakens due to the progression of distresses (e.g., cracking) and to changes in the material properties arising from wetting and freezing, among other factors. PM refers to a series of treatments that slow the deterioration of the pavement surface without necessarily increasing its structural capacity. These treatments are applied when the pavement surface is still in good condition in order to prevent higher damage rates and, thus, extend the service life of the pavement.

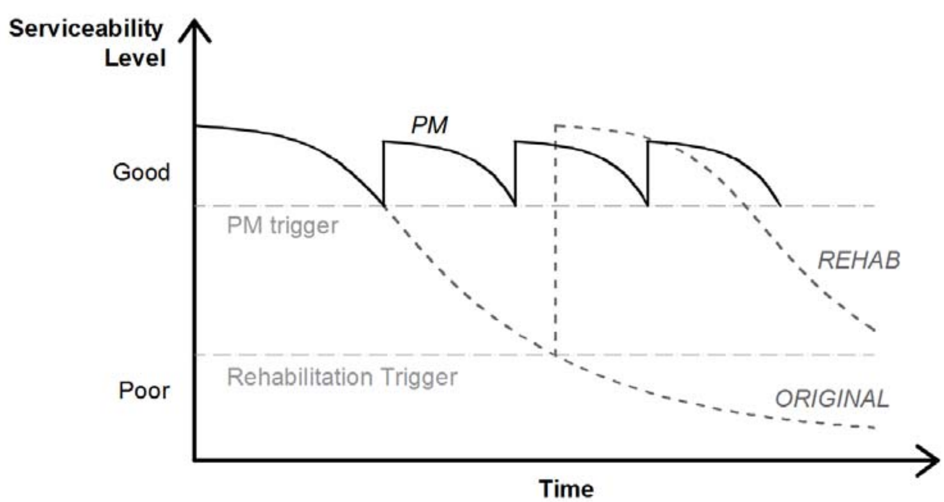


Figure 1.1: Theoretical Pavement Performance Curve for Different M&R Strategies

A number of PM treatments are available, including crack seals, thin overlays, chip seals, microsurfacing, cold in-place recycling, ultrathin friction course, fog seals, slurry seals, cape seals, and scrub seals. While some of these are interim measures are applied as stop-gaps before full rehabilitation, others are designed to provide extended service life. In contrast to conventional rehabilitation strategies, PM treatments are used on existing pavements with reduced remaining life. Therefore, these treatments will be subject to the pre-existing failure mechanisms of the underlying pavement, which may serve to accelerate deterioration and reduce the effectiveness of the PM treatment. The rate of deterioration of these treatments will vary depending on the condition or state of the underlying pavement but also other factors, including the quality of the treatment applied and the external influences of traffic and climate. For this reason, research is needed to provide a better understanding of the effectiveness of different preventative maintenance techniques and how these are impacted by different influence factors.

The next sections of this chapter provide a brief description of some of the most popular PM treatments applied in Texas.

1.1.1 Crack Sealing

Crack sealing is defined by TxDOT as "the application of sealing material directly in the cracks of the pavement surface (Figure 1.2) to prevent moisture damage" (TxDOT 2016 b). The sealing materials consist of a mixture of a neat or modified binder and its application aims to defer the deterioration of exiting cracks, minimize the erosion of the mixture, and reduce the amount of water available to saturate the base materials (David 2001).

Figure 1.2: Application of Crack Sealing (Sims 2016)

1.1.2 Seal Coat (or Chip Seal)

TxDOT defines seal coat as "a spray application of binder immediately covered by a single layer of one-sized aggregates. Seal coat can be placed in either single or multiple layers" (TxDOT 2016 b). The binder is applied by a bituminous distributer, and the aggregate is placed by an aggregate spreader then followed by the pass of a pneumatic roller (Figure 1.3). The rolling operation is intended to seat the aggregate into the binder and ensure chip retention. This PM treatment is also commonly referred to as "Chip Seal" and it is usually applied on low volume roadways to eliminate raveling, retard oxidation, reduce the intrusion of water, improve surface friction and seal cracks

(David 2001). The number of layers applied depends mainly on the condition of the pavement surface being treated (Figure 1.4).

Figure 1.3: Application of seal coat (left) and rolling operation (right) (TTI, 2015)

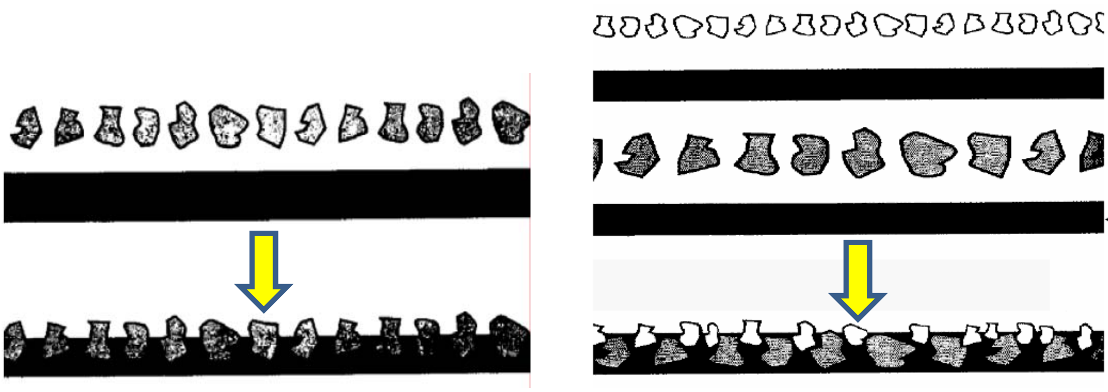


Figure 1.4: Single-layer (left) and Multilayer (right) Seal Coat Application (Caltrans, 2007)

1.1.3 Thin Hot-Mix Overlays

According to TxDOT definition, thin hot-mix overlays “are similar to conventional overlays except the thickness is 2 inches or less [Figure 1.5]. Generally, thin hot-mix overlays can correct irregularities that cannot be corrected with most other types of preventive maintenance” (TxDOT 2016 b). This treatment is applied using conventional construction methods (Figure 1.6) and is usually categorized as dense, open, or gap-graded depending on the aggregate gradation. Thin overlays are typically applied to protect the pavement structure, reduce the rate of pavement deterioration. and reduce permeability. They are also applied to improve the ride quality of the pavement, particularly when accompanied by a scratch course or surface milling (David 2001).

Figure 1.5: Layer of Thin Hot-mix Overlay (TTI, 2012)

Figure 1.6: Application of Thin Hot-mix Overlay (TTI, 2012)

1.1.4 Microsurface

Microsurface consists of the application of a thin surface, cold-applied paving mixture composed of polymer-modified asphalt emulsion, crushed aggregate, mineral filler, water, and other additives (David 2001). A self-propelled continuous loading machine or a truck-mounted machine is used to proportion and mix the materials and apply the mixture to the pavement surface (Figure 1.7). Microsurfaces are commonly applied to retard modeling raveling and oxidation, reduce the intrusion of water, improve surface friction, and remove minor surface irregularities (Sims 2016).

Figure 1.7: Application of Microsurface (Sims 2016)

1.1.5 Fog Seals

According to TxDOT definition, fog seals consist of "bitumen materials sprayed directly on the surface of the existing pavement (Figure 1.8). This treatment enriches the surface of the pavement edges and can prevent the loss of aggregates and seal coat" (TxDOT 2016 b). In addition, fog seals are commonly applied to improve surface appearance, seal, or waterproof (David 2001).

Figure 1.8: Application of Fog Seal (TxDOT, 2010)

Chapter 2. Estimation of Treatments' Deterioration Rate Using LTPP SPS-3 Data

This chapter documents the preliminary analysis performed to quantify the effectiveness of different PM treatments through a model-based approach using pavement sections included in the Specific Pavement Study-3 (SPS-3) experiment of the Federal Highway Administration (FHWA) Long-term Pavement Performance (LTPP) program.

For this analysis, the effectiveness of the different PM treatments was assessed and ranked through the statistical analysis and modelling of the performance response of a set of treated and non-treated (control) pavement sections. The pavement sections for the analyses were selected in order to address replication of all influence factors in terms of the pre-existing condition of the underlying pavement, quality of the treatment applied, traffic (in terms of volume, axle loads, and speed), and climate (in terms of temperature and rainfall). The proposed model aimed to explain the relationship between the loss in serviceability rate as a function of treatment type along with pavement, traffic, and climate conditions as well as their interaction with the PM treatment effectiveness. The models presented in this chapter will be adapted and estimated using TxDOT data.

2.1.1 Background

The LTPP SPS-3 experiment was designed to assess the effectiveness of PM treatments on flexible pavements and to evaluate the optimum timing to apply the treatments. This experiment considered four different PM treatments: thin hot-mix asphalt overlay (TH), slurry seal (SS), chip seal (CH), and crack seal (CS). These PM treatments were applied to consecutive sections of the road along with non-treated (control) sections at 81 sites located in the United States and Canada during the early 1990's. Thus, each site consisted of five consecutive sections all subjected to the same traffic loads, structure, and environmental conditions. Some of the experimental design factors considered for the SPS-3 experiment included four climatic regions and two subgrade types; however, the combinations of treatments were not considered.

A number of studies have used data from LTPP SPS-3 experiment to assess the effectiveness of PM treatments, adopting different performance indices and implementing methodologies that included multiple regression analysis (Morian et al. 1998), survival analysis (Eltahan et al. 1999; Morian et al. 2011), and various statistical comparison techniques (Hall et al. 2003; Shirazi et al. 2010; Morian et al. 2011). Although the previous studies provide information on the relative effectiveness of treatments, the authors believe that the use of a regression analysis to develop a model can be further explored.

The preliminary analysis presented in this chapter quantifies the effectiveness of PM treatments through a model-based approach using censored regression. The proposed approach overcomes limitations of previous studies in that it allows for comparing the treatment effectiveness for a particular experimental factor while controlling for the remaining factors and producing more robust estimates of the treatment's marginal effect. In addition, the proposed model specification accounts for more variables and more realistic assumptions than the previous regression analyses found in the literature.

2.1.2 Literature Review

In 1998, Morian et al., applied multi-variable regression analysis data on five-year SPS-3 data to evaluate the PM treatment performance. This study modeled different performance indicators in terms of treatment type, environmental zone, age, and initial condition among other factors. In the regression analysis, the independent variables were specified as integer indicator codes ranked from worst to best. The study concluded that TH had a significant effect in rutting and roughness reduction while the remaining PM treatments had slight or no effect. However, the researchers' assumption on the rank of each independent variable resulted in biased parameters, not capturing the true marginal effects of the different PM treatments.

