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GUIDE FOR TIMING OF ASPHALT-SURFACED PAVEMENT PRESERVATION

Final Report

Prepared for
NCHRP
Transportation Research Board
of
The National Academies

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The research reported herein was performed under NCHRP Project 14-38 by Amec Foster Wheeler Environment and Infrastructure, Inc., the National Center for Asphalt Technology at Auburn University, and R. Gary Hicks, LLC. Dr. Gonzalo R. Rada, P.E., Senior Principal at Amec Foster Wheeler, was the Project Director and Principal Investigator. The primary author was Dr. James Bryce, Senior Consultant at Amec Foster Wheeler. Other authors included Dr. Michael Heitzman, P.E., Assistant Director of the National Center for Asphalt Technology, and Dr. R. Gary Hicks, P.E. of R. Gary Hicks, LLC.

ABSTRACT

This report presents the results of a study that developed and validated a framework for determining the timing to apply pavement preservation. The project documented in this report expanded on the research found in literature and developed a preservation treatment timing framework based on cost-benefit analysis that also considers uncertainties (i.e., variability in projected costs and conditions that affect preservation timing). The framework contains methodologies for defining pavement performance, calculating benefits, calculating costs and combining the costs and benefits to determine preservation treatment timing, each of which were validated using data gathered from agencies. The framework and methodologies were then used as the foundation for the development of a preservation treatment timing guide, which is attached to this report. The results of this project demonstrated that using a cost-benefit based approach with uncertainties is an effective way to determine the timing of preservation treatments. Furthermore, this project demonstrated the extent to which the benefits of pavement preservation are derived from two effects; the immediate change in condition and the change in performance (i.e., long-term changes in condition over time). The benefits of preservation treatments are maximized when the marginal benefits from the two effects are jointly maximized.

CHAPTER 1. INTRODUCTION

BACKGROUND

Preservation is an essential activity that agencies employ to maintain and improve a pavement's functional condition at a relatively low cost. Although it is not expected that the application of preservation treatments will increase the structural capacity of the pavement, it is generally expected to lead to improved functional performance, longer service lives, and reduced life cycle costs (LCC). The expected improvement in pavement condition and increase in performance (i.e., a measure of condition over time) is not well documented for many preservation treatments, although the literature on this topic has expanded in recent years. Additionally, relationships between the performance of preservation treatments and many factors that are expected to affect performance, such as traffic, structure, initial pavement condition, and climate, have not been adequately developed. These relationships are essential for identifying the most appropriate timing when a preservation treatment should be applied to a pavement, which is an essential objective of this project.

The timing of asphalt concrete pavement (hereafter asphalt pavement) preservation is a question of when the most benefit is gained from applying the preservation treatment. In simple terms, it requires following a decision process to evaluate when the performance or service life of a pavement is maximized, while also minimizing the costs associated with placing the treatment. Therefore, understanding and evaluating the extent to which a preservation treatment affects pavement performance is required, as are the costs associated with the treatment whether monetary or in other terms (e.g., time delay).

Figure 1 illustrates the concepts and terminologies used to describe pavement performance and the effects of pavement preservation treatments on performance for measures that increase with worsening condition. The immediate change in condition depend on the type of the preservation treatment, the condition of the pavement at the time of treatment application, and the performance measures being considered. Pavement condition is measured at discrete points in time, and thus the term *change in condition* is used throughout this report to describe immediate changes when preservation is applied. Pavement performance is defined by the pavement condition over time, and is reflective of both condition and rates of change in the condition. Some important characteristics shown in Figure 1 include:

- The difference in performance between the treated and untreated pavement over the analysis period depends on the immediate change in condition and the difference in the rate of change following the application of preservation. The condition and rate of change can increase, decrease or stay the same following treatment.
- The service life extension is the time period between that required for the preserved pavement to reach a target condition and of that required for the untreated pavement to reach the same condition.
- The performance of the preserved pavement is compared to that of an equivalent untreated pavement to determine the expected change caused by preservation application.

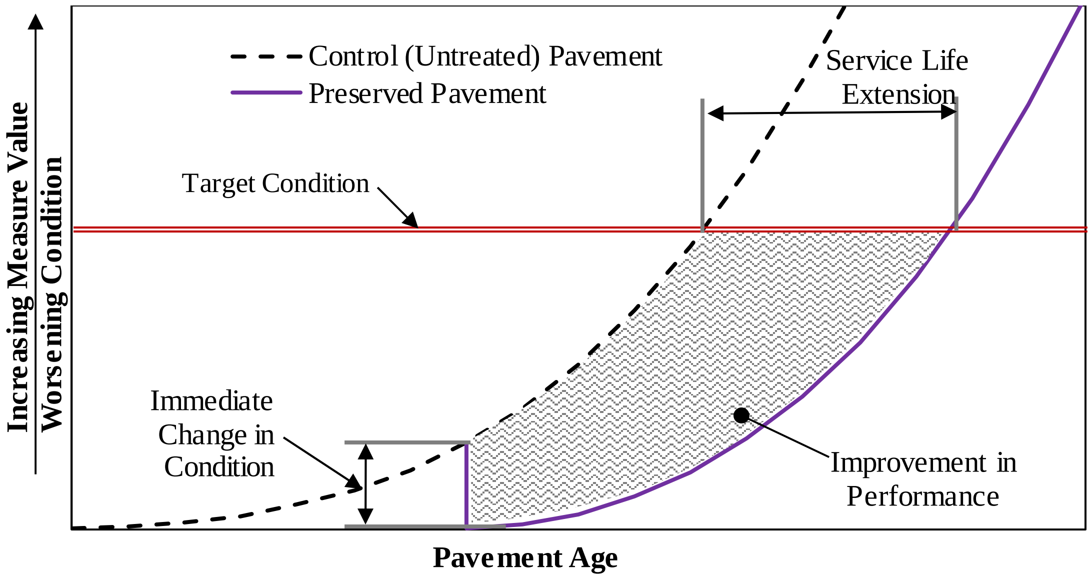


Figure 1. Schematic of pavement performance and the effect of preservation treatment.

Several methodologies are available to identify the best timing for pavement preservation, most of which include some form of cost-benefit analysis. However, the definition of benefits – a major component of the analysis – vary among references. Regardless of the definition used, performance models or sufficient information were available to describe deterioration over time for both untreated and treated pavements. The second component: cost, was defined in many ways (e.g., treatment cost versus project cost), and sometimes user costs were included with agency costs. The difference in these methods had a large effect on the results.

PROJECT OBJECTIVES AND SCOPE

The objective of NCHRP Project 14-38 "Guide for Timing of Asphalt-Surfaced Pavements Preservation" was to develop a guide for identifying the timing for preservation of asphalt pavements considering condition and non-condition-based factors. For the purpose of the research, preservation treatments are defined as treatments applied to preserve an existing roadway, slow future deterioration, and maintain and improve its functional condition (without substantially increasing structural capacity). This research included the following tasks:

1. Conduct a literature review and survey of agency practices.
2. Identify and evaluate methods for determining preservation treatment timing.
3. Develop and execute a work plan for developing and validating a preservation timing framework and supporting methodologies.
4. Prepare a report documenting the research effort.

As is detailed in this report, the completion of these tasks resulted in a recommended framework and set of methodologies and broad national performance models (hereafter referred to as example models) for determining the timing of pavement preservation. In addition, a guide was developed in this research to present detailed steps for determining pavement preservation timing.

The report describes approaches for defining the timing of a preservation treatment. The framework demonstrates how the timing of preservation is affected by the objective values of

measured pavement condition, climate variables, and others, and the subjective values of the relative weight applied to each performance measure or the interpretation of the uncertainties, and others. Therefore, the timing can change depending on these values.

REPORT ORGANIZATION

The report presents the major findings, outcomes, conclusions, and recommendations from the research effort, and is organized into seven chapters with one attachment. Chapter 1 provides background information, project objectives, and summarizes the approach used for conducting the research. Chapter 2 discusses existing practices, including major findings from the literature review and survey of State highway agencies. Chapter 3 details the evaluation of approaches for determining preservation timing and Chapter 4 describes the development of the proposed framework and approaches. Chapter 5 details the analysis of pavement performance data and development of example models for evaluating the recommended framework. Chapter 6 summarizes the development of a guide for preservation timing (hereafter referred to as the Guide), and Chapter 7 presents summary, conclusions, and recommendations for research. The references cited throughout the report are listed at the end of the report.

CHAPTER 2. LITERATURE REVIEW AND AGENCY SURVEY

This chapter presents the results of a literature review designed to assess the past research and the results of a survey to assess the current state of preservation timing. The methods found in the literature for determining the time to apply specific preservation treatments are generally based on a cost-benefit analysis. These methods define the time to apply a specific treatment as that minimizes the cost scaled by the benefit. The key differences in the various methods relate to how costs and benefits are defined. Methods that are not based on cost and/or benefit analysis are typically based on cycles of time (e.g., apply treatment every *x* number of years).

An important consideration in defining a method for determining the timing to apply preservation is the ability to evaluate the benefit of the preservation treatment, which requires a prediction of the performance of the pavement with and without treatment. In light of this, the literature review included and is consequently organized into the following topics:

- Review of literature pertaining to the timing of the application of pavement preservation treatments, including the methods used and other related information.
- Review of literature pertaining to the definition and calculation of costs and benefits.
- Review of literature pertaining to pavement performance following the application of preservation treatments, including an evaluation of the initial change in condition and the change over time following the treatment application.

Also, an internet survey and phone calls were conducted with State transportation agencies to obtain a clearer understanding of the agencies' practices for the consideration of preservation timing and preservation programs. The survey inquired if the agencies had pavement preservation guidelines, and pavement performance data that could be made available for this project. The results of the survey and follow-up calls are detailed in this chapter.

PRESERVATION TIMING

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 lifecycle cost (LCC) associated with the pavement. Therefore, understanding and evaluating the extent to which a preservation treatment affects the pavement performance required, and the costs associated with the treatment (monetary or in other terms such as user costs). While timing can be developed independent of costs by identifying the time of applying a treatment that maximizes performance, the inclusion of costs will reflect the decision-making processes followed by many agencies. Additionally, some costs associated with pavement preservation may change as the condition of the pavement prior to preservation changes, and the costs will change over time as a results of applying a discount or inflation rate.

Rada et al. (2016) describe a method that can be used to select both the preservation treatment type and timing based on the treatment selection process used by the Maryland State Highway Administration (MDSHA). The process is part of the network-level optimization conducted by MDSHA to choose the treatment that minimizes the agency costs, and also maximizing the extension of the pavement life. The life extension is determined as the time from when the treatment is applied to when the pavement remaining service life (RSL) returns back to the RSL just prior to treatment. The RSL is calculated as the minimum of the times it takes each distress to reach a predefined threshold.

Izeppi et al. (2015) developed a district-level preservation treatment selection tool using data for asphalt pavements in Virginia. The treatments considered included chip seal, slurry seal, microsurfacing, and thin overlays. This work focused on the method for selecting the best treatment type, and not necessarily the timing although they can be used to select timing. In this case, performance was defined as the area beneath the predicted condition versus time curve and only treatment costs were considered. Cost effectiveness for treatments was defined using the cost-benefit ratio, where the benefit is defined as the improvement in performance resulting from the application of preservation. In addition, Izeppi et al. (2015) developed a tool for engineers to use when selecting specific treatments.

Mahoney et al. (2014) assessed chip seals for the Washington State Department of Transportation (DOT) in order to develop a set of best practices, including timing that maximizes service life extension. These recommendations were based on a review of literature, interviews with 35 State DOTs, and meetings with stakeholders in Washington State. Mahoney et al. (2014) recommended applying a chip seal between overlays (timing was not recommended for pavements with traffic levels less than 20,000 vehicles per day).

Anderson et al. (2012) evaluated the timing of preservation based on environmental aging of asphalt pavements in the State of Minnesota. The approach used hypothesized that the application of the chip seal would slow the rate of oxidation of the underlying pavement and, therefore included rheological tests on the binder in the pavements that received a chip seal to evaluate changes in the asphalt properties over time. The results were based on the evaluation of a pavement test section that was divided into several segments, one was a control segment (no preservation), and each of the other segments received a chip seal at a different time. The results of the research indicated no discernable trends that relate the timing of the preservation treatment to changes in the rheological properties of the binder.

Zhi et al. (2012) assessed the timing for applying slurry seals based on pavement condition data collected in China. The condition indicators used in the study were crack ratio, rut depth, international roughness index (IRI), and sideway force coefficient (friction). For each indicator, performance curves were developed for do-nothing and post-slurry seal application scenarios. The post-slurry seal application performance curve was found to be dependent on the pavement condition at the time of treatment application. The relative benefit of applying the treatment is expressed as the ratio of the additional performance resulting from a preservation treatment to the expected performance of the untreated pavement and is calculated as the ratio of area *B* to area *A* in Figure 2. A higher ratio indicates better relative performance, and therefore the preservation should be placed in the year that results in the largest ratio.

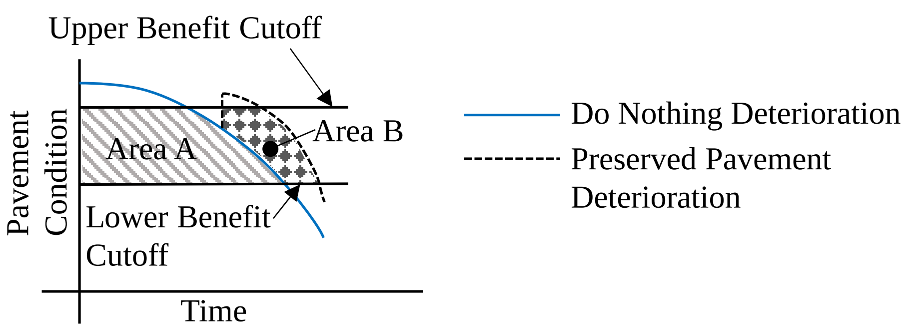


Figure 2. Relative improvement in performance. (Zhi et al. 2012)

Hajj et al. (2012) used pavement condition data collected by three local agencies in the State of Nevada to develop performance prediction models for the do-nothing condition and for two sequential applications of slurry seals at different times on both new pavement construction and overlay sections. Cost-benefit ratios were used to assess the timing for two sequential slurry seal applications, where the benefit was defined as the area under the curve for the treatment condition versus time up to a terminal condition (similar to the definition by Zhi et al., 2012). The study recommended the application of slurry seals at specific condition rating values.

Dosa (2012) assessed the effectiveness of chip seals in four climatic zones in the United States using life extension and relative benefit as indicators. Life extension was defined as the difference in time for the untreated pavement and that for the treatment pavement to reach a threshold or target condition value (as shown in Figure 1). The relative benefit that was defined the same way as in Zhi et al. (2012). Benefit-cost ratios were calculated for all initial pavement conditions in all climatic regions (dry freeze, dry non-freeze, wet freeze, wet non-freeze). Costs included only agency costs and were expressed as $/lane-mile. It was found that the treatment effectiveness was higher for sections were in smooth condition at the time of the treatment application. No significant difference in benefits were found between the climatic regions.