One year later, Eltahan et al. (1999) conducted survival analysis to evaluate the life expectancy and the effect of the original pavement condition. The authors estimated the failure probabilities of each treatment with respect to the original condition of the test sections using the Kaplan-Meier method. The study concluded that applying treatment to sections in poor condition increased the risk of failure by two to four times, and that CH outperformed the other four treatments.

In 2003, Hall et al. evaluated the initial and long-term effect of the different PM treatments on the pavement condition as well as the influence of pre-treatment condition and other experimental factors. The initial effect of the treatment was evaluated by comparing pre- and post-treatment measurements of roughness, rutting, and fatigue cracking, whereas the long-term effect was evaluated by comparing the last measurement for treated sections with the corresponding measurement for control sections. The comparisons were carried out using two-sided multiple comparisons with the control section and paired t-tests. The study concluded that the most effective treatment in SPS-3 experiment was TH, followed by CS and SS. Only TH produced an initial reduction and a significant long-term effect on roughness.

Another study conducted in 2003 by Chen et al. studied 14 SPS-3 test sites in Texas to investigate the effectiveness of PM treatments. The study concluded that CH was the best performer among the four analyzed PM treatments, followed by TH. Although the study presents a detailed discussion of the PM treatment effects on Texas specific sites, the results from the comparison were not based on statistical methods. In addition, factors such as subgrade type, moisture, and temperature were not taken into account.

In 2010, Shirazi et al. used Friedman tests and non-parametric randomized block analysis of variance to compare the performance of the different PM treatments for different levels of temperature, precipitation, subgrade, traffic, and initial condition. The performance indicator used in this study was the weighted average of distresses normalized by the period of analysis, which allowed for comparing different data collection periods. However, it did not take into account the deterioration rate and its trend. The study concluded that TH was the most effective treatment, whereas the effect of SS and CS was not statistically significant.

A more recent study in 2011 conducted by Morian et al. applied survival analysis on twenty-year SPS-3 data to assess life expectancy of the PM treatments; it also applied Friedman tests in order to compare structural effects of the treatments. The results from the survival analysis indicated that TH performed best at high-survival probabilities, whereas CH performed best for the case of low-survival probabilities. The Friedman test results showed that the structural benefits from all treatments (except for CS) were significant.

Lastly, Haider and Dwaikat (2011) estimated the optimum timing for PM treatment by maximizing the difference between the areas below the roughness curves for pre- and post-treated pavements. The International Roughness Index (IRI) value was modeled as a function of age using an exponential function. The effects of traffic, environmental, and subgrade factors were not taken into account in the analyses, and the study did not include a comparison between treatments.

2.2 Description of Damage Rate Model and Data

2.2.1 Damage Rate Model Specification

The main goal of developing a pavement damage rate model is two-fold: 1) to accurately predict the damage of a pavement section between data collection periods; and 2) to unveil the underlying intricate relationships between the pavement properties and the damage rate, which will allow for quantifying the effect of the different PM treatments. The pavement damage rate (DR) was defined as the loss in serviceability per unit traffic, and it was computed as the ratio between the change in IRI value and the increment in traffic demand observed between data collection dates, as expressed in Equation 2.1.

$$DR_{i,\Delta t} = \Delta IRI_{i,\Delta t} / \Delta N_{i,\Delta t} \tag{2.1}$$

where,
$DR_{i,\Delta t}$: Damage Rate for section i and period of analysis Δt, in m/km/kESAL
$\Delta IRI_{i,\Delta t}$: Change in IRI, in m/km
$\Delta N_{i,\Delta t}$: Increment in traffic, in kESAL
i: sub-index to indicate pavement section number
Δt: sub-index to indicate period between roughness data collection dates

The DR model in this study was specified as a linear combination of a number of explanatory variables that included the PM treatment types as well as influence structural, environmental, and traffic factors. The variables selected to explain the pavement DR are presented in Equation 2.2. A variable for temperature was not included in the model specification in order to avoid multi-collinearity issues due to its high correlation with the freezing index in the used dataset.

$$\begin{aligned} \boldsymbol{X}_{i,\Delta t} = [\, & TH_i, CH_i, SS_i, CS_i, AC_i, BA_i, SB_i, SG_i, \\ & log\left(N_{i,\Delta t}\right), FrInd_i, Precip_i, PreDam_i \,] \end{aligned} \tag{2.2}$$

Where:
$\boldsymbol{X}_{i,\Delta t}$: Vector of explanatory variables
TH: Application of Thin Overlay, equal to 1 for TH treatment and 0 otherwise
CH: Application of Chip Seal, equal to 1 for CH treatment and 0 otherwise
SS: Application of Slurry Seal, equal to 1 for SS treatment and 0 otherwise
CS: Application of Crack Seal, equal to 1 for CS treatment and 0 otherwise
AC_i: Total thickness of asphalt layers, in mm
BA_i: Total thickness of base layers, in mm
SB_i: Total thickness of sub-base layers, in mm
SG_i: Sub-grade type, equal to 0 for fine soil and 1 for coarse soil
$N_{i,\Delta t}$: Cumulated traffic until the period of analysis Δt, in kESAL

$FrInd_i$: Annual Average Freezing Index, in degrees Celsius (°C) degree-days
$Precip_i$: Annual Average Precipitation, in mm
$PreDam_i$: Measured IRI value of the section when the treatment was applied, in m/km.

The explanatory variables related to cumulated traffic or to age were log-transformed, allowing, thus, for non-linear relationship between damage rate and time. Furthermore, it should be noted from Equation 2.1 that DR is the first derivative of the roughness curve with respect to traffic for the case of an infinitesimal period of analysis. Therefore, the proposed DR linear model specification captures the observed non-linear trend of the pavement serviceability curve as a function of traffic, while allowing for the analytical convenience of estimating a linear model.

Censored Regression Model

Theoretically, DR is a non-negative random variable given that pavement roughness is expected to either increase or remain constant as a function of traffic. Therefore, the DR values computed from the data were censored, allowing only for positive values (i.e. censoring the observations for which the roughness decreased after the pavement was subjected to traffic loads for a period of time). The observed negative change in roughness between data collection periods is explained, in part, by measuring equipment error.

As observed in the data, the large portion of censored DR values corresponding to data points with no significant change in serviceability invalidates the conventional regression assumptions and would result in biased ordinary least squares (OLS) estimates. In order to properly account for the censored values, DR was modelled by adopting a type I Tobit model structure. This model structure is a particular case of censored regression, which is typically used for handling dependent variables dominated by a particular response (in this case, zeros). A standard Type I Tobit specification for our DR model is described in Equations 2.3, 2.4, and 2.5 (Wooldridge 2010).

$$DR_{i,\Delta t} = max\left(0, DR^*_{i,\Delta t}\right) \tag{2.3}$$

$$DR^*_{i,\Delta t} = \boldsymbol{X}'_{i,\Delta t}\boldsymbol{\beta} + u_{i,\Delta t} \tag{2.4}$$

$$u_{i,\Delta t} \sim Normal(0, \sigma^2) \tag{2.5}$$

Where:
DR^*_i: Latent damage rate
$\boldsymbol{X}_{i,\Delta t}$: Vector of explanatory variables
$\boldsymbol{\beta}$: Vector of regression coefficients
$u_{i,\Delta t}$: Idiosyncratic error term
σ: Standard deviation of the error term

The Tobit model is similar to a linear regression model except that the model recognizes the dichotomization of the dependent variable into zero and non-zero sets. This model allows for estimating the probability of a pavement section to exhibit zero-roughness change, which is useful in identifying the factors that contribute to maintaining a fairly unchanged pavement serviceability for a period of time. Moreover, the estimated regression parameters corresponding to the explanatory variables will be unbiased.

The predicted DR for a particular pavement section i and period time Δt is given by the expected value of the DR for a given set of explanatory variables, and estimated as shown in Equation 2.6. In addition, the probability of a pavement section to remain unchanged in terms of IRI is computed as shown in Equation 2.7.

$$E\left(DR_{i,\Delta t}|\boldsymbol{X}_{i,\Delta t}\right) = \Phi\left(\frac{\boldsymbol{X}'_{i,\Delta t}\boldsymbol{\beta}}{\sigma}\right)\boldsymbol{X}'_i\boldsymbol{\beta} + \sigma\phi\left(\frac{\boldsymbol{X}'_{i,\Delta t}\boldsymbol{\beta}}{\sigma}\right) \quad (2.6)$$

$$P\left(DR_{i,\Delta t} = 0\middle|\boldsymbol{X}_{i,\Delta t}\right) = 1 - \Phi\left(\frac{\boldsymbol{X}'_{i,\Delta t}\boldsymbol{\beta}}{\sigma}\right) \quad (2.7)$$

Where:
$\phi(\cdot)$: Probability density function of standard normal distribution
$\Phi(\cdot)$: Cumulative distribution function of the standard normal distribution

As observed in Equation 2.6, the explanatory variables are non-linearly related to the DR prediction; as such, the interpretation of the regression parameters, $\boldsymbol{\beta}$, is not straightforward. We used econometric elasticity to examine the sensitivity of explanatory variables on the pavement DR. Econometric elasticity, or marginal effect (for indicator variables), is defined as the change in the explained value per unit change in the explanatory variable while keeping the remaining variables fixed. Equation 2.8 was used to estimate the econometric elasticity of a continuous variable x_j, whereas Equation 2.9 was used to estimate the marginal effect of a binary variable x_r.

$$\frac{\partial E(DR|\boldsymbol{X})}{\partial x_j} = \Phi\left(\frac{\boldsymbol{X}'\boldsymbol{\beta}}{\sigma}\right)\beta_j \quad (2.8)$$

$$\frac{\partial E(DR|\boldsymbol{X})}{\partial x_r} = \frac{E\left(DR_{i,\Delta t}|(X_1,\ldots,X_r=1,\ldots,X_n)\right) - E\left(DR_{i,\Delta t}|(X_1,\ldots,X_r=0,\ldots,X_n)\right)}{1-0} \quad (2.9)$$

Both the magnitude and the corresponding standard errors of the aforementioned Tobit model parameters were obtained through maximum likelihood estimation (MLE) using R programming language (R Core Team 2014) employing the AER package (Kleiber and Zeileis 2015). A final specification was chosen carefully based on a rigorous model development process. Model refinement was carried out through exclusion of statistically insignificant variables by following standard stepwise procedures and statistical tests (e.g., F-test). Practical considerations played a role in the removal of insignificant variables rather than solely adopting a statistics-based mechanical approach. The results from the proposed Tobit regression model is presented in the following section of the chapter.

2.2.2 Processing of LTPP SPS-3 Dataset

The data used for estimating the proposed DR censored regression model was collected for the LTPP SPS-3 experiment and obtained from the Standard Data Release (SDR) version 29 (LTPP InfoPave 2015). The main filtering criteria applied to the original dataset consisted of considering only the pavement sections containing at least one computed annual number of equivalent single axle loads (ESAL) during the years for which the SPS-3 experiment was conducted. The computed annual number of ESALs was obtained from the "TRF_ESAL_COMPUTED" table, and was estimated from monitored axle data (Elkins et al. 2003). Traffic data estimated from other sources were filtered out in order to make use only of the best quality of data available for estimating the model.

The change in IRI values, $\Delta IRI_{i,\Delta t}$ (Equation 2.1), was computed as the difference between consecutive IRI measurements. Therefore, only sections with at least two roughness measurements collected during the SPS-3 experiment were considered for the study. The resulting dataset after applying the two mentioned filters included data at sixty-four SPS-3 sites (each site containing multiple pavement sections), which locations are shown in Figure 2.1. As observed from Figure 2.1, the filtered SPS-3 sites covered the different climatic regions in the study.

Figure 2.1: Location of LTPP SPS3 Sections Used in the Study

In addition, the increment in traffic values, $\Delta N_{i,\Delta t}$ (Equation 2.1), were estimated as the sum of all annual number of ESALs corresponding to section i, weighted by the proportion of time falling within the period of analysis Δt. The annual number of ESALs for the years with missing traffic data were estimated as the mean of the set of computed annual number of ESALs for the corresponding section.

Lastly, the values for cumulated traffic until the period of analysis, $N_{i,\Delta t}$ (Equation 2.2), were computed as the sum of all preceding increments of traffic ($\Delta N_{i,\Delta t}$) for the corresponding pavement section. The remaining explanatory variables from Equation 2.2 were extracted from the original dataset without further processing.

2.3 Results from Estimation of Damage Rate Models

2.3.1 PM Treatments' Marginal Effects

The model proposed for assessing the effectiveness of PM treatments followed the Tobit model structure presented in Equations 2.3, 2.4, and 2.5, with the latent damage rate specified as in Equation 2.10, where the pavement DR is expressed as a function of the PM treatment type along with structural, environmental, and traffic variables. Thus, the DR model is able to properly handle the significant portion of zero (censored) values in the distribution of the dependent variable, and it allows for estimating the marginal effect of the different treatments while accounting for multiple experimental variables simultaneously.

$$\begin{aligned} DR^*_{i,\Delta t} = {} & \beta_0 + \beta_{AC}AC_i + \beta_{BA}BA_i + \beta_{SB}SB_i + \beta_{SG}SG_i + \\ & \beta_{logN}\, log\left(N_{i,t}\right) + \beta_{logN}\, log\left(N_{i,t}\right) + \beta_{FrInd}FrInd_i + \\ & \beta_{Precip}Precip_i + \beta_{TH}TH_i + \beta_{CH}CH_i + \beta_{SS}SS_i + \beta_{CS}CS_i + \\ & u_{i,\Delta t} \end{aligned} \tag{2.10}$$

The model in Equation 2.10 was specified without interaction terms and using the control sections as the base; therefore, it was used to quantify the global marginal effect of the PM treatments with respect to non-treated pavements. The marginal effects of each treatment were quantified as in Equation 2.9, using the estimated parameters of the model and fixing the remaining variables at their mean value. In addition, the model specification was modified and estimated using the different treatments as the base indicator variables, one at a time, in order to rank the effectiveness of the different treatment strategies.

The estimated PM treatments' marginal effects are presented in Table 2.1, where each column corresponds to the models using the different indicator variables as the base. The negative sign on the marginal effect of every PM treatment relative to the control sections indicates that all of the treatments had, on average, a smaller damage rate than non-treated sections. Therefore, all treatments helped to slow down the loss in serviceability for any given combination of cumulated traffic, environmental, and structural factors.

The results from the models using different treatments as the base allowed researchers to perform pair-wise comparisons between the effectiveness of each pair of treatments and to rank the four PM treatments from most to least effective. From the comparison among the different treatments, none of the marginal effects were statistically significant (represented with a zero value in Table 2.1). Therefore, although all PM treatments were superior to non-treated sections, there was not enough evidence to determine which treatment was the most effective. Despite the statistically insignificant differences among the four treatments' effectiveness, the first column of Table 2.1 suggest that TH and CH were more efficient than SS and CS, with TH being the most efficient treatment.

The marginal effects from Table 2.1 can be used to estimate the expected difference in IRI for a given increment in traffic, ΔN. For example, at 79 kESALs per year, the median annual increment of traffic in the dataset, a pavement section treated with a thin overlay would present 0.43 m/km (27 in/mile) less IRI after five years of constant traffic than if the section would not have been treated. Clearly, the beneficial impact of applying the treatment will be more noticeable for sections with higher traffic levels and longer period of analysis.

Table 2.1: Marginal effect of PM treatments for the global model in Equation 2.10 using different base treatments.

	Marginal Effect of PM treatment [m/km/kESAL]				
	base = Co	*base = TH*	*base = CH*	*base = SS*	*base = CS*
Co	-	1.10E-03	0.96E-03	0.67E-03	0.79E-03
TH	-1.10E-03	-	0.00	0.00	0.00
CH	-0.96E-03	0.00	-	0.00	0.00
SS	-0.67E-03	0.00	0.00	-	0.00
CS	-0.79E-03	0.00	0.00	0.00	-

2.3.2 Impact of Preexisting Damage and Environmental Factors on PM Treatments' Effectiveness

The next step consisted of evaluating what variables in our dataset affect the effectiveness of the PM treatments in order to determine the optimal conditions for treating the pavement. For this, the latent DR variable from the Tobit model was used to study the global marginal effects of the PM treatments (Equation 2.10) and was modified by adding interaction terms to the treatment indicator variables as shown in Equation 2.11. The $PreDam_i$ variable incorporated into the new specification consists of the measured IRI value of the section when the treatment was applied; it is an indicator of the preexisting damage of the pavement. The main effect of the preexisting damage variable was not included in the model since it is not defined for the case of non-treated sections. Therefore, the new specification, estimated using censored regression, allowed for quantifying the effectiveness of each PM treatment as a function of the section's freezing index, precipitation, and preexisting damage.

$$\begin{aligned} DR^*_{i,\Delta t} = {} & \beta_0 + \beta_{AC}AC_i + \beta_{BA}BA_i + \beta_{SB}SB_i + \beta_{SG}SG_i + \\ & \beta_{logN}\, log\big(N_{i,t}\big) + \beta_{FrInd}FrInd_i + \beta_{Precip}Precip_i + \\ & \beta_{TH}TH_i + \beta_{CH}CH_i + \beta_{SS}SS_i + \beta_{CS}CS_i + TH_i\big[\beta_{TH} + \\ & \beta_{TH.FrInd}FrInd_i + \beta_{TH.InDam}PreDam_i + \\ & \beta_{TH.Precip}Precip_i\big] + CH_i\big[\beta_{CH} + \beta_{CH.FrInd}FrInd_i + \\ & \beta_{CH.InDam}PreDam_i + \beta_{CH.Precip}Precip_i\big] + \\ & CS_i\big[\beta_{CS} + \beta_{CS.FrInd}FrInd_i + \beta_{CS.InDam}PreDam_i + \\ & \beta_{CS.Precip}Precip_i\big] + SS_i\big[\beta_{SS} + \beta_{SS.FrInd}FrInd_i + \\ & \beta_{SS.InDam}PreDam_i + \beta_{SS.Precip}Precip_i\big] + u_{i,\Delta t} \end{aligned} \qquad (2.11)$$

Table 2.2 presents the MLE estimates, the p-values, and the mean elasticity of the parameters with a significant effect on the pavement DR. The parameters in Equation 2.11 not included in Table 2.2 were not statistically significant and therefore removed from the final model specification, except for the parameters β_{SG} and $\beta_{CS.PreDam}$. The results show that neither the main effect of the section’s freezing index nor its interaction with any of the PM treatments were statistically significant. Furthermore, the main effect of the precipitation variable was also not significant, indicating that the section’s annual mean precipitation does not have a significant effect on the control sections; however, data suggests that precipitation affects the effectiveness of the PM treatments.

The effect of the structural layer thicknesses and their relative importance were as expected. A statistically significant negative effect suggests that thicker layers are associated with slower deterioration of the pavement. The effect of the asphalt layer thickness was the most significant followed by the base thickness. The negative sign of the parameter on the subgrade variable reflects the slower DR of coarse subgrade relative to finer, and the expected difference is quantified by its marginal effect equal to -7.70E-04 m/km/kESAL. Finally, the parameter on the log of the cumulated traffic, which accounts for the effect of the pavement age, was negative and statistically significant. Therefore, the relationship between roughness and traffic demand was non-linear and the pavement DR decreases with time.

Regarding the interaction parameters of the model, it is observed that both the section’s preexisting damage and annual mean precipitation affected the effectiveness of the PM treatment as measured by the difference in damage rate relative to the non-treated sections. The positive sign of the parameters on the interaction terms between PM treatments and pavement preexisting damage indicates that PM treatment effectiveness decreases with the increase of initial IRI value. Therefore, the PM treatments were more effective when applied on sections with less preexisting damage. This observation reinforces the main purpose of applying PM, which is not to add structural capacity to the pavement but to delay structural failure. Furthermore, the effectiveness of CH and CS were less affected by the preexisting condition than for TH and SS treatments. Lastly, the negative sign of the parameters on the interaction terms between PM treatments and the precipitation variable indicates that all PM treatments were more effective when applied on sections with higher mean annual precipitation. This observation suggests the importance of the surface sealing provided by the PM treatments, which reduces the weakening of the pavement structure due to the presence of water and thereby slowing down the pavement DR.