Morian (2011) developed guidelines for determining the condition of the pavement at which a specific preservation treatment should be applied. To develop the guidelines, Morian (2011) developed pavement performance curves using the Pennsylvania DOT's overall pavement index (OPI) for three specific treatments (seal coat, microsurfacing, and a thin bonded wearing course). The condition data for each treatment were divided into four categories based on traffic levels and functional class:

- Average Annual Daily Traffic (AADT) less than 2000.
- AADT greater than 2000.
- National Highway System (NHS).
- Interstate Highways.

The approach taken by Morian (2011) was to first calculate a life extension for the three preservation treatments, and then to estimate when the life extension to cost ratio was maximized. The pavement life extension was defined as the number of additional years it takes the treated pavements to reach the terminal serviceability value. Terminal serviceability indices were defined for each of the traffic categories as the pavement condition at which the treatment is considered to be failed or require extensive repair or replacement.

A relationship between pavement life extension and pavement condition at the time of treatment was developed for all treatments within each traffic category at the good/fair OPI values and at the terminal overall pavement index (OPI). It was found that the pavement life extension for a specific treatment can be computed for any condition level using a second-order polynomial function. To determine the most cost-effective OPI scenario, a LCC analysis (LCCA) was conducted considering different initial pavement conditions. The research found that chip seals should be placed when the OPI was between 64 and 72, and thin overlays and micrsurfacing should be placed when the OPI was between 73 and 82.

Haider and Dwaikat (2011, 2012) used data from Long-term Pavement Performance (LTPP) Specific Pavement Studies Experiment 3 (SPS-3) to develop mathematical models to estimate the optimum timing based on treatment effectiveness. Pavement performance was measured in terms of roughness (IRI) but the same approach can be used for other distress types.

Two approaches were proposed to define the effectiveness of preservation for use in selecting preservation timing (Haider and Dwaikat, 2011). In one approach, preservation should be applied when the area delineating the change in performance in Figure 1 is maximized. In the other approach preservation timing is that when the service life extension (as defined in Figure 1) is maximized. Haider and Dwaikat (2011) also described an alternate area (as shown in Figure 3) for defining effectiveness which is bound by the condition when the preservation treatment is applied.

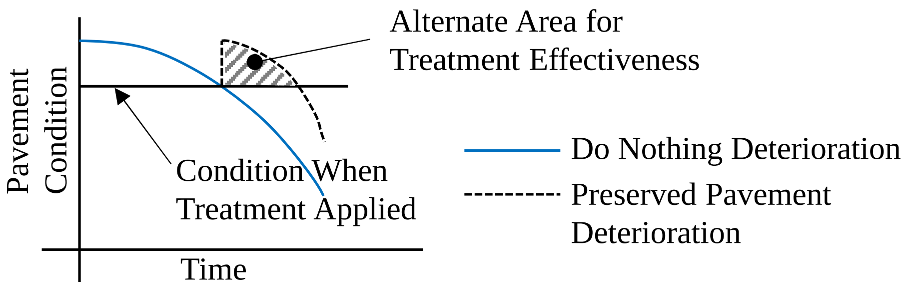


Figure 3. Alternate area for defining treatment effectiveness.

Dawson et al. (2011) presented a methodology to select the optimum pavement treatment type and timing at the project level using several relationships for predicting the costs and performance of a treatment (or series of treatments). Treatment costs include both agency and user costs, expressed in terms of their present worth value. These costs depend on the pavement type, pretreatment condition and treatment type. Benefits are estimated in terms of pavement life extension and performance (in terms of IRI), where performance is defined as the area bounded by the IRI condition curves before and after treatment and a given threshold value (similar to that illustrated in Figure 1). The optimum treatment time is that providing the lowest ratio of cost divided to benefit.

Li et al. (2010) presented an approach for selecting the timing of preservation, and for comparing many treatments and selecting the preferred treatment. This approach defines the costs and benefits for particular treatments and calculates relationships among them. Several performance indicators: IRI, rutting, and friction number; the benefits of four treatments (thin overlays, slurry seals, crack sealing and chip seals) were calculated as the difference of computed areas of performance between the treated pavement and the do-nothing condition. Costs used in the analysis included only those related to the treatment (e.g., material and placement) expressed as equivalent uniform annual cost (EUAC). This approach combines the benefits calculated for each performance indicator (e.g., IRI and rutting) and does not base the selection of preservation on one condition indicator.

Khurshid et al. (2010) presented a framework for selecting optimal condition thresholds for applying preservation. The framework, shown in Figure 4, is based on a cost-benefit analysis, and recommends the condition that maximizes cost effectiveness for applying preservation. Khurshid et al. (2010) conducted a cost effectiveness (CE) analysis to determine optimal timing thresholds for a thin asphalt overlay using data collected from the Indiana DOT that included traffic, climate, pavement condition and cost. Pavements were divided into several categories based on the functional class of the road. The performance indicators were IRI, pavement condition rating (PCR), and rut depth. Pretreatment and post-treatment performance models for each indicator were developed using traffic loading (in terms of cumulative annual truck traffic)

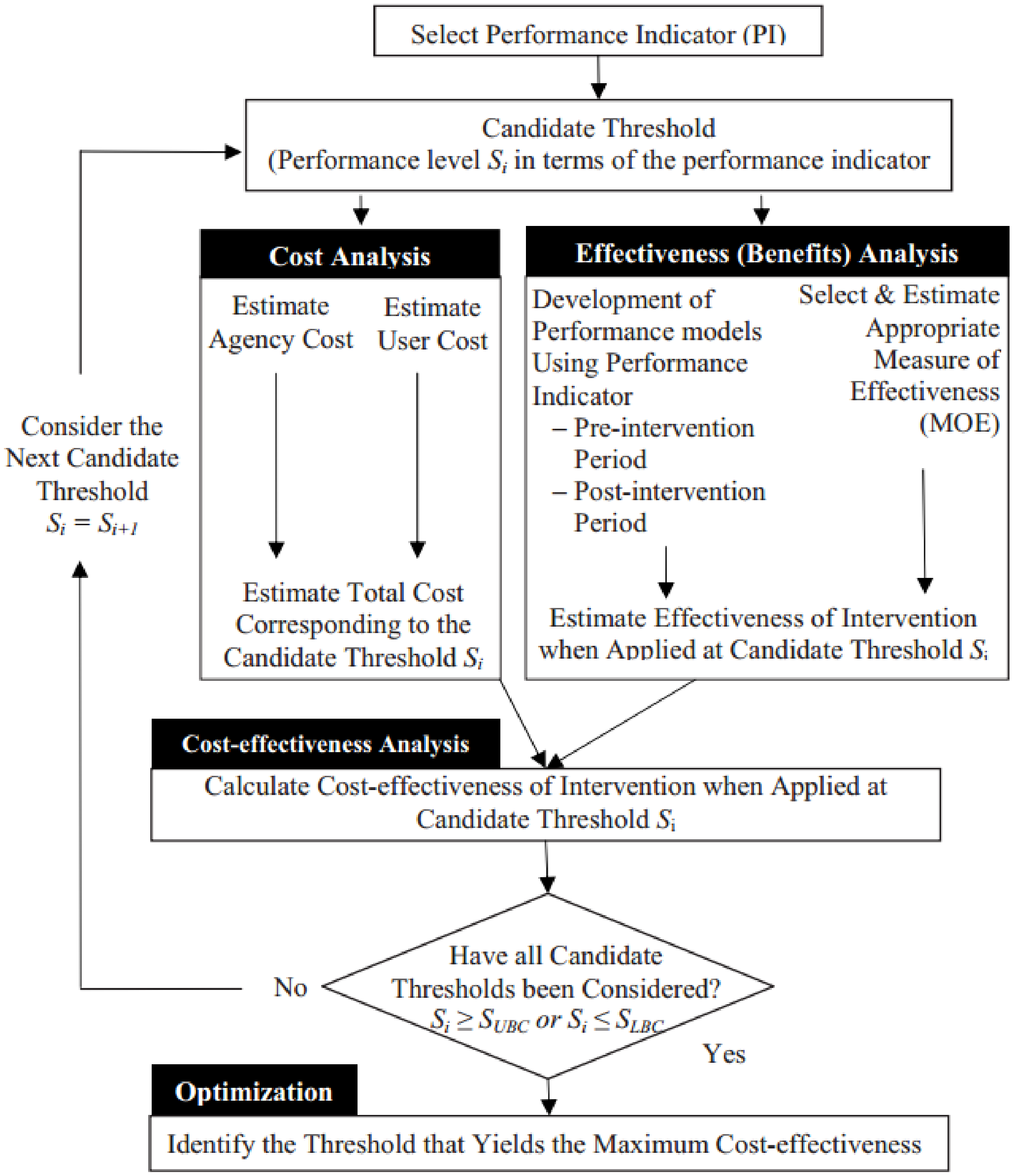
and climatic data as the explanatory variables. The service life was defined as the time in years required for the performance curve to reach a defined threshold. The effectiveness was measured as the area bounded by the performance curve, which is the same as the area delineating the change in performance shown in Figure 1. Cost models were developed for overlay as a function of preoverlay pavement condition; cost increased exponentially with worse preoverlay pavement condition. The optimal timing threshold was defined as the one that yielded the maximum CE as calculated using the process shown in figure 4. A sensitivity analysis was performed using the Monte Carlo simulation method to study the effect of varying traffic loadings and climate severity. It was found that pavements subjected to high truck traffic and located in areas with a high freezing index should be treated better pavement conditions than those subjected to low traffic and climatic severity. Further analysis was carried out to study the effect of including user costs on the estimated optimal timing thresholds. The results indicated that thresholds for applying the overlay were lower when both agency and user costs were included in the analysis than when only agency costs were used.

Shuler (2010) evaluated the performance, cost effectiveness, and timing of various preservation treatments used by Colorado DOT, and developed guidelines based on a review of literature, interviews with district engineers in charge of preservation programs and an assessment of several pavement segments in Colorado. Rajagopal (2010) evaluated the effectiveness of a chip seal and microsurfacing program at the Ohio DOT, and investigated the timing to apply each treatment. The timing of the preservation treatments for different pavement types was defined by the times at which the condition maximizes cost effectiveness based on cost-benefit analysis. The research recommended that chip seals be applied when the pavement condition rating (PCR) is between 66 and 80 and that microsurfacing be applied when the PCR is between 61 and 70.

Wu and Flintsch (2009) proposed an approach for pavement preservation programming that used multi-objective optimization and chance constraints. This approach can handle multiple incommensurable and conflicting objectives (e.g., minimizing costs and maximizing performance), while considering constrains related to the available budget over the analysis period.

Marasteanu et al. (2008) investigated the timing for the application of chip seals and fog seals based on the effect on aging characteristics of the asphalt binder for roads in Minnesota. The surface condition of the asphalt pavement was considered to be related to the aging characteristics of the asphalt mix and the change in its mechanical properties. Based on the relationship between average fracture properties and the age of the pavement at the time of treatment, Marasteanu et al. (2008) concluded that the best window of time for the application of the surface treatment was between 4 and 6 years, when the fracture toughness is at its highest.

Chou et al. (2008) studied the timing of placing thin overlays to maximize its benefits using performance data for thin overlays constructed in Ohio DOT since 1990. Performance was defined by the area under the curve representing condition as a function of time. It was found that the existing pavement condition had a significant influence on the cost effectiveness of thin overlays, as determined by the cost-benefit ratio. Cost was defined as the treatment cost divided by the service life (i.e., without accounting for the discounted value of money over time). In addition, it was found that the pavement type overlays on flexible pavements had a higher service life than those on composite pavements, increased snowfall lead to reduced service life and increased overlay thickness also increased the cost effectiveness of the treatment.



Note: S_i = Candidate threshold in terms of asset performance or serviceability level
S_{UBC} = Upper boundary for S_i; S_{LBC} = Lower boundary for S_i

Figure 4. Selecting optimal condition thresholds for preservation. (Khurshid et al., 2010)

Lamptey et al. (2008) developed a procedure to select the optimal preservation schedule for a given pavement section using decision support systems. This procedure consisted of the following steps:

- Identifying pavement family and obtaining or establishing project-level input data, analysis period, and performance and budgetary constraints.
- Identifying all feasible alternative preservation schedules over the analysis period.
- Obtaining models for estimating the immediate jump in pavement condition after treatment and for tracking the performance after treatment is applied.

- Establishing total agency and user costs.
- Performing optimization (based on LCC) to identify the most cost-effective schedule.

Peshkin et al. (2004) developed a method for selecting the optimal timing of pavement preservation treatments, and designed a Microsoft Excel based tool called OPTime for use in implementing the methodology. The method uses a cost-benefit analysis to compare the different times preservation treatment application, and then chooses the most cost effective timing. In this approach, an effectiveness index is calculated for a single pavement preservation treatment. The effectiveness index, a function of the benefit cost ratio, is calculated for each time of application considered such that benefit was determined for a specific condition indicator (e.g., rutting, cracking, friction, composite condition indices). The effectiveness index was calculated as the difference in area associated with the pavement performance after application of a preservation treatment and the area associated with the pavement performance in the do-nothing scenario. The areas are defined by the shape of the pavement condition curves shown in Figure 2 and the upper and lower benefit cutoff values. The upper cutoff value provides a limit above which no benefit is considered; the lower cutoff value defines the lowest condition value that will be considered, this may be a rehabilitation trigger value, or value at which the pavement preservation treatment has failed or no longer provides a benefit.

The benefit for each condition indicator is defined the area bound by the change in performance curve and the upper and lower cutoff values. An overall benefit combines the individual benefits by applying a weighting factor to each condition indicator. Costs related to the application of the preservation treatment (e.g., treatment costs, rehabilitation costs, and work-zone user delay costs) are calculated as EUAC using a LCCA approach. Benefit cost ratios are determined for each time of application, and by normalizing the benefit cost ratios relative to the highest value among all application times considered, an effectiveness index is calculated on a scale of 0 to 100 to identify the most cost-effective timing.

The OPTime tool allows two types of analysis: simplified or detailed. The simplified approach allows agencies to assess several timing scenarios when adequate performance data do not exist to develop relationships between a specific treatment and changes in condition or performance resulting from applying the treatment at specific times. The detailed approach allows for agencies to use their data to develop relationships that are then used to identify for timing.

IDENTIFYING TIMING FOR PRESERVATION

The review of the literature revealed that the majority of the approaches to identify timing are based on some form of cost-benefit analysis. However, the definition of costs and benefits vary throughout in these methods. For example, some approaches defined benefits as the area under the condition versus time curve (e.g., Peshkin et al., 2004), but others define benefits as a relative life extension (e.g., in Rada et al., 2016). The methods for defining costs and benefits were reviewed and are discussed in the following sections.

Defining Costs

For treatment or strategy selection purposes, costs were expressed in two forms:

- Net Present Value (NPV).
- Equivalent Uniform Annual Costs (EUAC).

The NPV is calculated by discounting all costs to a base year to account for the effects of discount rates. This method presents all costs in terms of present-day dollars such that all costs can be compared on the same terms. NPV is defined by Equation 1.

$$NPV = IC + \sum_{k=1}^{n} Cost_k \left[\frac{1}{(1+i)^k}\right] \quad (1)$$

Where:

IC = Initial cost (i.e., costs accrued in the current year).

i = Discount rate.

k = Year of expenditure.

$Cost_k$ = Cost accrued in year k.

n = Analysis period.

$$EUAC = NPV \left[\frac{i(1+i)^n}{(1+i)^n - 1}\right] \quad (2)$$

Where:

NPV = Net present value of all costs.

i = Discount rate.

n = Number of years considered in analysis.

Costs can include agency costs, user costs or both. Agency costs typically refer to treatment costs and can be obtained from agency records or bids. User costs associated with the treatment include factors such as delays, vehicle operating costs. Previous studies have focused only on the delay cost portion because operating and crash costs are assumed to be similar for the preservation treatments (Khurshid et al., 2010; Peshkin et al., 2004). Nonetheless, calculation of user delay costs requires traffic data, work zone closure data, and value of time (Walls & Smith, 1998).

Khurshid et al. (2010) observed that the inclusion of user costs affected the estimated optimal threshold for application of thin asphalt overlays. However, user costs are generally not included in the analysis because they are hard to evaluate precisely and impartially, and are generally much greater than agency costs and tend to dominate the decision process, especially if multi-objective optimization methods are used (Wu and Flintsch, 2009).

The EUAC converts the NPV to a series of uniform costs over a defined time period (e.g., the service life of the treatment). Luhr and Rydholm (2015) discuss the use of the EUAC to assess when a treatment should be considered for pavements in Washington State. EUAC is defined by Equation 2.

It was found that each agency has a different approach for calculating life cycle costs standardized within each agency. In addition, costs are defined in terms of only those accrued by the agency, or also include a measure of user costs. Therefore, the approach for defining preservation timing will have to consider the effect of these differences.

Defining Benefits

When assessing the timing for applying preservation using a cost-benefit analysis, the benefit side of the equation captures the effect of the preservation treatment on the pavement.

There are various approaches to quantify the benefit resulting from the application of preservation treatments. For example, Morian (2011) defined net benefit as the EUAC difference between the do-nothing and treatment scenarios; thus considering both cost and time in the assessment.

The most common approach found in literature for defining benefit is to use the area bounded by the performance curves of the treated and untreated scenarios and agency defined threshold values; e.g., Peshkin et al. (2004), Khurshid et al., (2010) and Hajj et al. (2012). For a specific condition indicator, the benefit is determined by the difference in computed areas associated with the post-treatment condition indicator curve and the do-nothing curve, as shown in Figure 5.

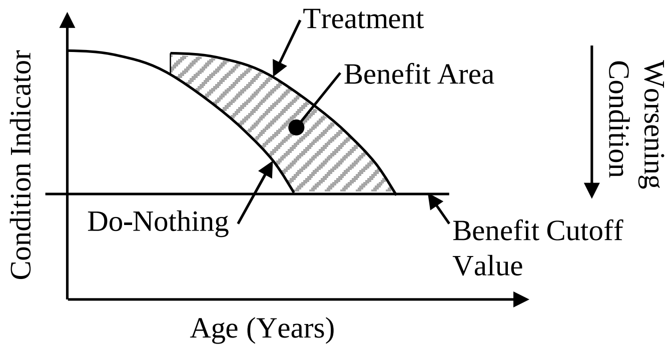


Figure 5. Illustration of preservation benefit.

Another approach to defining the benefit is to normalize the benefit area by the do-nothing area (Hajj et al. (2011,2012), Dosa (2012)). This approach is especially useful when multiple condition indicators expressed in different units are used because their benefits can be expressed in percentages.

The use of more than one performance indicator to assess preservation benefits was discussed (Peshkin et al., 2004; Chou et al., 2008; Zhi et al., 2012). Zhi et al. (2012) used crack ratio, rut depth, IRI, and friction to evaluate pavement condition. For each indicator, benefit was calculated as the ratio of the areas associated with the post-treatment case to that of the do-nothing case. If more than one condition indicator is used in the analysis, the individual benefits may be combined after applying weighting factors selected based on engineering judgment and additional analysis to produce to produce the overall benefit (Peshkin et al., 2004).

Chou et al. (2008) quantified benefit of thin overlays as the time extension of the pavement's service life, see Figure 1. They then calculated the equivalent annual cost of thin overlays and minor rehabilitations by dividing the average unit cost per lane-mile by the time extension. The overlay was considered cost effective if its equivalent annual cost was less than the equivalent annual cost of a minor rehabilitation.

Dawson et al. (2011) examined the benefit of a treatment using two different methods. One method considered was life extension as defined by the number of years the treated pavement will perform beyond the do-nothing pavement based on a reconstruction threshold value. The other method considered treatment life as defined by the number of years until the condition of the preservation segment reaches that of the pre-preservation condition, see Figure 1. However, defining treatment life as shown in Figure 6 will show some treatments have no life when using certain metrics. For example, chip seals do not cause an immediate change in IRI,

and would have no treatment life, although chip seals are expected to reduce the rate of growth of roughness, and have some effect on pavement performance (Mamlouk & Dosa, 2014).

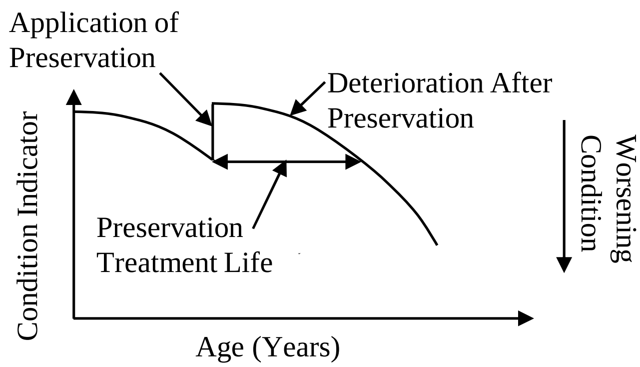


Figure 6. Treatment benefits as presented by Dawson et al. (2011)

Identifying Timing for Preservation

Each of the methods for assessing the timing of preservation incorporates a method to calculate the timing once the costs and benefits of preservation treatments are estimated. For example, some approaches involve prioritization or near optimization techniques, whereas others identify and assess possible timing scenarios.

Many methods discussed in literature review recognize that a relatively small number of possible options are available for selecting the time to apply a specific preservation treatment on a pavement segment. Calculating the costs and benefits for those options results in relatively few possible outcomes. For example, the approach discussed by Izeppi et al. (2015) begins by listing the possible treatment applications, and then calculating the benefits and costs of each application. Considering the scenario of a single preservation treatment applied to a single pavement, possible timings are enumerated and cost-benefit calculations are performed for each relatively efficiently. However, if many additional factors or many pavement segments are considered, a large number of calculations may be required.

Another technique discussed in literature is optimization, which is a technique used to find a solution that best meets a specific objective considering certain constraints. Optimization may be appropriate to address preservation timing (because of the many combinations to be considered). Wu and Flintsch (2009) discuss the application of optimization for treatment selection in the case of many pavements. Rada et al. (2016) discusses the use of optimization within the MDSHA treatment selection process when multiple treatments and long-term performance are considered.

PAVEMENT PRESERVATION PERFORMANCE

The performance of the preserved pavement is required to determine the timing of preservation. The literature addressing the effect of preservation on pavement performance is presented in this section.

Two components describe the effect of preservation on pavement performance (Qiao et al. 2016):

- The immediate change in condition. This is the difference in condition measured prior to and after the placement of the preservation treatment.
- The long-term changes in performance. This effect reflects the change in performance or the rate of deterioration following preservation treatment application.

Each of these two effects are illustrated in Figure 7. The immediate change in condition is shown as *J(R, Tx)*, noting that the change in condition (*J*) depends on the treatment type (*Tx*) and the condition when the treatment is placed (*R*). For some treatments an immediate improvement can be expected. This condition jump has been noted for several preservation treatments. For example, Carvalho et al. (2011) noted a relationship between condition jump and initial condition for several treatments when using the LTPP database. The long-term change in performance, is shown in Figure 7 as the difference in the performance of a control segment (*R(t)*) and a pavement segment which received a preservation treatment (*R'(t)*). This differences in performance have been shown to depend on many factors, including; traffic, climate, and the initial condition of the pavement (Mamlouk & Dosa, 2014; Carvalho et al., 2011).

The two components that describe the effects of preservation on pavement performance depend on the preservation treatment type, the condition of the pavement when the treatment is applied, and the specific performance measures used. For example, Mamlouk and Dosa (2014) showed that the application of a chip seal does not cause an immediate change in the IRI, but it affects a progression of IRI. In other words, they have a long-term effect on IRI.

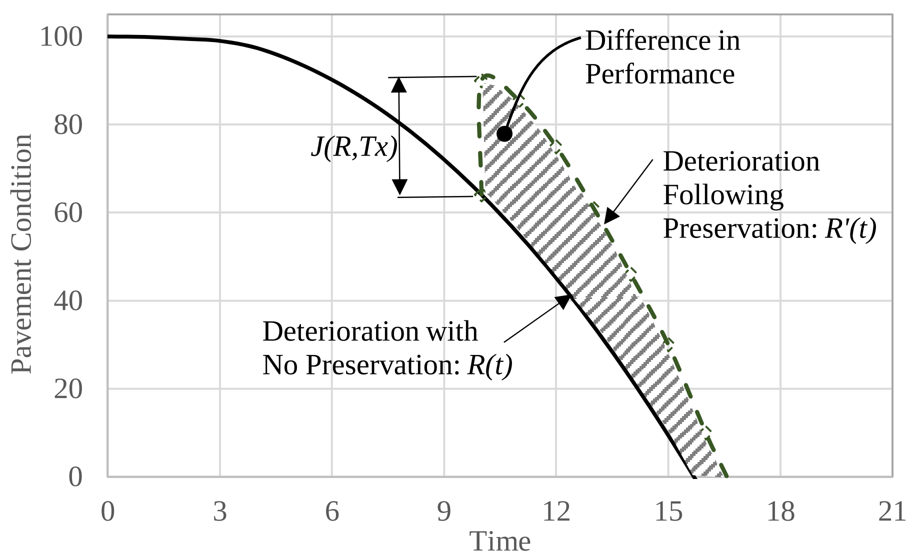


Figure 7. Illustration of the effect of preservation on performance.

Generally, the performance following preservation application is compared to that of a control scenario. Ideally, each treated pavement segment should be matched with an equivalent untreated segment in order to compare the performance, as in the LTPP SPS-3 study. However, control segments are not always available if control segments are not readily identifiable, other options can be used, such as:

- Comparing the performance of the preserved pavements to that predicted for untreated pavement using a deterioration model (e.g., as in Chou et al. (2008)).
- Identifying pavement segments that were previously candidates for preservation, but did not have preservation applied for various reasons (e.g., budget constraints), and comparing the performance of the preserved segments to that of these segments. This approach is used in this project, and is described in Chapter 4.

Carvalho et al. (2011) evaluated data from the LTPP database and found that significant differences exist between the performance of control segments and the segments using different treatments. The researchers found that thin overlays reduce the progression of roughness over time, only for pavements in freeze zone climates, pavements with high traffic, or those having a poor initial condition, chip seals, slurry seals, and crack sealing has no effect. They modeled the effects of preservation, and showed that in many cases, these effects depend on the condition of the pavement at the time of preservation application, and the following.

- Thin overlays and chip seals had an effect on pavement rutting.
- Slurry seals and crack sealing did not lead to a change in rutting performance.
- Thin overlays and chip seals had an effect on fatigue cracking.

Lui et al. (2010) calculated the service life, performance, and EUAC for several preservation treatments using data from the Kansas pavement management system (PMS) database, and modeled the effects of preservation as initial change in condition and long-term change in performance. Mamlouk and Dosa (2014) evaluated LTPP data and developed relationships for the performance of chip seal sections as a function of initial condition and climate. The results showed that chip seals have no immediate effect on roughness, but they decrease in the rate of roughness growth; the decrease depends on the initial roughness.

Ji et al. (2013) and Labi et al. (2007) evaluated microsurfacing on Indiana roads, and found the immediate changes in rutting and roughness to be a function of the rutting and roughness prior to treatment application. Prapaitrakul et al. (2007) found that permeability of pavements was not significantly reduced after the application of fog seals, and there was no significant difference in the asphalt properties between control sites and sites that were treated by fog seals. Cuelho et al. (2006) used five years Montana highways for data and found crack sealing had no effect on IRI performance. Zinke et al. (2005) conducted a literature review and crack sealing

RESULTS OF AGENCY SURVEY AND FOLLOW-UP CALLS

The purpose of the survey and follow-up interviews was to obtain a clearer understanding of the agencies' procedures for preservation timing, pavement preservation guidelines, and pavement performance data and those willing to provide information to support the research. The follow-up interviews were conducted with the agencies that indicated availability of guidelines and willingness to provide data.

Thirty-two agencies responded to the survey and 17participated in follow-up interviews. The interview addressed preservation timing and pavement management data. From the information collected in the survey and interviews, the following observations were made:

- Each agency had a unique process for selecting pavement sections for preservation.

- Nine agencies used pavement condition measures as the primary trigger for determining the time for preservation (e.g., IRI, rutting, and cracking, or a composite index). Three agencies solely used time to establish the frequency for preservation. For example, one agency's program called for preservation at 3 and 10 years, and rehabilitation at 17 years.
- There was a wide range of agencies experience and involvement in pavement preservation. Three agencies were just developing preservation programs, and eight agencies have established preservation programs for more than ten years.
- Five agencies have acceptable data in their databases for use in this study, including pavement condition data was collected on an annual or two-year basis, performance measures for asphalt pavements and preservation treatments for more than ten years.
- Some agencies noted the lack of dedicated preservation funds (only 3 of the interviewed agencies indicated having dedicated funding for this preservation program). Two agencies expressed a concern that the length of the project development process (as long as 6 years) is not conducive to planning for preservation, but needs to be considered in a pavement preservation timing methodology.

This survey and follow-up interviews highlighted the diversity of agency preservation programs, which was considered in the development of the pavement preservation timing model. The timing model must be flexible enough to be an effective tool for both mature agency preservation programs and for new programs with limited data. The most common preservation program relies on central office pavement condition measurement and management to identify pavement sections that meet preservation criteria, and then the agency regional office selects projects for implementation.