Table 2.2: MLE estimates, p-value, and mean elasticities of parameters from the model with interactions (Equation 2.11).

	coeff	*p-value*	*elasticity*
$\boldsymbol{\beta_0}$	1.30E-02	0.000	-
$\boldsymbol{\beta_{AC}}$	-7.31E-06	0.041	-1.00E-04
$\boldsymbol{\beta_{BA}}$	-6.39E-06	0.006	-8.74E-05
$\boldsymbol{\beta_{SB}}$	-4.13E-06	0.003	-5.64E-05
$\boldsymbol{\beta_{SG}}$	-8.14E-04	0.129	-7.70E-04
$\boldsymbol{\beta_{logN}}$	-1.43E-03	0.000	-1.00E-04
$\boldsymbol{\beta_{TH.PreDam}}$	2.30E-03	0.045	1.16E-03
$\boldsymbol{\beta_{CH.PreDam}}$	1.03E-03	0.053	5.64E-04
$\boldsymbol{\beta_{SS.PreDam}}$	2.04E-03	0.005	1.10E-03
$\boldsymbol{\beta_{CS.PreDam}}$	1.00E-03	0.190	5.50E-04
$\boldsymbol{\beta_{TH.Precip}}$	-5.49E-06	0.000	-2.78E-06
$\boldsymbol{\beta_{CH.Precip}}$	-3.82E-06	0.000	-2.08E-06
$\boldsymbol{\beta_{SS.Precip}}$	-4.92E-06	0.000	-2.65E-06
$\boldsymbol{\beta_{CS.Precip}}$	-2.98E-06	0.038	-1.63E-06

The effect of the section's preexisting damage and annual mean precipitation on the PM treatment effectiveness are illustrated in Figures 2.2 and 2.3. The predicted IRI values for a pavement section with mean structural and environmental conditions and fine subgrade were calculated as shown in Equation 2.12, derived from Equation 2.1, and Equation 2.6.

$$\widehat{IRI}_t = IRI_0 + \sum\nolimits_0^t E[DR_{\Delta t}|\boldsymbol{X}]\Delta N_{\Delta t}$$
$$= IRI_0 + \sum\nolimits_0^t \left[\Phi\left(\frac{\overline{\boldsymbol{X}}'_{\Delta t}\widehat{\boldsymbol{\beta}}}{\hat{\sigma}}\right)\widehat{\boldsymbol{X}}'_{\Delta t}\widehat{\boldsymbol{\beta}} + \sigma\phi\left(\frac{\overline{\boldsymbol{X}}'_{\Delta t}\widehat{\boldsymbol{\beta}}}{\hat{\sigma}}\right)\right]\Delta N_{\Delta t} \qquad (2.12)$$

Where:
$\widehat{IRI}_{\mathrm{t}}$: Predicted IRI value at time t,
IRI_0: Initial IRI value
$\overline{\boldsymbol{X}}_{\Delta t}$: Explanatory variables set to the cumulated traffic for the period of analysis, fine subgrade and mean values for the remaining variables.
$\widehat{\boldsymbol{\beta}}$: MLE estimates (Table 2.2) from censored regression of model with interactions
$\hat{\sigma}$: Estimated standard deviation of the model's error term

Figure 2.2 shows the predicted IRI curves corresponding to each PM treatment and control for two levels of mean annual precipitation: the 75th (solid lines) and the 25th (dashed lines) percentiles. All other explanatory variables were fixed to their mean value and fine subgrade. Since control has been found to be not significantly affected by the mean annual precipitation, its IRI curve for both precipitation levels overlap. As noted from Figure 2.2, all treatment levels lay below the control curve and, therefore, the application of the treatment slowed down the evolution of the roughness. Furthermore, the greater effectiveness of the PM treatments on wet areas noted from the interpretation of the model's parameters is reflected by the greater distance between the PM treatment curves and the control curve for the case of higher mean annual precipitation.

Figure 2.3 shows the predicted IRI curves corresponding to each PM treatment and control for two preexisting serviceability levels: the 15th (dashed lines) and 85th (solid lines) percentiles of initial IRI value. Since this variable affects only the sections with PM treatment, the control curves for both preexisting condition levels are parallel and shifted by the difference in initial IRI value. From the figure it is observed that the distance between the control curve and the PM treatments is greater for the case with lower initial IRI, which illustrates the greater effectiveness of the treatment when applied on smoother pavements.

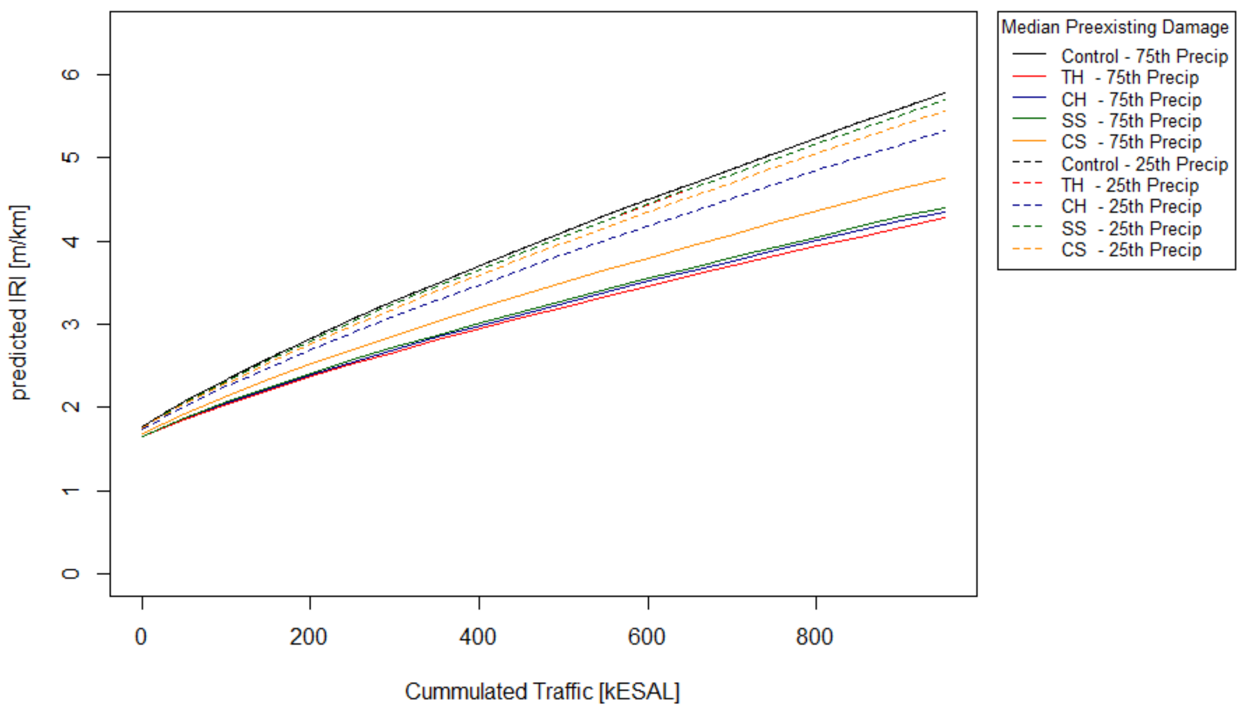


Figure 2.2: Comparison of Predicted IRI Curves for High and Low Annual Precipitation

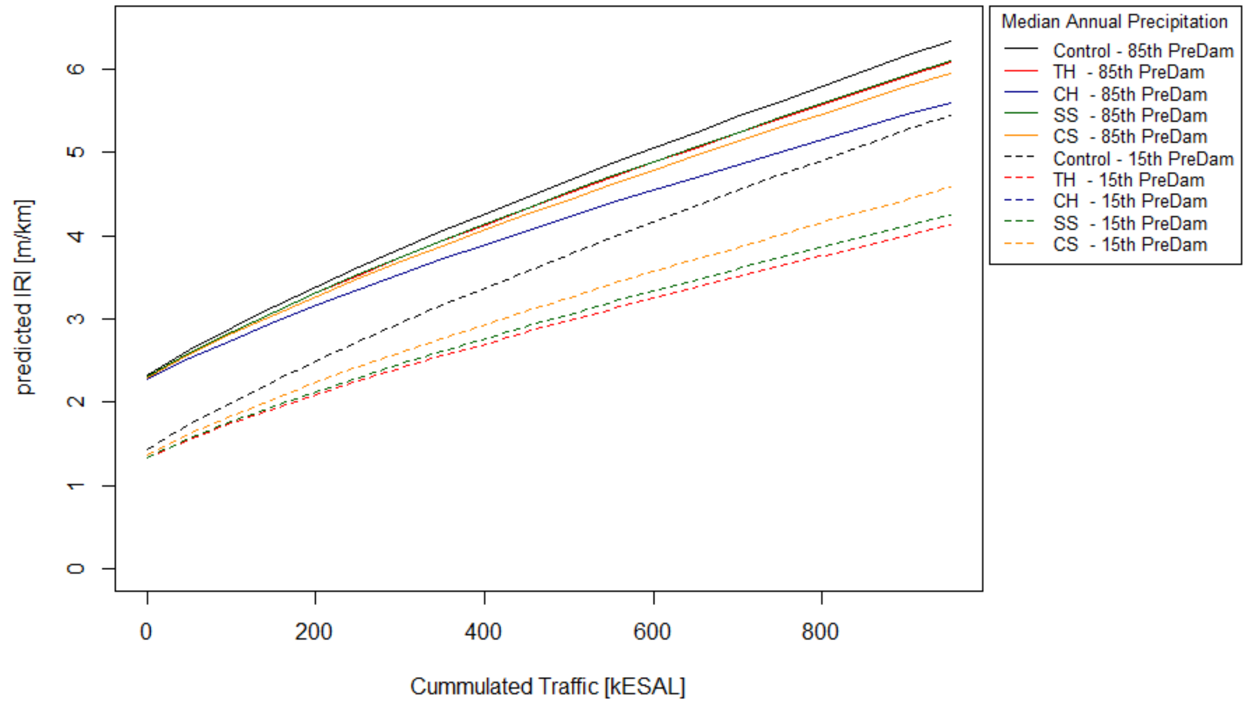


Figure 2.3: Comparison of Predicted IRI Curves for High and Low Preexisting Damage Values

2.4 Preliminary Summary and Conclusions

This chapter reports the preliminary analyses to study the effectiveness of four PM treatments applying a censored regression model-based approach using data collected for the LTPP SPS-3 experiment. The effectiveness of the PM treatments was evaluated as the difference in pavement damage rate relative to the non-treated sections, where damage rate was defined as the loss in serviceability (as measured by the IRI) per unit traffic. The damage rate model was specified as a function of the PM treatment type along with various experimental variables and followed a type 1 Tobit model structure in order to properly account for the significant portion of observations with censored DR.

The developed censored regression model allowed for estimating unbiased marginal effects of the different PM treatments accounting for multiple influence factors simultaneously. In addition, the study assessed the interaction between the treatments' effectiveness and the different experimental factors in order to determine the optimal conditions for treating the pavement.

The main observations and conclusions are the following:

- All four PM treatments presented slower serviceability loss relative to non-treated sections on an average base for any given combination of cumulated traffic, environmental, and structural factors.
- TH and CH were more efficient than SS and CS in slowing down the evolution of pavement roughness relative to non-treated sections on an average base; however, the differences among treatments were not statistically significant.

- The estimated global marginal effects for the PM treatments ranged between -0.67E-03 m/km/kESAL (for SS) and -1.10E-03 m/km/kESAL (for TH). This marginal effect resulted in 0.43 m/km (27 in/mile) to 0.26 m/km (16 in/mile) less IRI than if the section would not have been treated, after five years of median annual traffic and for an average pavement section.
- The effectiveness of the PM treatments was affected by the annual mean precipitation and by the pre-existing damage of the pavement but it was not significantly affected by the section's average freezing index.
- All PM treatments except CS were significantly more effective when applied on sections with less preexisting damage. This observation reinforces the main purpose of applying PM, which is not to add structural capacity to the pavement but to delay its structural failure.
- All four PM treatments were significantly more effective when applied on sections with higher mean annual precipitation. This observation may be explained by the effect of the surface sealing provided by the PM treatments, which reduces the weakening of the pavement structure due to the presence of water.

Chapter 3. Estimation of Treatments' Life Using TxDOT Data

This chapter documents the preliminary processing and analysis of TxDOT databases containing historical M&R and pavement performance data to evaluate the effectiveness of popular PM treatments in Texas. The effectiveness of these treatments, which include CH or seal coats, microsurfacing (MS), TH, and fog seals (FS), among others, is evaluated through the estimation of their duration as a function of the underlying pavement characteristics, quality of applied treatment, and external influences with regard to traffic and climate.

3.1 Data and Methodology to Evaluate PM Duration in Texas

In order to evaluate the effectiveness of different popular PM treatments in Texas, the research team is processing a number of TxDOT databases that include more than 20 years of relevant design, construction, and performance data of M&R works. TxDOT maintains around 90,000 centerline miles (one-way direction roadbed miles) of roadway. This roadway network comprises the following pavement surface types: 51% asphalt concrete, 41% surface treatments, and 8% Portland cement concrete. Among asphalt concrete pavements, 28% are less than 2.5-inch thick; therefore, more than half of the network (55%) consists of surface treatments and thin asphalt pavements, both of which are relevant to this study.

Every year TxDOT collects and stores pavement roughness and surface distress data throughout the Texas roadway network, assessing 0.5-mile long roadway sections and recording the findings in a pavement management information system (PMIS). Surface condition data for the more than 193,000 PMIS sections are used for predicting future pavement performance, estimating, and allocating budget needs, and designing M&R strategies, among other managerial decisions. As an example, Figure 3.1 shows the pavement condition throughout time for a surface treatment section on Farm to Market (FM) Road 774, located in Refugio County. Pavement condition at each point in time is expressed by the PMIS Condition Score (CS), which combines ride quality and surface distress severity and extent into an index that ranges from 0 to 100, where 100 indicates best condition. A pavement surface is considered in good condition by TxDOT if the CS is above 70. It should be noted from Figure 3.1 that each time a CH was applied, the pavement was still in good condition, as intended when performing PM.

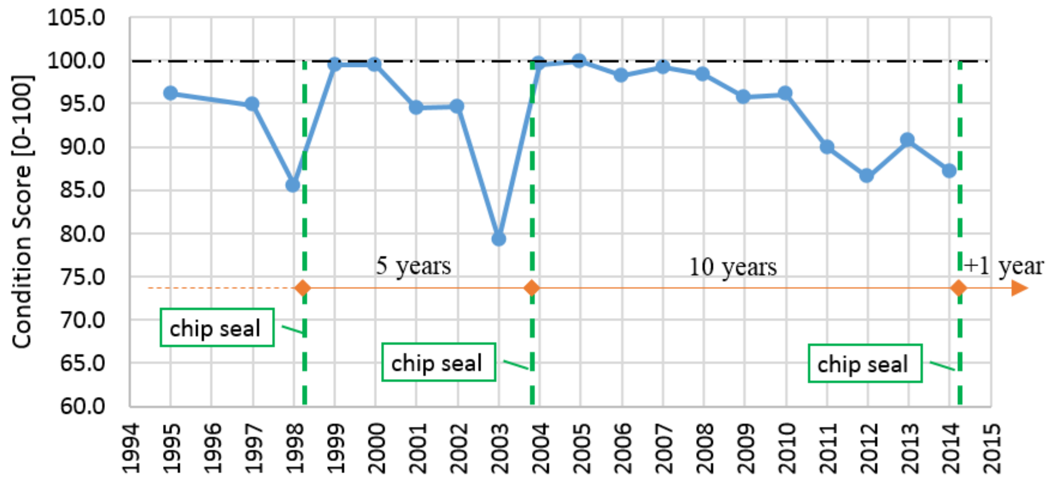


Figure 3.1: Performance and M&R History Data of Flexible Pavement on FM774, Texas

The elapsed time between applying the treatment and applying another surface over it is an indicator of the treatment's effectiveness. This duration time does not discriminate between reactive (i.e., in response to surface condition) and scheduled work; however, it provides an estimate of the treatment's "effective life" based on realistic field pavement data. For instance, the seal coat applied in 2003 (Figure 3.1) lasted approximately twice as long as the one applied in 1998. The longer effective life can be explained by the selected materials and construction procedures of the applied treatment, the condition of the underlying pavement (time of application), and the amount and type of traffic loads and environmental conditions to which the treated pavement has been exposed during those years. Statistical analysis of historical pavement performance and M&R data will provide realistic estimates of the different PM treatment's life spans, accounting for relevant influence factors.

3.2 Processing of TxDOT databases

The proposed approach requires the development of a database containing the relevant design, construction, and performance data of PM treatments. This section describes the progress on the processing and merging of a number of existing databases extracted from TxDOT's various information systems, such as the Design and Construction Information System (DCIS), SiteManager, the Maintenance Management Information System (MMIS), Compass, and PMIS.

TxDOT databases containing M&R project-related information can be divided into two groups regarding data formatting and content. The first group, which includes DCIS and SiteManager, contains data from contracted projects, while the second, which includes MMIS and Compass, contains data from internal or in-house projects performed by TxDOT personnel. Data from the first group contains more detailed information and has been processed to a greater extent by the research team.

DCIS has "as designed" information for contracted projects, as well as cost-tracking information; SiteManager has "as constructed" information. Both databases contain important information for our analysis and complement each other. For instance, DCIS contains information regarding the design of the work, such as the selected materials, that is not included in SiteManager. On the other hand, SiteManager data has been used in this study to confirm that a project appearing in DCIS has been completed and provides more detailed information regarding the completion date of the work. Compass includes information regarding TxDOT internal M&R projects from FY 2012 to the present. Information from previous years is archived in MMIS databases.

The main objective of processing the aforementioned databases consists of extracting location, date, and design-related information for each PM project. The following sections describe the main criteria applied to extract these pieces of information from the M&R contracted works data, as well as the processing of other databases to extract information regarding external factors.

3.2.1 Location

Every TxDOT-contracted M&R work is assigned a unique number referred to as the Control Section Job (CSJ). A CSJ consists of a nine-digit number, where the first six digits correspond to the Control Sections (CSec) in which the job was performed and the last three digits identify the job. Each CSec, assigned for maintenance purposes, refers to a unique segment of roadway in the TxDOT highway network. As an example, Figure 3.2 shows a number of CSecs (colored lines) located near the town of Refugio, Texas. CSec 0047-04 (blue line) is located on State Highway 202, between U.S. Route 183 and the Bee County line.

In most cases, the M&R job does not extend over the entire CSec. Therefore, the location of each contracted work is defined by the CSec and by a beginning and an ending point located within the CSec. The location of both limiting points for each CSJ is contained in DCIS in descriptive language (as in the majority of cases), such as “0.7 mi S of LP 256 in Palestine” or “Begin curb and gutter in Frankston”,” or as defined by the distance to a highway reference marker (RM), such as “210+0.21,” which indicates that the limiting point of the job is located 0.21 miles after RM 210 on the highway’s direction of travel. Having location information of the CSJ in descriptive language requires manual processing of the data, which is not practical considering the size of the databases. Therefore, the analysis will include only CSecs that have all their CSJs with distance-to-RM information. It should be mentioned that the researchers manually determined the distance-to-RM information of approximately 300 CSJs using the descriptive sentence-form location data in order to increase the number of projects for particular PM treatments, such as TH and MS.

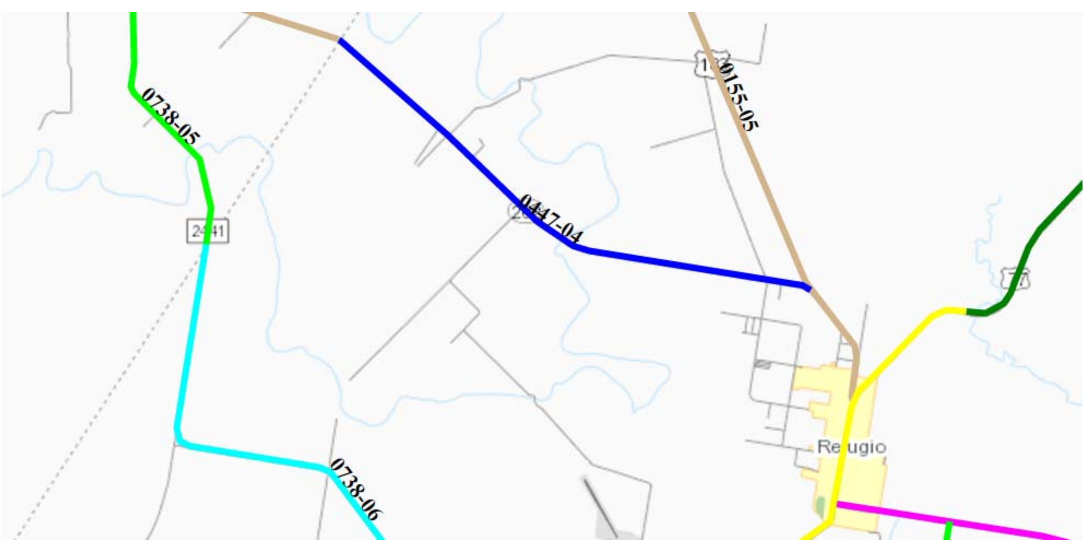


Figure 3.2: Screenshot of TxDOT Statewide Planning Map (TxDOT, 2016)

The location of a CSJ might overlap, at least partially, other CSJs applied at different points in time, resulting in segments of the roadway with different M&R history. Figure 3.3 illustrates this situation where the black lines show the location limits of three CSJs applied within the same CSec in 1998, 2006, and 2012, respectively. The overlapping segments of these three M&R works results in five different stretches of road with a different number of treatments applied (e.g., the segment between 212-0.56 and 216+0.10 had two M&R works while the segment between 216+0.10 and 218-0.18 had three). Therefore, each CSec in our data was segmented, as shown in Figure 3.3.