KEY FINDINGS FROM LITERATURE REVIEW AND SURVEY

The review of literature and the agency survey and interviews revealed the following findings:

- Much work has been performed in recent years regarding the timing of preservation. In many cases, the recommended timing is derived from the analysis of data available in agency pavement management databases, but in some cases timing is based on best practices.
- The majority of methods reported in the literature by researchers define timing based on pavement condition account for the difference in deterioration rate.
- The majority of the methods for defining the timing of preservation are based on cost-benefit analysis; with costs and benefits defined differently.

Benefits are generally defined by (1) the service life extension or difference in time for preserved pavement to reach a threshold value and that of the control pavement to reach the same threshold value, or (2) the area bounded by the performance curves and the defined threshold values.

CHAPTER 3. TIMING FRAMEWORK FORMULATION

This chapter presents an assessment of the general approaches and methods identified in the literature, and recommends a framework for pavement preservation timing. Validation of the methodologies considered in the framework for calculating benefits is prescribed in Chapter 4.

ASSESSING IDENTIFIED APPROACHES

Twenty-two approaches for assessing the timing of preservation were identified having varying degrees of similarity. These approaches can be classified into the following two categories:

- Network level – This approach category generally produces a set of rules and/or thresholds on when to apply preservation treatments for implementation into an agency's PMS. Those rules may define specific time intervals or condition thresholds for applying treatments using one of the following two approaches:
    + Evaluate the costs and benefits of applying preservation at specific time intervals and recommend an age range at which preservation should be applied to a pavement.
    + Evaluate the costs and benefits of applying preservation at specific condition thresholds and recommend a range of conditions at which preservation should be applied to a pavement.
- Project level – This approach category produces a specific time or condition to apply a specific treatment to a pavement. These involve one of 3 processes:
    + Conducting a cost-benefit analysis of applying the preservation in certain years to identify the timing at which the cost-benefits are optimized.
    + Assessing the benefits of applying preservation in specific years, and selecting the timing as the year at which the benefits are maximized.
    + Evaluating the effect of preservation on the material properties of the existing asphalt pavement, and recommend timing at which the preservation affects these properties (e.g., fracture properties most optimally)

However, the literature revealed that the approaches at the network level are essentially an aggregation of results from the project level approaches. For example, cost-benefit analysis is conducted for specific pavements at the project level, and network level results can be obtained by aggregating a wide range of these project level analyses to develop age or condition based rules or recommendations for the network. Therefore no such differentiation will be used the remainder of this chapter.

The survey of state DOTs has shown that many agencies use similar approaches to those found in the literature review. These approaches define a set of condition thresholds at the network level for use as benchmarks for preservation timing. However, some agencies (e.g., Maryland DOT State Highway Administration) perform a thorough assessment by estimating costs and benefits for different treatment types and different timings to serve as a basis for preservation decisions. An evaluation of the twenty-two identified revealed that the following:

- Fifteen approaches use some form of cost-benefit analysis to define timing. These approaches require the effects of preservation on condition metrics to be defined, and benefits were defined as a relative life extension, or as an area bound by the condition as a function of time. Costs were generally limited to agency costs (i.e., excluded user or other costs).
- Three approaches sought to only maximize effectiveness (i.e., costs were not considered). The definition of effectiveness varied. Some approaches defined effectiveness in terms of service life extension but others defined it as the area beneath the performance curve. These approaches include a step for assessing effectiveness to calculate the benefits.
- Two approaches evaluated the effect of preservation on the material properties of the existing pavement, to define preservation timing as the age when the preservation treatment had the greatest positive effect on the pavement material properties. These approaches were not considered further because they are not extensive enough to generalize results, and only focuses on one benefit of applying preservation (i.e., slowing down the oxidation of the underlying asphalt pavement).
- Two approaches used expert judgment to assess the timing of preservation. These approaches were not considered further in the project because of possible biases.

It was concluded that the most promising approach to defining the timing of preservation is based on a cost-benefit analysis. It is expected that basing an approach on cost-benefit analysis leverages existing methods used to estimate the costs and benefits of pavement projects within agencies. For example, it is expected that agencies have existing methods for estimating the costs of specific projects. Also, extensive literature exists documenting the effects of preservation on pavement condition and performance, and an approach based on cost-benefit anlysis can use these results. The calculation of benefits requires the change in condition and changes in performance that result from the application of preservation, and much research regarding these changes for specific preservation treatments has been documented in the literature. Finally, a cost-benefit based approach is expected to provide flexibility for agencies to define costs in parallel with their best practices.

Uncertainties in the predicted costs and benefits were not addressed in any of the identified literature; uncertainties are defined as the variability in the projected costs and benefits resulting from many potential sources (e.g., performance prediction, cost estimation). Much of the literature demonstrating the effects of preservation showed the results to have significant uncertainies (e.g., Ji et al. (2013), Labi et al. (2007) and more). Although the final timing for preservation is a single value, this project demonstrates the benefits of considering uncertainties.

General Approach for Assessing Preservation Timing

Several approaches based on cost-benefit analysis were assessed and were generally found to have the following seven steps in common:

Step 1: Select the performance measure or condition indicator that will be assessed. Most of the approaches found throughout literature do not require that only a single indicator be selected, but instead recommended methods for combining the results from using multiple measures or indicators. Each of the performance measures or indicators are affected differently by preservation treatments.

Step 2: Define the preservation treatment under consideration.

Step 3: Define a set of rules for when the treatment should no longer be considered as a set of condition thresholds beyond which specific preservation treatments are no longer a consideration.

Step 4: Calculate the costs and the benefits of applying the preservation treatment starting with the first year under consideration. A detailed discussion of this step is provided in Chapter 4.

Step 5: Combine the costs and benefits into a single value using a defined mathematical function, which is detailed in Chapter 4. Three types of functions were identified:

- The function implemented by the MDSHA (Rada et al., 2016) seeks to maximize effectiveness divided by the agency cost for applying the treatment, where the cost is adjusted by a factor of vehicle miles traveled and AADT.
- The function developed in NCHRP Report 523 (Peshkin et al., 2004) seeks to maximize the benefits divided by the costs of applying a specific treatment. All timing scenarios are normalized by the optimal scenario for comparison purposes.
- Thirteen of the remaining 20 approaches seek to maximize cost-effectiveness (i.e., maximizes benefits divided by costs) or to minimize cost-benefit (i.e., minimize costs divided by benefits).

Another important aspect of Step 5 is to define how the benefits or effectiveness are combined. For example, Peshkin et al. (2004) recommend the use of benefit weighting factors, which are used to assign a relative level of importance to each benefit, and the combined benefit is the sum of the products of each benefit and its corresponding weighting factor.

Step 6: Repeat Step 4 and Step 5 for the number of years considered in the analysis, as long as the pavement segment still meets the requirements defined in Step 3.

Step 7: Select the timing as the year that the function from step 5 is best satisfied. For example, if the defined function is to minimize costs divided by benefits, select the timing as the year in the analysis when the costs divided by the benefits is minimized.

Models describing the effects of preservation on pavements have a significant amount of uncertainties, and those were not included in any approach defined in literature. Both the performance prediction of pavements and the estimation of costs add uncertainty to the timing. The framework developed in this project includes uncertainties.

RECOMMENDED TIMING FRAMEWORK

A recommended framework was developed in this project based on the approach outlined in the previous section, and is shown in Figure 8; the major framework steps are detailed over the remainder of this section.

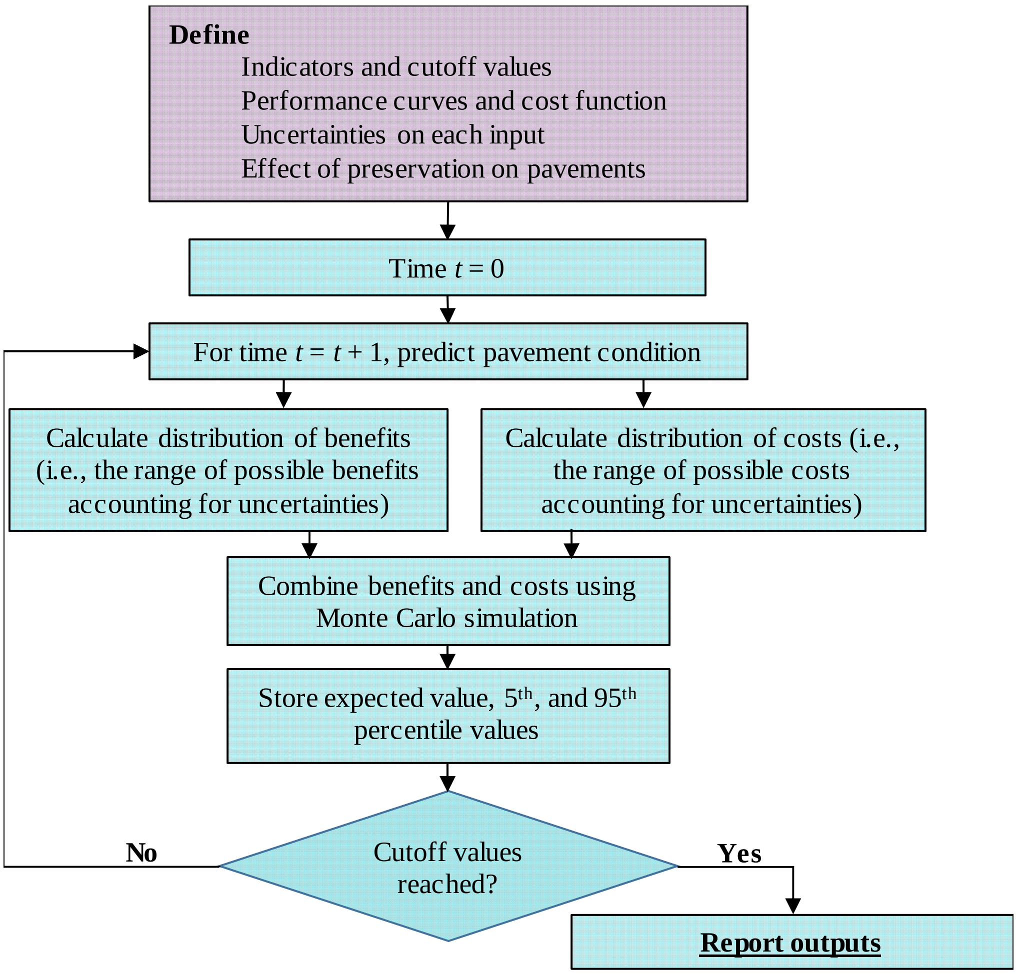


Figure 8. Framework for selecting the timing of preservation.

Defining Inputs

The first step is to define the performance measures or indicators that will be used, as well as a set of cutoff values. For each performance measure or indicator, the cutoff value is the threshold beyond which preservation should no longer be considered. Other variables defined in the first step include the performance curves, a cost function that may include the cost to apply the preservation as a function of time or pavement condition and the uncertainties associated with each input.

Calculating Distributions of Costs

It was found that each agency defines costs differently, both in terms of what costs are included, and in terms of how the costs change as a function of time (e.g., a discount or inflation factor added to the costs). As discussed in NCHRP Report 523 (Peshkin et al., 2004), the following costs are generally associated with preservation:

- Agency costs, including material and construction costs, as well as other ancillary costs associated with planning, designing and construction.
- Work zone related costs to the users (e.g., user delay costs, etc.).
- Costs associated with routine maintenance.

- Cost of future maintenance activities.

Many additional costs not included in the preceding list can be considered, such as vehicle operating or environmental mitigation costs. The Guide provided as an attachment to this report details approaches for calculating costs for multiple preservation treatments.

Calculating and Combining Benefits

The benefits of applying preservation can be defined in many ways, and the two most common methods are to define the benefit as a relative service life extension, or a relative increase in performance. This project recommends calculating the benefits as the relative increase in performance, and the development of that recommendation is detailed in Chapter 4. The Guide also presents an approach for calculating a combined benefit based on a relative weighting of each performance measure.

Calculating Preservation Timing Function Values

The next step in the framework is to calculate values of the defined timing function, also known as an objective function. The term objective function will be used for the remainder of the report. The recommended objective function is described in Chapter 4, and the approach to calculating and using the results of the objective function is presented in the Guide.

Reporting the Results

The final steps in the recommended framework are checking whether the defined cutoff values have been reached, and reporting the results; examples of reporting the results are demonstrated in the Guide.

SUMMARY OF APPROACHES AND FRAMEWORK

By critically reviewing the approaches identified in the literature, it was found that a consistent set of steps can be followed for determining the timing of pavement preservation. Those steps were described in this chapter, culminating in a framework for preservation timing, and the development of specific methods within those steps is detailed in Chapter 4. The framework developed in this project requires many analysis methods to support the calculations, and the development of those methods is detailed in Chapter 4. In addition, specific recommendations for how to apply those methods within the framework are detailed in the Guide provided as an attachment to this report.

CHAPTER 4. TIMING FRAMEWORK DEVELOPMENT

This chapter presents the results of developing and validating methods to implement the framework from Chapter 3, and it makes recommendations for the methods supporting the framework. The recommendations were based on collecting and evaluating extensive databases of pavement performance from State DOTs and the LTPP program. The gathered data were used for modeling the effects of preservation on pavement performance, and details of the example models are presented in Chapter 5.

The first part of the chapter details the assessment of inputs to the performance models required by the framework. Second, a method for calculating benefits is recommended. Third, assessment of cost components is described, and finally, a method for combining costs and benefits is recommended.

IDENTIFYING AND ASSESSING CRITICAL INPUTS

The first step in developing and validating approaches for implementing the framework presented in Chapter 3 was to identify the required inputs. The following are the primary inputs to the framework:

- Current measured conditions for the pavement segment.
- Cutoff or threshold values defining the range of conditions for which preservation can be considered.
- Performance models for a control segment (described later in this chapter).
- Cost functions.
- Models defining the immediate change in condition and changes in performance associated with the preservation treatment under consideration.
- Uncertainty values associated with each input.

Of the inputs that are required for the framework, the most data intensive are the models defining the immediate and long-term effect of preservation treatments. Assessing the critical inputs to the preservation treatment effects models was the first assessment in the validation of the framework. Data were gathered from the LTPP SPS-3 in order to identify critical inputs and model characteristics. The data gathered included:

- Traffic in terms of AADT.
- Climate in terms of mean annual precipitation, mean average annual temperature (MAAT), the mean annual number of freeze thaw cycles (FTC), the freezing index, and the mean annual number of degree days above 90 degrees Fahrenheit.
- Existing thickness and material type of all layers above the subgrade.
- Existing pavement condition in terms of the IRI, rutting, total length of transverse cracking, total area of fatigue cracking, and total length of longitudinal cracking.

These data were gathered for thin overlays, chip seals, and slurry seals.