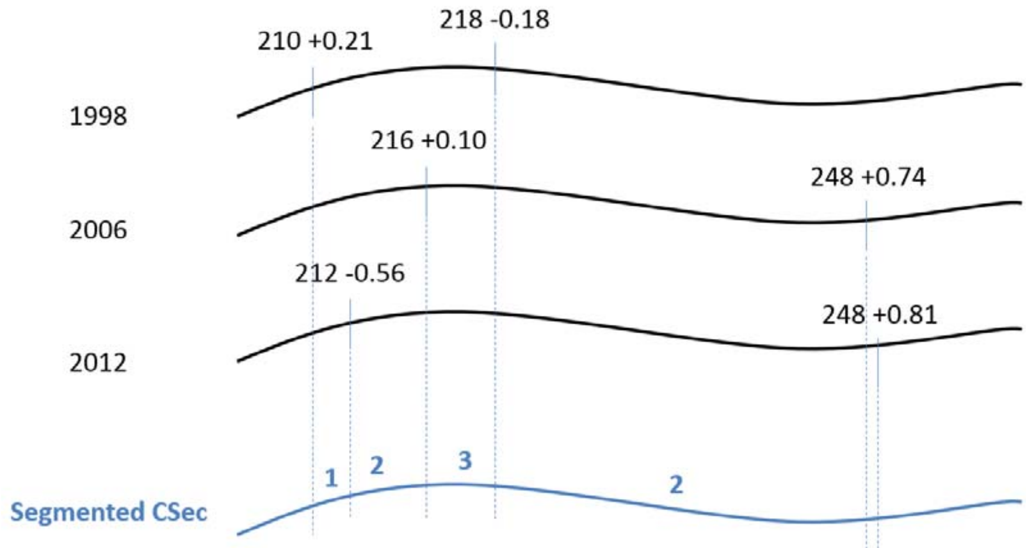


Figure 3.3: Segmenting of TxDOT Control Sections

3.2.2 Timeline

The starting time of a PM treatment life span was defined in our study as the date at which the surface treatment was completed and opened to traffic. The completion date for each CSJ was directly extracted from a SiteManager database. Similarly, the ending time of the PM treatment life span (if observed) was defined as the completion date of the next M&R job applied to the same pavement surface. The cases in which no other M&R work occurred after a PM treatment were marked as censored observations for the survival analysis and their ending time was arbitrarily defined as 07/26/2015. This ending date was chosen because it falls at least 30 days after the latest CSJ completion date in the available data.

Once the starting and ending times for each CSJ were extracted from the databases with contracted projects, each ending time was corrected, if necessary, using information from internal works data. For this, M&R information extracted from contracted works data from MMIS databases was used to check if internal jobs were performed during the service life of each PM treatment and, if there were, to correct the ending date of the corresponding CSJ as the earliest internal M&R work applied during the PM treatments' life span. Therefore, the extracted data for analysis includes information from both contracted and internal works.

3.2.3 Work Type

The next essential piece of information to extract after the date and location information of each CSJ was the type of treatment applied. Every CSJ in DCIS comprises one or multiple items, each of them related to a TxDOT standard specification (SSp). As an example, Table 3.1 shows fields from a DCIS database, including the SSp and the specification year of each item for four different CSJs. The analyzed dataset included TxDOT SSps corresponding to the specifications from 1982, 1993, 1995, 2004, and 2014. TxDOT SSps related to PM treatments are, for example, 316 for seal coats or CH, 315 for FS, 350 for MS, and 247 for TH (TxDOT 2014), in addition to a large number of special specifications and provisions.

The work type of each CSJ was determined by analyzing the assigned SSps, as well as the job descriptions. For instance, both the SSp number (316) and the description of the single item assigned to CSJ 047907004 indicate that the job consisted of applying a CH. This example illustrates a case for which defining the treatment type was straightforward. Potential complications arise when multiple items are assigned to the same CSJ or when the information provided in the job description is not clear enough to determine the work type.

An example where the item information suggests that the work type does not correspond to a PM treatment is given by CSJ 039901009. As shown in Table 3.1, this CSJ has seven items assigned, which include SSps corresponding to a surface treatment, a prime coat, a dense-graded hot-mix asphalt (HMA), and a milling job; its description indicates that the job consisted of road widening. In this case, the seal coat is placed beneath the HMA layer, per TxDOT standard practice, to provide an impermeable barrier to prevent moisture ingress into the underlying flexible base layer and to improve adhesion between the HMA and granular base layers. It was important to distinguish these rehabilitation projects from those where the seal coat is placed on the surface as a PM treatment.

Table 3.1: SS and other information used to determine the CSJ's work type.

csj	descr	compdate	SS	spec_yr
039901009	CCSJ: 020202015 | WORK: WIDEN ROADWAY | FROM:...	20090917	316	4
039901009	CCSJ: 020202015 | WORK: WIDEN ROADWAY | FROM:...	20090917	316	4
039901009	CCSJ: 020202015 | WORK: WIDEN ROADWAY | FROM:...	20090917	316	4
039901009	CCSJ: 020202015 | WORK: WIDEN ROADWAY | FROM:...	20090917	310	4
039901009	CCSJ: 020202015 | WORK: WIDEN ROADWAY | FROM:...	20090917	316	4
039901009	CCSJ: 020202015 | WORK: WIDEN ROADWAY | FROM:...	20090917	340	4
039901009	CCSJ: 020202015 | WORK: WIDEN ROADWAY | FROM:...	20090917	354	4
047907005	CCSJ: 000501094 | WORK: SEAL COAT PROGRAM | FR...	20020924	316	93
047907005	CCSJ: 000501094 | WORK: SEAL COAT PROGRAM | FR...	20020924	316	93
047907004	CCSJ: 007502020 | WORK: SEAL COAT | FROM: PECOS...	19950907	316	95
166302011	CCSJ: 004801062 | WORK: SEAL COAT,PVMT MKGS | ...	20131002	316	4
166302011	CCSJ: 004801062 | WORK: SEAL COAT,PVMT MKGS | ...	20131002	316	4
166302011	CCSJ: 004801062 | WORK: SEAL COAT,PVMT MKGS | ...	20131002	316	4
166302011	CCSJ: 004801062 | WORK: SEAL COAT,PVMT MKGS | ...	20131002	316	4

3.2.4 External Factors

The external factors processed for the preliminary analysis include three variables: temperature, precipitation, and traffic. Temperature and precipitation data were extracted from the latest release of the National Oceanic and Atmospheric Administration (NOAA) 30-year Climate Normals (NOAA 2016). Climate Normals consist of 30-year averages of climatological values (Arguez et al. 2012). The temperature and precipitation values assigned to each treated pavement section consisted of the average Normals of all weather stations for the corresponding county. The average climatic values computed for each county in Texas are presented in Figure 3.4. The mean annual temperatures range from 55 to 75 degrees Fahrenheit (north-to-south) and the annual total precipitations range from 10 to 60 inches per year (west-to-east).

The effect of traffic was incorporated in the preliminary analysis through the average number of ESALs applied to the pavement section during the life of the PM treatment. This information was extracted from a PMIS database and its processing consisted of identifying and averaging the PMIS sections located within the analyzed treated section. In addition to these climatic and traffic variables, the research team is currently processing PMIS data to extract more explanatory variables related to the pre-existing condition and type of the underlying pavement surface, as well as more detailed information regarding the quality of the applied PM treatment.

The pre-existing condition of the pavement will be characterized by the last CS of the surface before applying the treatment. As for the surface type of the underlying pavement, PMIS identifies the surface of each 0.5-mile long section using a 10-group category system. The main limitation of this category system is that some of the relevant surface types are not descriptive enough for the purpose of this study.

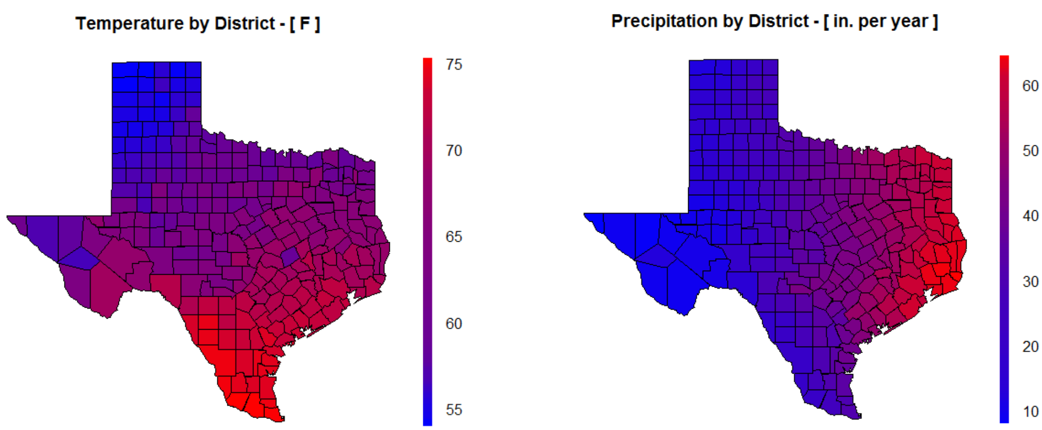


Figure 3.4: Counties' Temperature and Precipitation (NOAA's Climate Normals)

3.3 Preliminary Analysis

This section reports the preliminary analysis performed on the PM data processed to date. These data contain approximately 20 years of M&R works information, including three PM treatment types (CH, TH, and MS). The more than 10,000 PM-treated sections included in this preliminary analysis are spread throughout Texas, including the majority of the 254 Texas counties (Figure 3.5), thus covering the different climatic regions of the state and a wide range of traffic levels and highway characteristics.