Statistical models were developed to relate the change in performance of the pavement to the gathered variables. It was found that each of the data collected were significant for different performance measures and different preservation treatments. For example, the transverse

cracking models were more sensitive to temperature data, whereas the rutting models were more sensitive to pavement thickness and traffic data. In all cases, the change in performance was related to the pre-existing condition for the specific performance measure being modeled.

Two significant findings that resulted from this effort are:

1. No single model functional form is adequate to describe the change in performance for each preservation type for a given performance measure. This is based on the finding that each variable was not consistently relevant across the preservation treatments. Therefore, a separate regression was performed for each treatment type and performance measure to identify significant variables.
2. Climate data were significant in each model and subgrade soil data were significant in many models, and therefore a consistent set of inputs were needed for each of these sets of data. This resulted in the use of national level soil and climate data to develop a set of climate and subgrade soil databases for each county in the United States; this effort is detailed next. These national level soil and climate data were used to develop and validate the example models (see Chapter 5).

The next sections detail the development of default climate and subgrade soil data. No agency included detailed climate data with the information submitted for this project, and only one agency submitted estimates for subgrade resilient modulus values. The LTPP SPS-3 experiment contains climate data, but not subgrade resilient modulus values. The data detailed in the following sections were used for model development purposes.

Developing Climate Data

The climate inputs were derived from the Modern-Era Retrospective analysis for Research and Applications (MERRA) database that was developed by the National Aeronautics and Space Administration (NASA). MERRA was used in the LTPP program to provide an improved source of climate values (Schwartz, et al. 2015). The MERRA data set extends from 1979 to the present, and is a result of the NASA Center for Climate Simulation. MERRA is based on satellite imaging information, and is available at an hourly temporal resolution and a horizontal spatial resolution of 0.5 degrees latitude by 0.67 degrees longitude (which is approximately 31 miles by 37 miles at mid-latitudes). Each of the individual areas of spatial resolution are referred to as cells, and are identified by coordinates that define the centroid of each cell.

The MERRA data used on this project were extracted from LTPP InfoPave Climate tool, including information from the year 2000 through the year 2014 (inclusive) – this was the average range of the pavement performance data gathered in this project. In addition, a listing of all counties in the contiguous US, along with the coordinates of their centroids were gathered from the US Census Bureau website. The centroid of each county was paired with the closest MERRA cells, and the corresponding climate properties were then mapped to the county. Many counties are covered by multiple cells, and thus the approach to defining variables for each county was to find the 3x3 grid of MERRA cells that had a centroid nearest to the county centroid. This approach was taken to reduce significant variability that was found in adjacent cells near mountainous areas or areas near large bodies of water. As an example, Figure 9 shows the map of the county level mean annual temperature values used in this analysis.

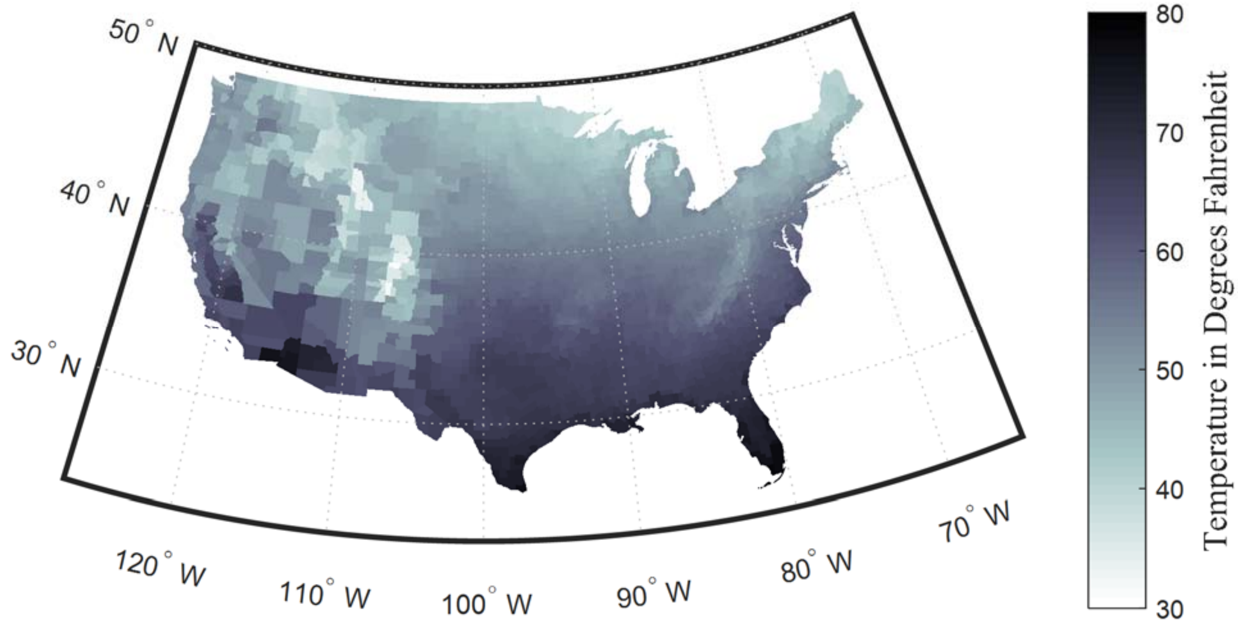


Figure 9. Map of county level mean annual temperature used in this analysis.

Developing Consistent Subgrade Soil Data

Subgrade soil data was derived from the US Department of Agriculture's (USDA) Natural Resources Conservation Service (NRCS) soil survey. A project with the National Cooperative Highway Research Program (NCHRP Project 9-23A) investigated the use of the NRCS data to obtain soil engineering properties for use with the Mechanistic Empirical Pavement Design Guide (MEPDG) (Zapata 2010). The properties stemming from NCHRP Project 9-23A are mapped as homogenous soil types, and not based on county level boundaries. Therefore, the first necessary step was to link the soil types to each county in the US based on the percentage of each soil type within each county. This was done by importing the NCHRP soil engineering properties database into a geographic information system (GIS) application, and then overlaying the US county map onto the soil database. Then, each soil type that covers more than 10 percent of the county (by area) was identified, and their properties were extracted.

The soil data were extracted such that soil layers that extend at least to a depth of 18 inches were sought. If data for soils at this depth were not available, then data for the layers extending at least to 12 inches of depth were used. Finally, the soil properties in each county and each soil type were averaged by percent area. After extracting the data and splitting it into fine and coarse grained soil types, it was found that information was available for 99 percent of counties in the US. Counties with missing soil properties were matched with the properties from the nearest county. The results of this effort were a consistent set of county-level subgrade soil modulus values for each county in the contiguous US, as illustrated in Figure 10.

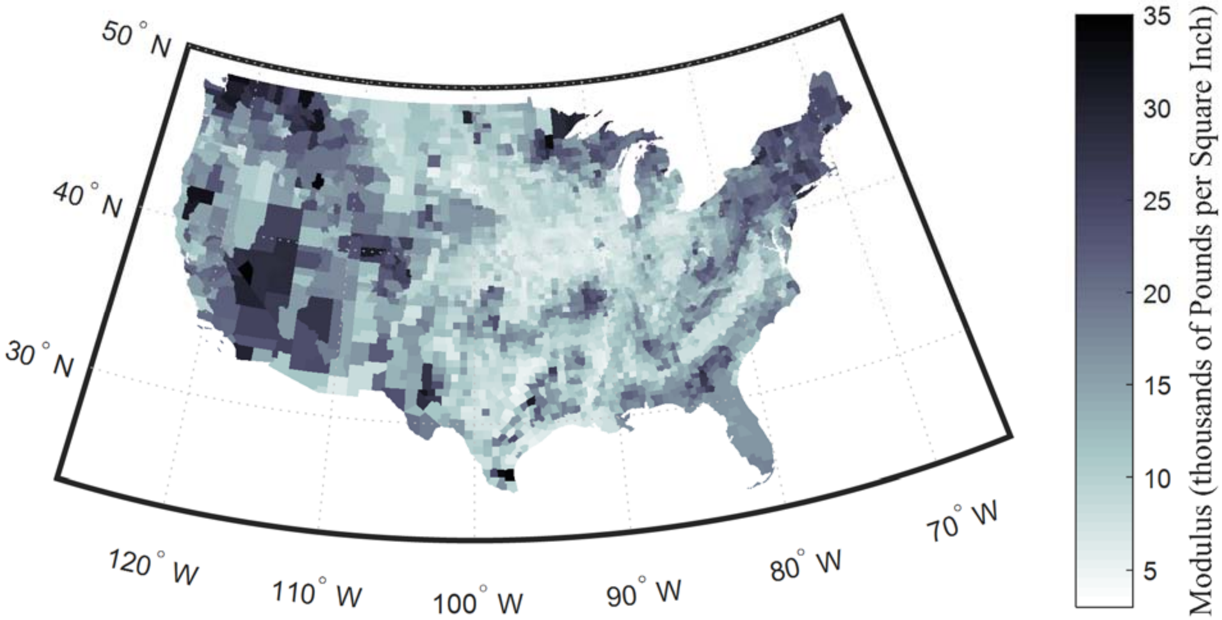


Figure 10. Map of county level subgrade resilient modulus values used in the analysis.

Agency Data Gathering

Pavement condition and construction history data were gathered from multiple agencies and the LTPP, as summarized in Table 1.

Table 1. Treatment data.

Agency	Number of Years in Condition Data	Thin AC OL	Chip Seal	Microsurfacing	Slurry Seals
Maryland SHA	15	✓		✓	
Virginia DOT	8	✓	✓		
Kansas DOT	16	✓	✓		✓
Idaho DOT	15		✓		✓
Utah DOT	3		✓	✓	
Texas DOT	10		✓		
Ohio DOT	30+ (Entire Database)	✓	✓	✓	
Tennessee DOT	16	✓			
Maine DOT	16	✓		✓	
Louisiana DOTD[1]	15	✓	✓	✓	
LTPP	10-15 (Site Dependent)	✓	✓		✓

✓ Indicates data received
Blank cell indicates that a given State did not provide data for a given treatment
1. Louisiana Department of Transportation and Development (DOTD)

A consistent set of performance measures (i.e., those that could be obtained from multiple sources) was identified to compare the effects of preservation. In many cases, agencies that contributed data to this effort included both composite measures (e.g., Pavement Condition Indexes) and individual distress data. The composite measures submitted by each agency were unique and were not considered in this research. The models of the effects of preservation were developed for the following performance measures:

- Pavement roughness in terms of the IRI.
- Rutting.
- Length of transverse cracking.
- Length of non-wheel path longitudinal cracking.
- Area of fatigue cracking.

Combining the list of treatments with the performance measures reduced the number of data sources available for any given treatment-measure combination. For example, only IRI data could be used from one specific agency given that they did not include rutting data or detailed cracking data in their database. In addition, cost data were submitted by many agencies, but those data were not provided in a consistent way. In some cases, a single cost was given for preservation from the network-level pavement management decision trees, whereas some agencies provided detailed expected costs per treatment, and others provided actual contract costs for projects.

Factors Considered in Modeling

Pavement performance is affected by the separate and combined effects of traffic loading, climate, subgrade soil, construction quality and the materials and structure of the pavement. Variables related to each factor that affects pavement performance were not available, so only a subset could be used in this project. The following factors were used when evaluating the approaches and developing the example models in Chapter 5:

- Climate variables:
  - Mean annual number of freeze thaw cycles
  - Count of the degree days above 90°F
  - Mean annual air temperature
  - Mean Annual Precipitation
- Traffic in terms of estimates of AADT
- Structure in terms of the overall pavement thickness above the subgrade
- Subgrade resilient modulus estimates

Many additional variables can and should be considered when developing performance models, such as a more detailed estimate of traffic data (e.g., load spectra) or a more detailed estimate of pavement structure (e.g., Structural Number). However, those variables were not available in this project, and thus were not used.

QUANTIFYING PRESERVATION BENEFITS

Defining benefits required the development of models that describe the effects of preservation on pavement performance. The first step was to define the immediate change in condition expected from the application of preservation. The second step was to model the changes in performance resulting from the application of the preservation treatment, and the last step was use the information from the first two steps to calculate benefits. Each of those activities are detailed in this section, and the example models that were developed using State DOT and LTPP data are detailed in Chapter 5. The models developed for each treatment and performance measure combination are presented in Table 2. In some cases the data did not show that statistically significant models could be developed (e.g., IRI model for microsurfacing), and those are marked accordingly.

Table 2. Treatment and performance measures modelled in Chapter 5.

	IRI	Rutting	Transverse Cracking	Fatigue Cracking	Non-Wheel Path Longitudinal Cracking
Thin Overlay	✓	✓	✓	✓	✓
Chip Seal	✓	✓	✓	X	✓
Microsurfacing	X	✓	✓	X	✓
Slurry Seal	✓	✓	✓	✓	✓

✓ = models were developed for these treatment / performance measure combinations
X = there was insufficient data to support the development of a model

Modeling Immediate Change in Condition

The immediate change in condition can be directly estimated by calculating the difference in the performance measure before and after the application of preservation. The data for this analysis were restricted to only those segments with annual measurements to reduce the error caused by not having measurements immediately before and immediately following the application of the treatment. Chapter 5 details the results of calculating the immediate change in condition for each performance measure and preservation treatment combination defined in Table 2.

In addition, it was found that the primary variable for explaining the immediate change in condition following preservation was the pavement condition prior to the application of the treatment. Therefore, the only explanatory variables necessary to estimate the immediate change are the preservation treatment type and the condition of the pavement.

Modeling Change in Performance

Modeling the change in performance includes many steps, and details for completing those steps are provided in Chapter 3 of the Guide attached to this report. The recommended approach estimates the growth rate of each distress from measured condition data, and then predicts distress growth as a function of many independent variables (e.g., climate, condition). Although distress growth rates are generally not linear throughout time, the assumption of linearity over a short time period (i.e., 5 to 8 years) is used for estimating the growth rates for a particular set of input variables. Then, the growth rates for a group of pavements are matched with the independent variables to create a model. Chapter 3 of the attached Guide details each step in the approach with examples using data collected during this project.

The approach for modeling the change in performance is:

1. Gather all available data on each preservation segment, including all available independent variables (e.g., condition, climate).
2. Select an appropriate set of control segments, and gather data for all available independent variables consistent with the previous step.
3. Assess the data to minimize the potential of including segments with unrecorded maintenance. Unrecorded maintenance may show as unexplained significant change in performance measures.

4. Develop a model for the immediate change in condition due to the application of preservation and compare it to the change in the control segments to assess the model significance.
5. Estimate the growth rate of each performance measure for each pavement segment by fitting a linear model to condition measurements following the application of preservation (or for the selected analysis period in the case of control segments).
6. Combine the results from step 5 for each treatment and performance measure combination and compare the overall distribution of growth rates for preservation and control segments.
7. Develop a model to relate independent variables to the growth rates and include an indicator variable in the model that denotes if it is a preservation or control segment.
8. Assess the model for its viability in predicting performance over a broad range of conditions, as well as to ensure the relationships match engineering expectation.