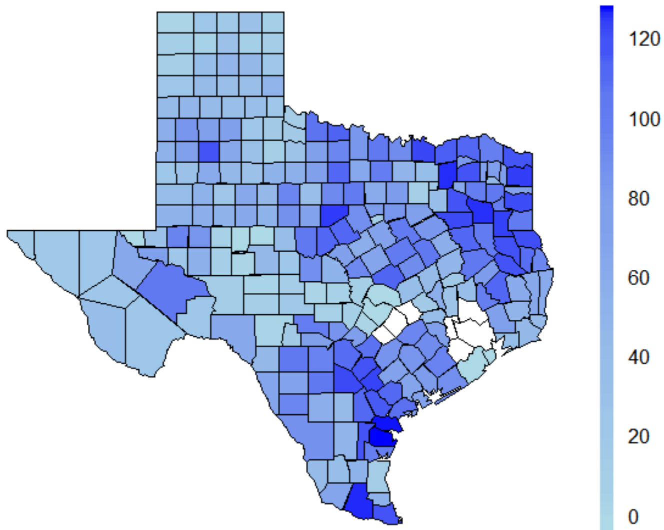


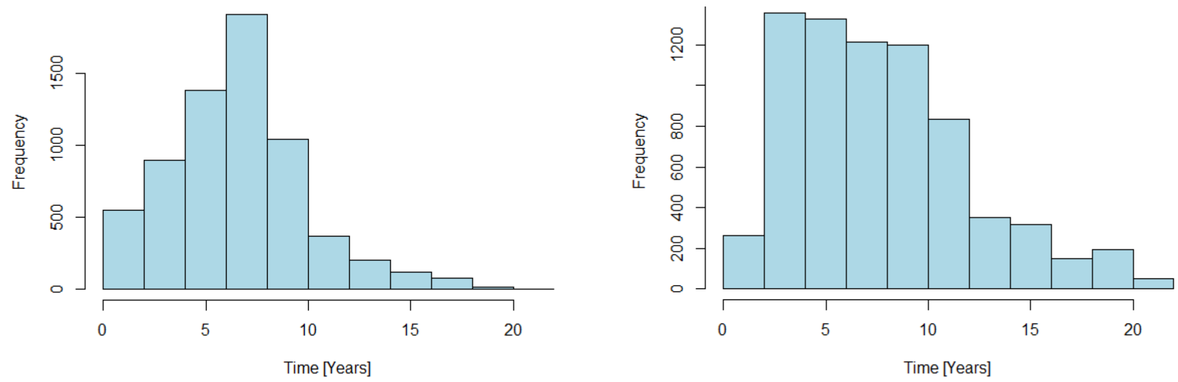
Figure 3.5: Number of PM Projects per County Included in the Analysis

3.3.1 PM Treatment's Effective Life

The treatment's effective life was defined in this study as the time lapse between the application of the treatment and when another surface is applied over it. To estimate the effective life of each PM treatment, we conducted survival analysis using the processed TxDOT data. Survival analysis allows for including the cases for which "death" or end-of-service life has not yet been observed (i.e., treated pavement sections that have not been resurfaced by the latest data collection date). These cases are referred to as censored observations and including them in our analysis will provide more robust estimates of the treatment's effective life.

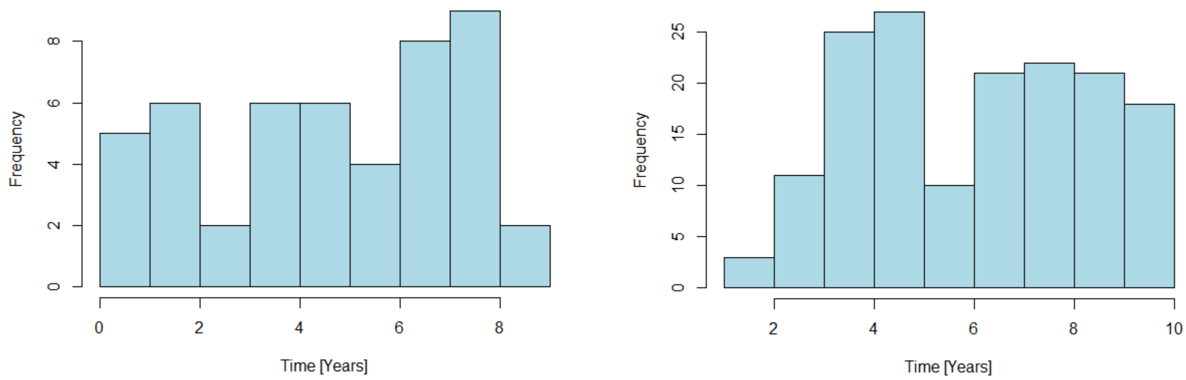
Figures 3.6, 3.7, and 3.8 show histograms of the observed (on the left) and the censored (on the right) effective lives for the three PM treatments analyzed. Among the histograms with PM projects whose end-of-service life has been observed, the effective lives of CHs and MS present heavier left tails while TH present a less concentrated distribution. The histograms with censored effective lives show higher dispersion, with the majority of the observations being shorter than 12 years.

The number of observations, as well as the median, mean, and quartiles of the observed effective life distribution for each PM treatment, are reported in the first five columns of Table 3.2. In addition, the modes (i.e., most frequent effective life observed) of each of these three distributions are 6.97 years, 3.20 years, and 6.77 years for CH, MS, and TH, respectively. It should be noted that a common criteria used by TxDOT District engineers for applying a surface treatment is age, with seven years being a common age threshold for scheduling a treatment. The multimodal distribution of the TH might reflect the different behavior of the surfaces categorized into the TH group (e.g., ultra-thin overlays, crack attenuating mixtures, porous friction courses, etc.) for this preliminary analysis, and it is also explained by the smaller number of observations available for TH projects.



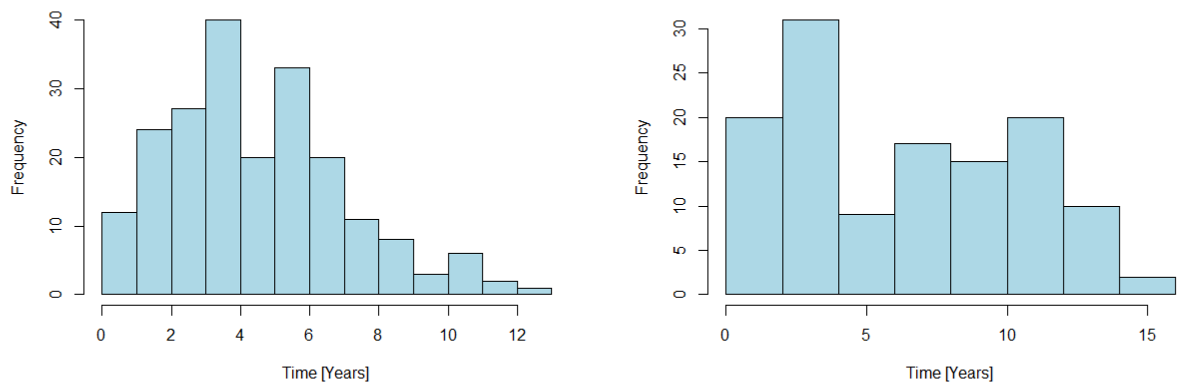
Observed Effective Life Censored Effective Life

Figure 3.6: Histograms of CH Effective Life



Observed Effective Life Censored Effective Life

Figure 3.7: Histograms of TH Effective Life



Observed Effective Life Censored Effective Life

Figure 3.8: Histograms of MS Effective Life

The cases with durations of less than two years observed for the three PM treatments is unexpected and will be further analyzed by the research team. A potential explanation suggested by a TxDOT engineer refers to stage-construction projects where the treatment layers are applied at different points in time, usually a few months apart, and input as different projects in their databases. Other potential explanations are poor performance of the treatments, inaccuracies in location data, or high levels of traffic. Projects with long durations are explained by not registering M&R works performed between the analyzed years—e.g., missing data, exceptional performance of the treatment, or low M&R funding levels, among other causes.

PM Treatments' Survival Curve

Figure 3.9 shows the Kaplan-Meier (K-M) survival curves for the three analyzed PM treatments. This non-parametric technique incorporates both observed and censored observations to analyze the PM effective lives. Each point of the survival curve indicates the probability of the treated surface to last at least a given number of years. For instance, the probability of an average MS surface to last more than seven years is 0.36, while it is 0.51 for the case of an average CH surface. The CH survival curve lies above the MS curve along the entire range of durations indicating superior performance. The TH survival curve lies below the CH curve for durations shorter than 3.5 years but presents similar or higher probabilities for longer durations. This reflects the large number of observed projects with short lives and the large number of censored observations as noted from Figure 3.7.

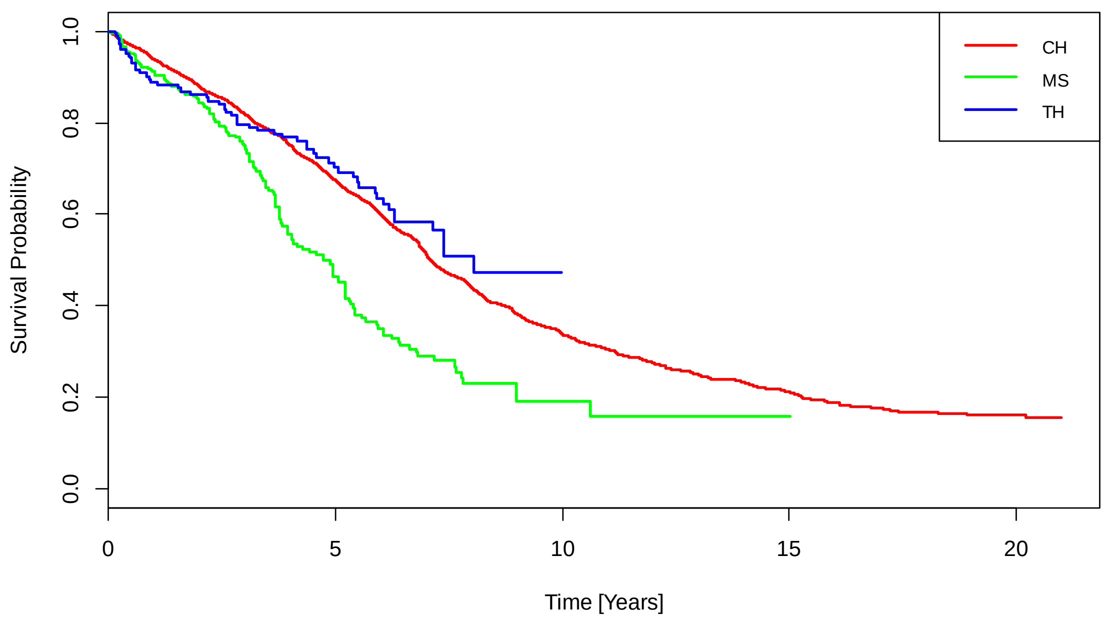


Figure 3.9: KM Survival Curves for CH, MS, and TH

The last four columns of Table 3.2 report the number of observations, as well as statistics of the K-M estimated median for each PM treatment. The reported median estimates the duration corresponding to a survival probability of 0.50. Thus, an average CH pavement has a 50% chance of lasting more than 7.1 years. This statistic will also be used to quantify the effectiveness of the different treatments in our analyses. The "0.95LCL" and "0.95UCL" columns report the lower and upper 95% confidence limits for the estimated median. A comparison of the lower confidence limits for the median suggests that both CH and TH are more likely to last longer than MS-treated surfaces, similar to what was observed when comparing the modes of the different treatment's observed effective lives.