The outcome is a model to compare the performance of control segments to the performance of segments that receive a preservation treatment, which are required to calculate the preservation treatment benefits. The two sets of example models (immediate change and changes in performance) were developed in this project using DOT and LTPP data, and they are detailed in Chapter 5.

Calculating Preservation Treatment Benefits

Two approaches for defining preservation treatment benefits were investigated in this research, the service life extension and the benefit area (see Figure 5). Note that the graph in Figure 5 is commonly used to present pavement performance in terms of a composite index and the graph in Figure 11 is used to present pavement performance for an individual pavement condition, such as rutting. Referencing Figure 11, the specific approach to calculating the benefit area in this research is defined as Area A divided by the sum of Area A and Area B. The benefit area calculation results in a value between zero (no effects from preservation) and one (maximum benefits from preservation).

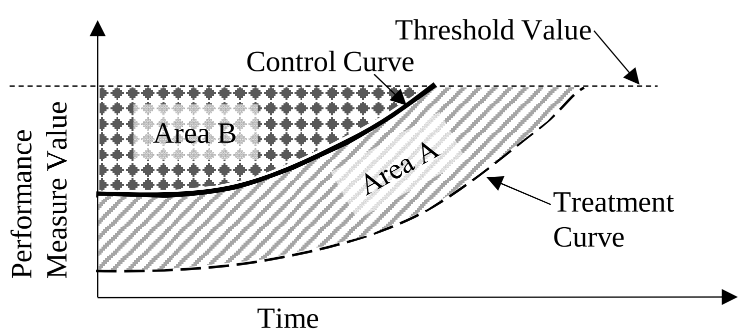


Figure 11. Schematic of normalized performance.

A simulation was performed using the thin overlay models (see Chapter 5) to assess the advantages and drawbacks of each definition of preservation effectiveness. IRI, rutting, transverse cracking and non-wheel path longitudinal cracking were considered in this assessment. The assessment consisted of defining a set of inputs for the thin overlay model, and then varying the threshold values for each performance measure. The results of the analysis

showed that the service life extension and benefit area are both equally sensitive to the defined thresholds, though relatively small correlation was found between the service life extension and improvement in performance.

It was found that defining the benefits of preservation as the benefit area more closely captures the non-linearity in the condition as a function of time. The reason for this is demonstrated in Figure 12, where the two treatment curves result in the same life extension, but different benefit areas. Defining the performance as the normalized area encompassed by the control and treatment performance curves during the analysis period accounts for differences in the shape of the performance function, whereas using service life extension only considers the time difference until a threshold is reached. Defining benefits as Area A divided by the sum of Area A and Area B in Figure 11 is the recommendation of this project, as is detailed in Chapter 3 of the Guide attached to this report.

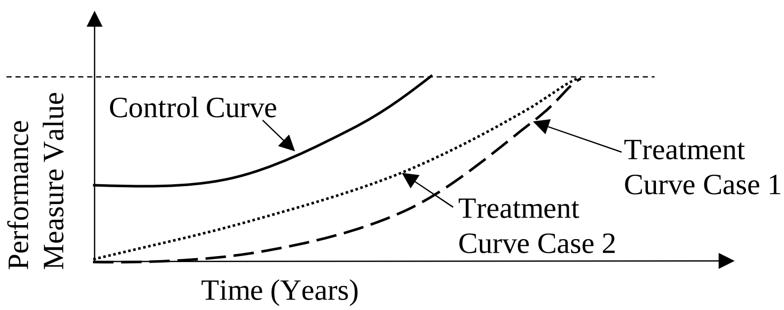


Figure 12. Schematic of control and two treatment curves with equal service life extensions but different benefit areas.

To demonstrate the recommended benefit area, a set of example calculations comparing rutting and transverse cracking was developed. The thin overlay models presented in Chapter 5 were applied to a pavement with the following inputs:

- IRI before the overlay is 110 inches/mile.
- Rutting before the overlay is 0.15 inches.
- Transverse cracking before the overlay is 150 feet/mile.
- Average annual daily traffic is 2,500.
- Mean annual air temperature is 48 degrees Fahrenheit.
- Mean annual precipitation is 35 inches.
- Count of the degree days above 90 degrees Fahrenheit is 28.
- Subgrade resilient modulus is 12,000 pounds per square inch.

A threshold for rutting was assumed as 0.18 inches, and a threshold for transverse cracking was assumed as 1,500 feet/mile, and the benefit area was calculated using those performance measures. Figure 13 shows the performance of control and preservation segments, and the values of the calculated benefit area for both performance measures. Figure 13(a) shows a relatively small benefit area for transverse cracking, whereas Figure 13(b) shows a relatively large benefit in terms of rutting. Thus, it can be interpreted that rutting has more than twice the relative benefit from the overlay when compared to transverse cracking.

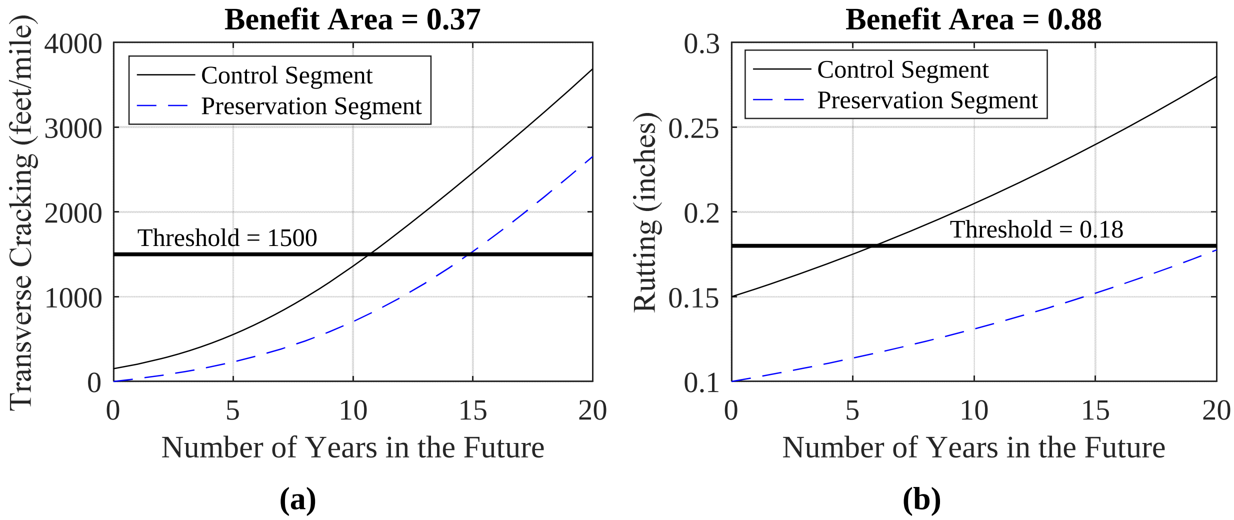


Figure 13. Example benefit areas.

DEFINING PRESERVATION COSTS

The recommended framework is based on cost-benefit analysis as a function of time, which requires an assessment of preservation costs. Zimmerman (2017) discusses the prevalence of cost data in PMSs and notes that, although the majority (77 percent) of State agencies have cost data in their PMS, there is no consistent set of costs across all agencies. In other words, cost data are specific to agencies, and specifying a list of cost elements to be included in this assessment would not reflect the wide array of practices at the agencies. At a minimum, the costs input to the framework should include the expected costs of the preservation activity with all associated costs (e.g., mobilization, signage, etc.) included.

An assessment evaluated whether preservation costs vary as a function of pavement condition. However, a direct assessment of the cost as a function of condition could not be performed because the cost data provided by DOTs was too limited. Therefore, the elements of the cost data from DOTs that submitted some detail with their costs were investigated in more detail. The comparison revealed that one DOT does account for pavement condition before preservation when estimating expected preservation costs. For example, the assessment for that particular agency showed that the costs of thin overlays can be expected to increase by up to 10 percent from a baseline value when the existing pavement condition goes from good to poor condition. Data from other DOTs did not show pre-existing pavement condition as a factor when developing cost estimates. For example, the detail included in the estimate of microsurfacing costs from one DOT that submitted data for this project was investigated. The total expected cost of microsurfacing for two lane-miles is estimated as 64,000 US dollars, and includes:

- 46,200 dollars for the cost of the treatment (materials and transportation).
- 3,700 dollars for mobilization (8 percent of treatment costs).
- 3,700 dollars for temporary signs and barricades (8 percent of treatment costs).
- 2,800 dollars for temporary pavement markings.
- 250 dollars for reflectors on raised pavement.
- 3,700 dollars for pavement striping.
- 3,700 dollars for construction layout (8 percent of treatment costs).

The cost estimate for microsurfacing for the DOT is the sum of above costs. Although the cost amounts will vary, it is expected that agencies can follow a similar process to develop cost estimates. Furthermore, Chapter 3 of the Guide provided with this report presents more detail regarding the development of cost models.

Finally, future costs are discounted, and correlate to deterioration in pavement performance measures. Therefore, even in the case that condition is not a direct input to the cost calculation, the covariance between cost and condition is non-zero. The results of these assessments demonstrate that cost should not be treated as a fixed constant in the calculations, but instead should be treated as a function of time (i.e., discounted or inflated) and condition.

DEFINING THE OBJECTIVE OF THE ANALYSIS

The next step is to define the mathematical equation that will be optimized in the timing analysis, otherwise known as an objective function. Objective functions are defined as the mathematical representation of the goal of the analysis. For example, if an agency is only concerned with minimizing costs while maintaining pavement condition above specified thresholds, then the objective function will be defined as the cost for maintaining the pavement segment and the condition thresholds will be set as analysis constraints. Two objective functions were evaluated as part of this project. The first objective function was to minimize costs divided by benefits, which is shown in Equation 3.

$$\min z = \frac{\left(\frac{Cost_i}{\min(Cost_i)}\right)}{1+WB_i} \tag{3}$$

Where:

z = value of the objective function.

$Cost_i$ = cost calculated in year i.

WB_i = weighted benefits associated with applying preservation in year i.

The second objective function is based on a cost-benefit vector length calculation, and is shown as Equation 4. The concept behind using a cost-benefit vector is demonstrated after the equation. The objective function shown in Equation 4 is based on methods widely used in decision analysis settings (e.g., Romero et al. (1998), Eiselt and Sandblom (2007), and Bryce et al. (2014)).

$$\min z = \left[w_b(1-WB_i)^2 + w_c\left(\frac{Cost_i}{\max(Cost)}\right)^2\right]^{\frac{1}{2}} \tag{4}$$

Where:

Z = value that is being minimized – this value represents the cost-benefit vector length between the optimal hypothetical solution and the calculated outcomes of each potential timing (i.e., each cost and benefit calculated for each potential timing)

WB_i = weighted benefits associated with applying preservation in year i

$Cost_i$ = net present cost associated with applying preservation in year i

w_b = weight assigned to reflect the relative importance of benefits to the overall assessment

w_c = weight assigned to reflect the relative importance of costs to the overall assessment

A schematic that demonstrates the concept of the cost-benefit vector is shown in Figure 14. Fundamentally, the cost-benefit vector estimates how far each potential preservation timing scenario is from the most ideal point – i.e., the origin on the plot where the lowest costs and maximum benefits are observed. The origin on the plot is a hypothetical location with zero cost and maximum benefit, and thus is referred to as the optimal hypothetical solution. The point on the plot that is closest to the optimal hypothetical solution is selected as the best outcome, and the timing associated with that point is selected as the optimal preservation timing.

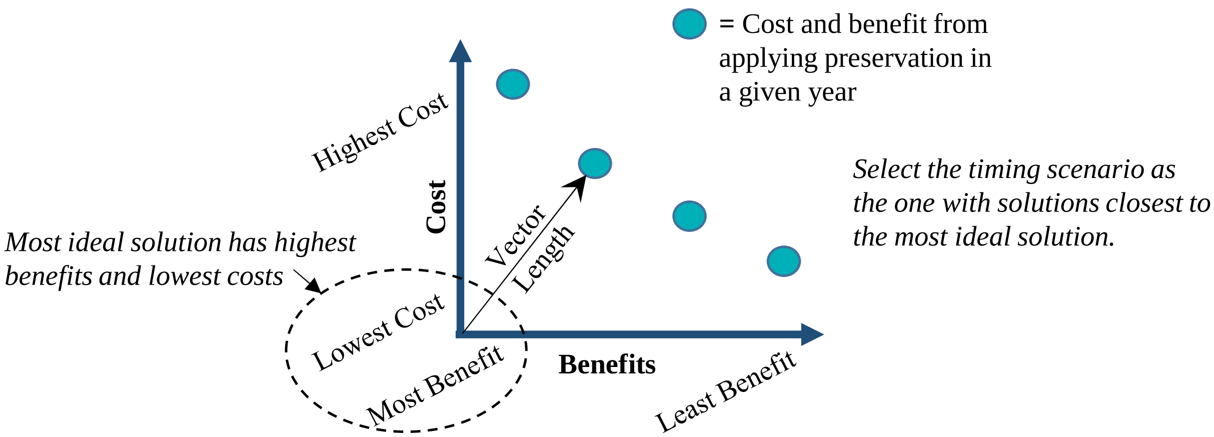


Figure 14. Schematic of cost-benefit vector based approach.

Both functions were assessed for their benefits and drawbacks. The function shown in Equation 3 is a common representation of costs scaled by benefits, such that increasing costs has the same effect as decreasing the benefits by the same proportion. The objective function in Equation 4 accounts for the magnitude of the costs and benefits, and therefore increasing costs by a certain percentage does not have the same effect as decreasing benefits by the same percentage.

Several analyses were performed to assess the benefits and drawbacks of Equations 3 and 4. First, an estimation of the sensitivity of each equation to uncertainties was performed, where the models described in Chapter 5 were used with randomly generated inputs to simulate many possible scenarios. The sensitivity results were investigated to understand how the timing changed with the inputs, and both equations had similar levels of sensitivity to the input variables. Then, several examples were analyzed where costs and benefits were each varied and the outputs from both equations were evaluated. Figure 15 shows a comparison of the timing recommendations using both equations. The variation in timing (from 2 to 10 years) shown in Figure 15 is driven primarily by the variation in costs, and principally by the variations in the discount rate in the illustrated results. A higher discount rate leads to lower future costs, which lead to a larger timing recommendations. Figure 15 also shows that, although both equations are sensitive to costs, Equation 4 is less sensitive to variations in cost.