Table 3.2: Statistics of the PMs' observed effective life and survival analysis.

	Observed Effective Life [Years]					**K-M Survival Analysis [Years]**			
	# obs.	1st Quart.	Mean	Median	3rd Quart.	*# obs.*	0.95LCL	Median	0.95UCL
CH	*6,580*	4.23	5.53	6.56	8.19	*13,835*	7.02	7.10	7.20
MS	*207*	2.76	4.53	4.04	5.96	*331*	3.95	4.74	5.22
TH	*48*	2.84	4.66	4.91	6.96	*206*	6.30	8.07	NA

PM Treatments' Survival Model

In order to reduce the impact of potential confounding factors on the comparison of the different PM treatment's effectiveness, their survival probabilities were jointly estimated, accounting for influence factors through the development of an Accelerated Lifetime Model (ALM) adopting a Weibull distribution. This survival model was specified using CH as the base treatment and four covariates: precipitation (in inches per year), temperature (in Fahrenheit), pre-existing condition (distress score before applying treatment), and traffic (in 10^3 ESAL). This ALM model was estimated using the R statistical programming language (R Core Team 2014) employing the SURVIVAL package (Therneau 2015). The outputs are presented in Figure 3.10.

```
Call:
survreg(formula = Surv(time, event) ~ Temperature + Precipitation +
    MS + TH + kESAL + PreDS + PreIRI, dist = "weibull")
                  Value Std. Error       z        p
(Intercept)    2.88e+00   2.60e-01  11.044 2.34e-28
Temperature   -1.38e-02   3.91e-03  -3.543 3.95e-04
Precipitation -3.22e-03   1.10e-03  -2.924 3.46e-03
MS            -2.68e-01   7.21e-02  -3.718 2.00e-04
TH             1.05e-01   1.09e-01   0.963 3.36e-01
kESAL         -2.28e-05   2.46e-06  -9.254 2.17e-20
PreDS          4.42e-03   5.91e-04   7.487 7.04e-14
```

Figure 3.10: Outputs from Estimation of ALM Model

The results of the estimated model indicate that all of the coefficients were significant, with more than 95% confidence, except for the TH indicator variable. This output indicates that the effective lives of CH and TH were not significantly different, while both of them were more likely to last longer than MS surfaces for the same traffic and environmental conditions. The positive sign on the temperature, precipitation, and traffic variables indicate that the probability of a PM treatment to survive decreases as they increase in value, as expected. The estimated hazard ratio of the climatic factors can potentially be used by TxDOT to update or modify their existing District Rainfall Factors used for allocating M&R funding. The negative sign on the pre-existing condition variable (i.e., PreDS) indicates that treatments are expected to last longer as the condition of the pavement surface being treated is better.

3.4 Preliminary Observations

Following are the most important observations from the preliminary analysis conducted on the contracted M&R works in Texas:

- Some of the challenges and limitations presented by the preliminary processing of the TxDOT M&R databases include:
    - A large proportion of CSJs had missing starting or ending RM location information, significantly reducing the sample size for the analysis. “Materials selected for the treatment” was another variable missing a significant amount of data.
    - The poor level of detail of some relevant variables, such as the surface type of the underlying pavement or the PM treatment type, undermines the inferences from the analysis of the study.
- The vast majority of PM treatments found in the processed databases consisted of CH surfaces.
- The PM projects obtained from the preliminary analysis are spread throughout Texas, covering all of the state’s climatic regions.
- The survival analysis conducted on the more than 10,000 treated surfaces that included CH, TH, and MS treatments provided the following preliminary observations:
    - From the survival analysis it was observed that the median expected life spans are 7.1 years, 4.7 years, and 8.1 years for CH, MS, and TH, respectively.
    - The expected effective life of CH is, on average, 24% longer than for MS and 11% shorter than for TH. However, the difference in effective life between CH and TH was not statistically significant.
    - PM treatments placed in cold, dry regions had a higher probability of lasting longer.
    - Higher traffic levels (as measured by ESAL) significantly reduced the PM treatment’s effective life.
    - Pre-existing condition of the pavement surface has a significant effect on the PM treatment effective life. The probability of the PM-treated surface being replaced is, on average, 0.44% higher with every unit decrease of pre-existing distress score.

The subsequent tasks of the study will consist of evaluating the effect of additional experimental factors, such as pavement type, among other factors.

References

Arguez, A., S. Applequist, R.S. Vose, I. Durre, M.F. Squires, and X. Yin. "NOAA's 1981–2010 Climate Normals: Methodology of Temperature-related Normals." NCDC Report, 2012. Accessed on 01/22/2016. ftp://ftp.ncdc.noaa.gov/pub/data/normals/1981-2010/.

Caltrans. *Maintenance Technical Advisory Guide (MTAG)*, Volume I: Flexible Pavement Preservation (Second Edition), Chapter 7. Division of Maintenance, 2007.

Chen, D. H., D. F. Lin, and H. L. Luo. "Effectiveness of Preventative Maintenance Treatments Using Fourteen SPS-3 Sites in Texas." *Journal of Performance of Constructed Facilities* 17(3) (2003): 136–143.

David, P. *Pavement Preventive Maintenance Program Guidelines*. Ohio Department of Transportation. The Office of Pavement Engineering, 2001.

Elkins, G. E., P. Schmalzer, T. Thompson, and A. Simpson. *Long-Term Pavement Performance Information Management System, Pavement Performance Database User Guide*. Report No. FHWA-RD-03-088. Federal Highway Administration, Office of Infrastructure Research and Development, Washington, D.C., 2003.

Eltahan, A., J. Daleiden, and A. Simpson. Effectiveness of Maintenance Treatments of Flexible Pavements. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1680. Washington, DC: Transportation Research Board of the National Academies, 1999: 18–25.

Haider, S., and M. Dwaikat. Estimating Optimum Timing for Preventive Maintenance Treatment to Mitigate Pavement Roughness, 43–53. *Transportation Research Record: Journal of the Transportation Research Board* (2235), 2011.

Hall, K., C. Correa, and A. Simpson. "Performance of Flexible Pavement Maintenance Treatments in the Long-Term Pavement Performance SPS-3 Experiment." *Transportation Research Record: Journal of the Transportation Research Board* (1823), 2003: 47–54.

Kleiber, C., and A. Zeileis. *Applied Econometrics with R*. New York: Springer-Verlag, 2008. Accessed July 15, 2015. http://CRAN.R-project.org/package=AER.

LTPP InfoPave. *Standard Data Release*. Accessed July 15, 2015.http://www.infopave.com/Data/StandardDataRelease/.

Morian, D. A., G. Wang, D. Frith, and J. B. Reiter. Analysis of Completed Monitoring Data for SPS-3 Experiment. *Transportation Research Board 90th Annual Meeting*. Washington, D.C.: Transportation Research Board of the National Academies, 2011.

Morian, D. A., S. D. Gibson, and J. A. Epps. *Maintaining Flexible Pavements—The Long-Term Pavement Performance Experiment SPS-3 5-Year Data Analysis*. Report No. FHWA-RD-97-102. Washington, D.C.:Federal Highway Administration, Office of Infrastructure Research and Development, 1998.

R Core Team. *R: A Language and Environment for Statistical Computing*. Vienna: R Foundation for Statistical Computing, 2014.

Shirazi, H., R. L. Carvalho, M. Ayres, Jr, and O. I. Selezneva. "Statistical Analysis of LTPP SPS-3 Experiment on Preventive Maintenance of Flexible Pavements." Newport Beach, CA: First International Conference on Pavement Preservation, 2010.

Sims T. B. *Texas Pavement Preservation Program*. Accessed on 08/05/2016. http://www.utexas.edu/research/tppc/pubs/sims.pdf.

Therneau, T., *A Package for Survival Analysis in S* (version 2.38). Accessed 08/27/2016. http://CRAN.R-project.org/package=survival.

Texas Transportation Institute (TTI). *Thin Is In: Thin Asphalt Overlay Helps Stretch Budgets Further*. Accessed on 08/05/2016. http://tti.tamu.edu/2012/09/01/thin-is-in-thin-asphalt-overlay-helps-stretch-budgets-further/.

Texas Transportation Institute (TTI). *Training Courses Teach TxDOT Personnel Best Practices in Seal-Coat Projects*. Accessed on 08/05/2016. https://tti.tamu.edu/2015/09/01/seal-coats-sharing-lessons-learned-testing-new-methods/.

TxDOT. *Seal Coat and Surface Treatment Manual*, Austin, Texas: Maintenance Division, 2010.

TxDOT. *Standard Specifications for Construction and Maintenance of Highways, Streets, and Bridges*, Austin, Texas: Maintenance Division, 2014.

TxDOT. *Statewide Planning Map*. Accessed on 01/22/2016. http://www.txdot.gov/inside-txdot/division/transportation-planning/maps/statewide-planning.html.

TxDOT. *Maintenance Operations Manual*. Austin, Texas: Maintenance Division, 2016.

Wooldridge, J. M. *Econometric Analysis of Cross Section and Panel Data*. Cambridge: MIT Press, 2010.