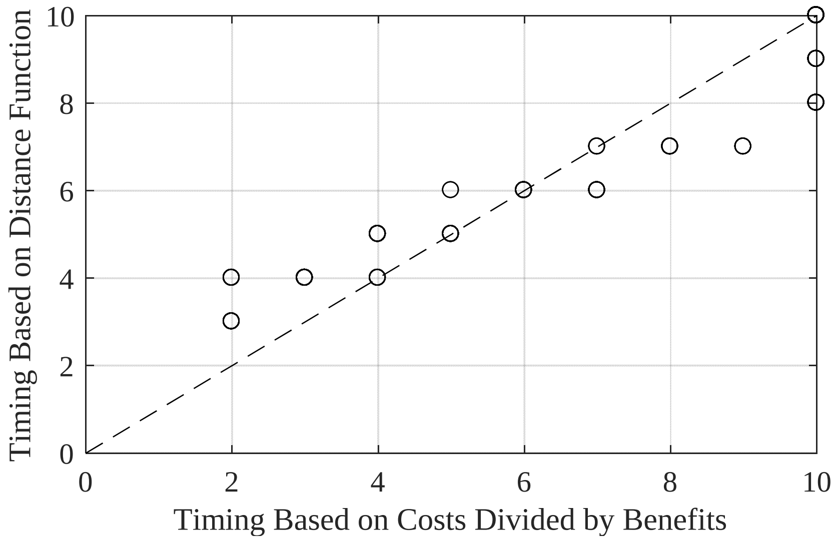


Figure 15. Comparison of timing using both objective functions.

An additional analysis was performed to investigate how the sensitivity of the results to variations in cost and benefit terms was affected by the weights to each term; lower sensitivity to the weights is desirable because they are subjective. This analysis was done by applying random weighting factors to the cost terms in each equation, and then evaluating the impact of the weighting factors. The results for weighting the benefits two times the costs in both equations are shown in Figure 16. The sensitivity of timing based on Equation 4 was reduced much more than the sensitivity from Equation 3. The benefit of lower sensitivity to the weights for costs and benefits is that the timing recommendation is not as significantly affected by subjective preferences.

As a result of the analyses, it was recommended that Equation 4 be used as the function to determine preservation timing. The benefit of using Equation 4 is that the two inputs (cost and benefits) can be adjusted independently, and the contribution of costs and benefits to the overall timing can be weighted separately in a linearly additive manner.

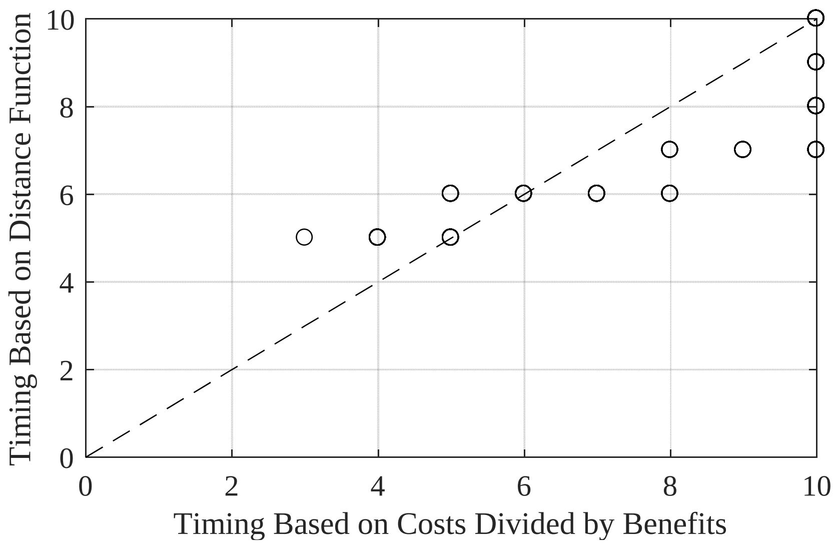


Figure 16. Comparison of timing using revised objective functions.

ESTIMATING UNCERTAINTIES

The recommended preservation timing framework includes uncertainties related to variability in performance prediction and costs. Chapter 5 presents the variability in the performance prediction models, and it is recommended that a qualitative approach to uncertainty be used when defining costs. Two methods of determining uncertainty are described next, quantitative (data driven) and qualitative (expert opinion).

Quantitative Uncertainties

Quantitative uncertainties are those that are developed as a direct result of analyzing the variability in a set of data or a prediction model. To demonstrate the calculation of quantitative uncertainties, rutting data before and after the application of the overlay were gathered from a DOT that submitted data for this project. The data were used to develop a model to predict the change in rutting following the application of a thin overlay using the approach detailed in Chapter 3 of the Guide; the results of that model are shown in Figure 17. Equation 5 gives the immediate effect of the thin overlay on rutting based on the data.

$$Rut_{Post} = 0.107 - 0.15 \times Rut_{Pre} \quad (5)$$

Where:

Rut_{Post} = rutting (inches) predicted after the overlay

Rut_{Pre} = rutting (inches) measured before the overlay

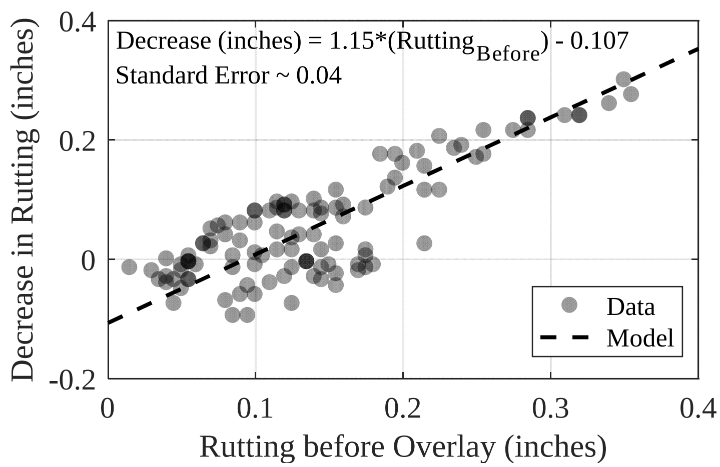


Figure 17. Immediate change in rutting following a thin overlay.

The standard error of the model, which is a measure of the variability of predictions, is 0.04 inches. For simplified cases, this can be used as an estimate of the uncertainties in the predicted values. Another approach for estimating the prediction errors of a model is to withhold a subset of data from the model development, then use the withheld data to validate the model. The approach for withholding data or using cross-validation techniques to estimate model uncertainties can be found in Carroll et al. (2006) among other sources. Figure 18 shows the distribution of errors when using a cross-validation technique for comparison to the standard error estimate. The results in the figure indicate that the standard deviation of the predicted change in rutting is 0.05 inches, which is similar to the standard error shown in Figure 17.

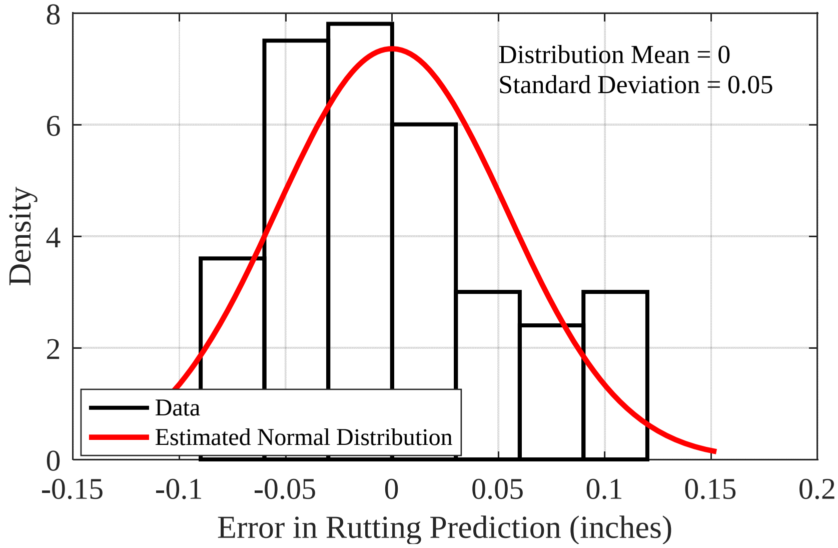


Figure 18. Error in predictions for changes in rutting following a thin overlay.

The uncertainties provide a direct estimate for how much confidence should be placed in a set of results. For example, using the Equation 5 with the results in Figure 18, an analyst can be 95 percent confident that a thin overlay placed on a pavement with 0.2 inches of rutting will cause a reduction in rutting between 0.025 and 0.2 inches (predicted value ± 1.96 standard deviations), which is a very wide prediction margin. Chapter 4 of the Guide demonstrates how combining the estimates for uncertainty provides insight into how much confidence can be placed in the timing estimation.

Qualitative Uncertainties

A second set of uncertainties that can be used are qualitative uncertainties, which are estimates of uncertainties that are not derived from data, but instead are based on the expertise of an analyst. The recommended approach for qualitative uncertainties is based on the methods developed by the Federal Highway Administration (FHWA) for use in the RealCost software (FHWA, 2004). The user selects a mean value for costs, along with variations in the costs based on several pre-defined distributions. The distribution types, choice of mean value and choice of variance are decisions that must be made by the analysts. This is detailed further in Chapter 3 of the Guide, and is demonstrated using examples in Chapter 4 of the Guide.

SUMMARIZING THE RECOMMENDED FRAMEWORK AND METHODS

The preservation timing framework described in Chapter 3 requires methods for completing each step in the framework, and this chapter detailed the development and validation of those methods. Significant effort was expended on developing a set of example models that explain the effects of pavement preservation in terms of both condition and non-condition based factors. These example models are detailed in Chapter 5, and they provide several key insights, including:

- The models highlight the condition and non-condition based factors that affect the performance of a preserved pavement using data gathered from 10 State DOTs and the LTPP database.

- The relationships between the performance of a preserved pavement and the condition and non-condition based variables collected in this effort are not consistent between the various preservation treatments.
- The models developed in this effort can be used as a set of example national models. The model development was focused on understanding the interactions between condition and non-condition based variables, and was not necessarily optimized for prediction (e.g., they will predict negative values). However, it is recommended that each agency attempt to develop models using this approach for their own use.

The inputs to the framework also require uncertainties for the costs and the benefit calculations, and this chapter described two approaches for developing those uncertainties. Chapter 4 of the Guide demonstrates how uncertainties can be combined to provide additional information to the preservation treatment timing scenarios.

The framework also requires costs and benefits as a function of time. This project found that costs varied significantly across agencies, and no single set of cost items were recommended. Instead, the framework is flexible to allow for each agency to define costs using their techniques. For benefits, it was recommended that the change in performance be quantified as opposed to using the service life extension; the change in performance can capture the non-linearity of pavement performance much more closely than the service life extension.

Finally, the preservation timing framework requires a method for combining the costs and benefits, and the recommendation for this is to use an approach based on reference point programming. This approach has not been used extensively in pavement literature, but provides the benefit of expressing costs and benefits in additive terms as opposed to multiplicative terms. That means that the costs and benefits can be scaled independently, and the range of values in each term (as opposed to only the relative change in each term) is accounted for.

The framework presented in Chapter 3, along with the methodologies detailed in this chapter combine to represent a robust approach for estimating the timing of pavement preservation. The Guide details step-by-step instructions for determining preservation timing using the methods detailed in this report.

CHAPTER 5. ANALYSIS OF DATA AND MODEL DEVELOPMENT

This chapter presents the results of analyzing the data gathered from DOTs and the LTPP, and developing example performance models to support the preservation treatment timing framework detailed in Chapter 3 and the methodologies detailed in Chapter 4. The data gathering effort for the models was presented in Chapter 4. The detailed approach for developing the models in this chapter is presented in Chapter 3 of the Guide.

The primary objective of the analyses presented in this chapter was understanding the interactions between condition and non-condition based variables. This is important to note because the example models presented in this chapter are not necessarily optimized for prediction (e.g., they will predict negative values). The Guide details approaches for performing regression so that negative predictions are not permitted, and a set of correction factors are presented at the end of this chapter that can be used with the models to address negative values.

A consistent set of independent variables were defined and used throughout the models, and those variables were detailed in Chapter 4 with the data gathering information. Additionally, statistical significance as described in this chapter refers to the results of a hypothesis test (e.g., a t-test) conducted at the 95 percent confidence level. The statistical significance of model variables were relaxed to only require 90 percent confidence, though limited cases had variables show significant between 90 and 95 percent confidence. Pavement thickness data were requested from each of the ten agencies that submitted information for this project. Although some DOT's did provide thickness data, the way in which they were provided was not consistent. For example, one agency provided thickness as an equivalent three layer approach, whereas another provided only thickness related to asphalt layers. Therefore, thickness is not reflected in most of the models in this chapter.

The following sections of this chapter are organized per preservation treatment. Within each preservation treatment, the immediate change in condition is detailed first, followed by the performance models. The performance models are organized by performance measure, starting with IRI, then rutting, transverse cracking, fatigue cracking and then non-wheelpath longitudinal cracking. For each preservation treatment and performance measure, the performance model results are presented first by illustrating the distributions of growth rates for control and treatment cases, then the model fit results are illustrated and the model is presented in a table. Next, the range of predicted values of the models is presented – these are the results of using Monte Carlo simulation with 1 million iterations to extrapolate the model results across broad US conditions. Finally, the results of a sensitivity analysis are illustrated.

THIN OVERLAY

Thin asphalt overlays were evaluated for thicknesses that fell within the range of 0.75 inch to 1.5 inch. This range was selected based on comparing the definitions of thin overlays across multiple agencies. Data were gathered from State DOT's and the LTPP SPS-3, and any overlays that are specifically labelled as polymer modified or occurring in conjunction with additional treatments (e.g., patching immediately preceding the overlay) were removed from the analysis in order to compare only similar treatments. Thicknesses for thin overlays from State data ranged from 0.75 to 1 inch, whereas thicknesses from the LTPP SPS-3 were 1.5 inch.

Immediate Change

For the case of thin overlays, the immediate change in condition was calculated for rutting and IRI. It was expected that the immediate change in cracking (for all evaluated types) following the overlay results in cracking being reset to zero, and this result was verified using the available data. It is important to note that some agencies include construction joints in their cracking definitions, and therefore cracking may not reset to zero following the overlay in every case. However, this research has not included construction joints in cracking, and therefore the expectation of no cracking following the overlay is verified.

For the case of rutting, it was found that the thin overlay reset the rut depth to approximately 0.1 inches, though with significant variability. Figure 19 shows the change in rutting due to the application of a thin overlay as a function of the rut depth before the overlay for data from the following sources: Tennessee DOT, Maryland SHA, Kansas DOT and the LTPP database. Several important findings can be seen in Figure 19, including:

- The data are parallel to the line of maximum possible improvement (i.e., where rutting is zero after the overlay) with an offset of approximately 0.1 inches.
- Many cases with low values for initial rutting show a negative effect following overlay (i.e., rutting increases).
- When the rutting before overlay is 0.1 inches, the expected change in rutting following the overlay is zero, and the uncertainty is evenly distributed around zero.

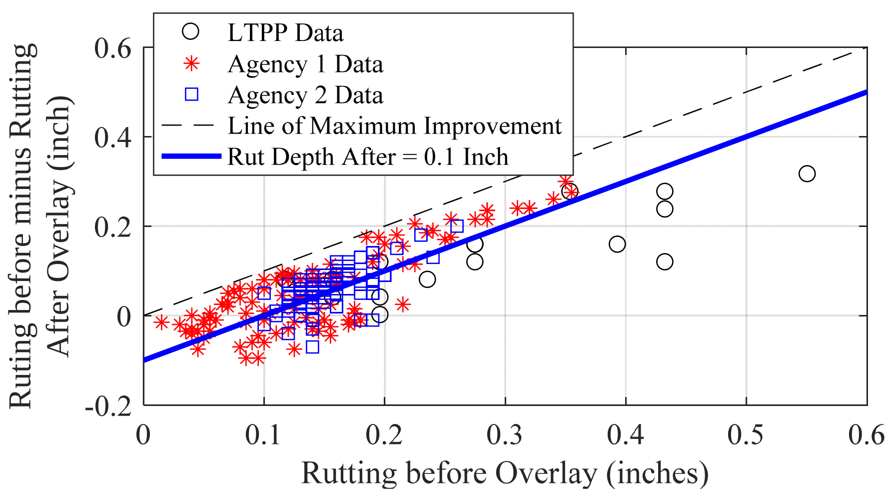


Figure 19. Rutting following thin overlay.

The model for predicting the immediate change in IRI following a thin overlay is shown in Figure 20, using data from the following sources: Tennessee DOT, Virginia DOT, Maryland SHA, Kansas DOT and the LTPP database. Some differences were found in each data source. For example, the expected change in IRI following a thin overlay in Kansas was found to be larger than the expected change in IRI following a thin overlay in Maryland or Virginia. Furthermore, all State data have an expected decrease in IRI when the thin overlay is placed on a pavement with an initial IRI of 50 inches/mile or more, whereas LTPP data has an expected increase in IRI if the overlay is placed on a pavement with an initial IRI of 70 inches per mile or less. In other words, the State data and the LTPP data have differing conclusions when the overlay is placed on a pavement with an initial IRI between 50 and 70 inches/mile.

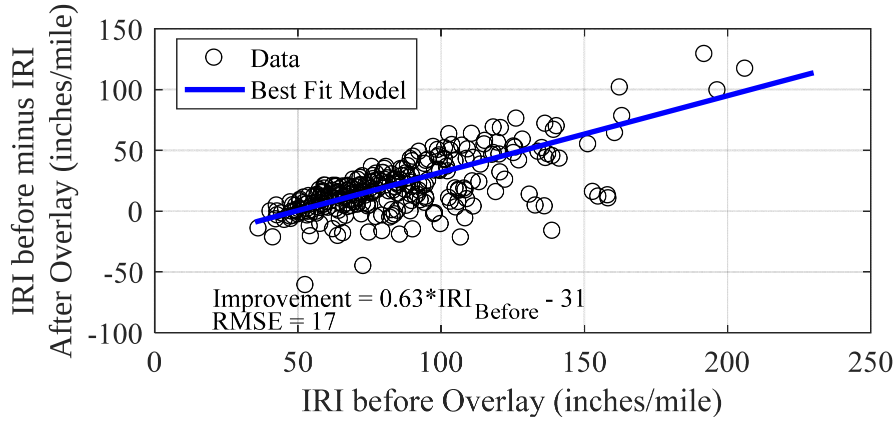


Figure 20. Effect of thin overlay on the immediate values of IRI.

Growth Rates

Roughness (IRI)

The IRI growth rates following a thin overlay were evaluated using six data sources: Kansas DOT, Maine DOT, Maryland SHA, Virginia DOT, Louisiana DOTD and the LTPP database. Figure 21 shows a comparison of the overall growth rates for each measure for the treatment and control segments. Assuming the population for each of the factors (e.g., climate, traffic, etc.) is similar between the treatment and control segments, and if the distributions of growth rates is significantly different, that provides an indication of differences in expected growth rates due to the application of the overlay. The mean growth rates are the same (approximately 4 inches/mile/year), although the control segments have a higher portion of negative growth rates. Importantly, some significant differences were found across different data sources. For example, the LTPP and some agencies had little differences in the growth rates, whereas some agencies had significant differences – in one case the mean growth rates were different by 3 inches/mile.

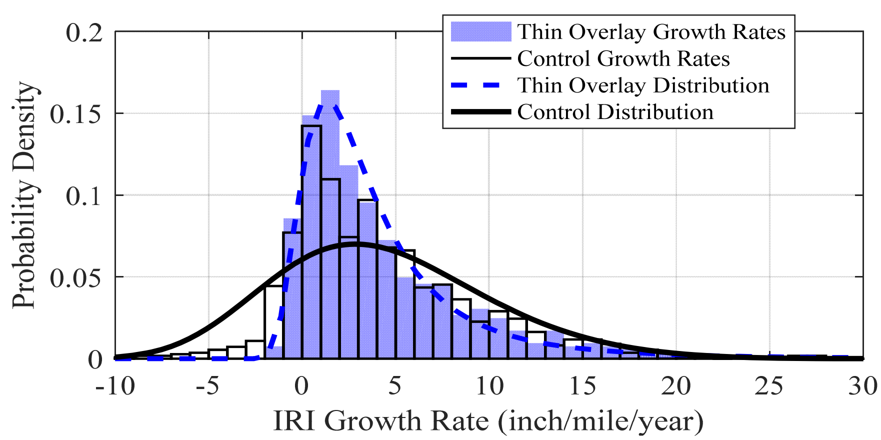


Figure 21. IRI growth rates for control and treatment segments following thin overlay.

Next, the model was developed and the significant variables (i.e., condition and non-condition based factors) were assessed. A binary variable was included in the model to indicate whether a preservation treatment has been applied, and it showed as statistically significant. A model was fit and a comparison of fitted data to measured data is shown in Figure 22. It can be seen that the model tends to under predict high growth rates, which is reasonable given that IRI

growth rates above 15 inches/mile/year are not generally expected in practice. The resulting model is shown in Equation 6.

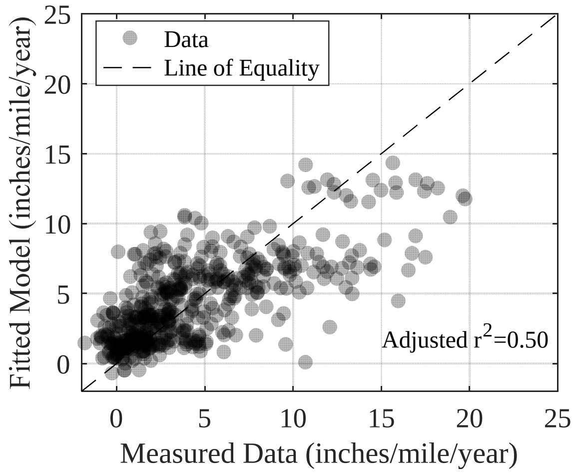


Figure 22. Model fit results for IRI Growth following a thin overlay.

$$IRI_{TO} = 9.78 + 0.104 \times IRI_{Pre} - 13.9 \times Log_{10}(AADT) + 1.04 \times Precip - 0.375 \times HiTemp - 2.43 \times Pres_{Ind} + 3.08 \times Log_{10}(AADT)^2 + 3.73 \times 10^{-3} \times HiTemp^2 - 1.35 \times 10^{-3} \times IRI_{Pre} \times MAAT + 9.04 \times 10^{-2} \times Log_{10}(AADT) \times MAAT - 0.356 \times Log_{10}(AADT) \times Precip \quad (6)$$

Where:
IRI_{TO} = Predicted IRI growth rate after thin overlay (inch/mile/year)
IRI_{Pre} = IRI before preservation (inch/mile)
AADT = Average annual daily traffic
Precip = Mean Annual Precipitation (inches)
HiTemp = Count of the degree days above 90°F
MAAT = Mean annual air temperature in degrees Fahrenheit
$Pres_{Ind}$ = Binary variable (equals 1 if preservation applied and 0 otherwise)

Next, the model results were extrapolated across US conditions to assess whether it provides anomalous results. This was accomplished by using data from the LTPP database and the climate and subgrade databases described in Chapter 4 to develop distributions of input values representative of the contiguous US. The distributions were then sampled using Monte Carlo simulation with 1 million iterations and the IRI growth rate was calculated using equation 6 for each case. Correlations between the variables (e.g., mean annual temperature and the count of the degree days above 90°F) were accounted for by estimating their values with LTPP data and using the correlation matrix as discussed in Rubinstein and Kroese (2008). This process was followed for each model described in this chapter and is further detailed in the Guide.

The histogram of predicted values using this simulation is shown in Figure 23; the mean predicted growth rate is 3.7 inch/mile/year. Finally, the sensitivity of the models to each of the inputs was assessed, and the results are shown in Figure 24. The results show that, as temperature increases, the IRI growth rate decreases. As the IRI before overlay increases, the IRI growth rate also increases. One unexpected result is demonstrated; increasing AADT results in lower IRI growth rates. However, this relationship may be reflective of some unobserved relationship. Traffic is a significant input to pavement design equations, and it is expected that

higher traffic values will contribute to increased pavement thickness and stronger materials used in pavement construction. Therefore, this relationships may be reflective of the pavement design (e.g., lower AADT results in reduced pavement thickness, which will result in a higher IRI growth rate than for a thicker pavement with all else equal).

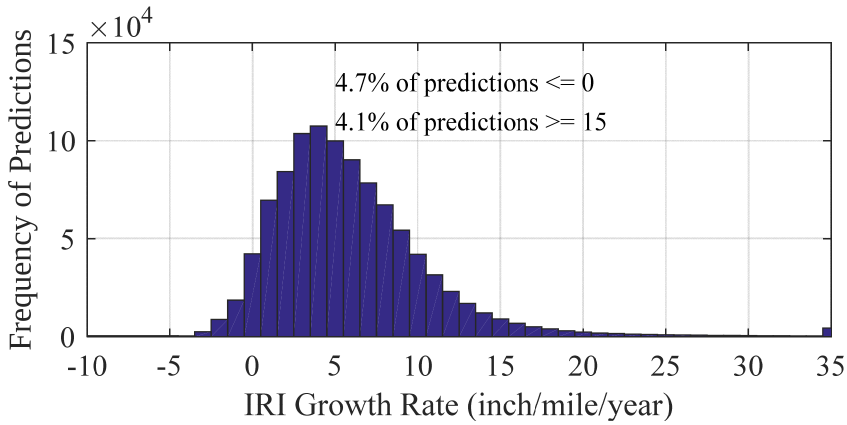


Figure 23. Range of predicted values for IRI growth rate for thin overlay.

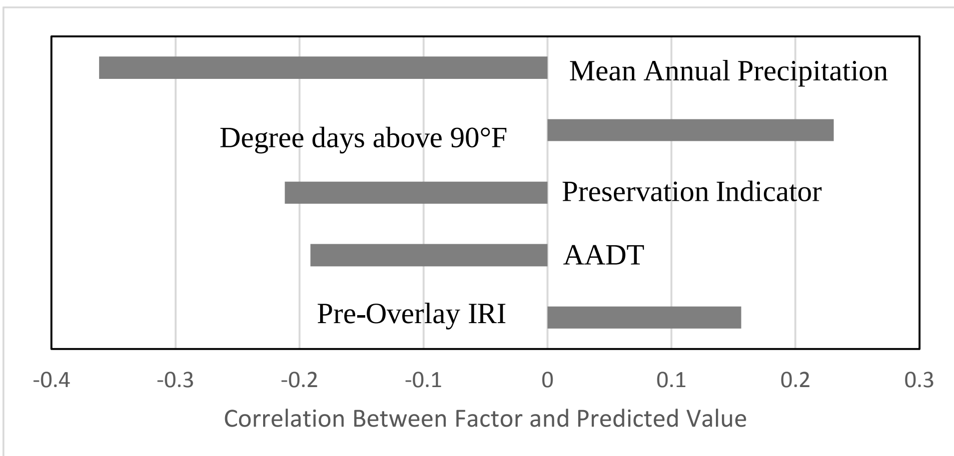


Figure 24. Sensitivity of factors in IRI prediction model following thin overlay.

Rutting

Data for rutting following a thin asphalt overlay was gathered from the following sources: Kansas DOT, Maine DOT, Maryland SHA, Virginia DOT and the LTPP database. The distribution comparing rutting growth rates for overlay segments and control segments is shown in Figure 25. The mean rutting growth rates for overlay segments is 0.011 inches/year and the rutting growth rates for control segments is 0.009 inches/year.

The next step was to fit a relationship to the data using the available variables. It was found that the significant variables affecting rut growth were different for composite (asphalt surface over a rigid pavement) and asphalt surfaced over existing asphalt pavements; however, a composite pavement model could not be developed with the available variables. The results for fitting the model for asphalt pavements showed that the location (i.e., where the data were gathered from) was more significant than any of the remaining factors. This indicates that some significant differences exist between States beyond the climate, soil and condition data gathered in this project, and these differences affect rutting growth. A model was developed using

variables collected, and the results of the model are shown in Figure 26 and Equation 7. Figure 26 shows that the model only moderately fits the data, and tends to significantly under-predict rut growth for high values of rut growth rate. The model results indicate that the application of the thin overlay has no statistically significant effect on the rutting growth rate.

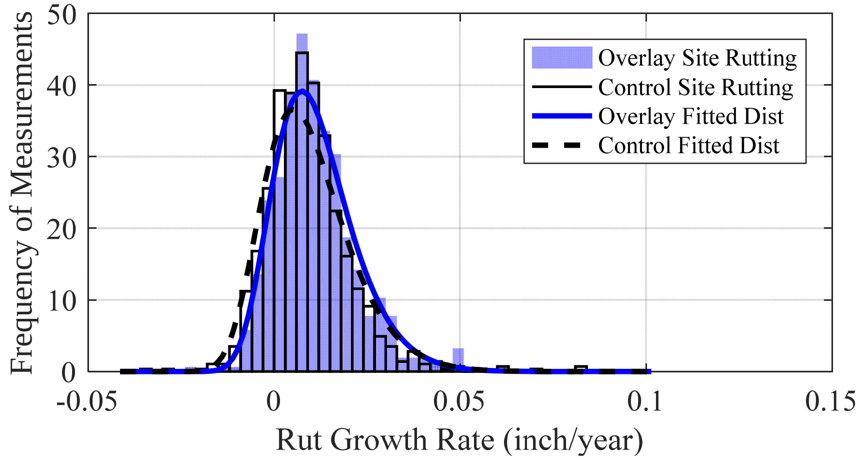


Figure 25. Rutting growth rates for control and treatment segments.

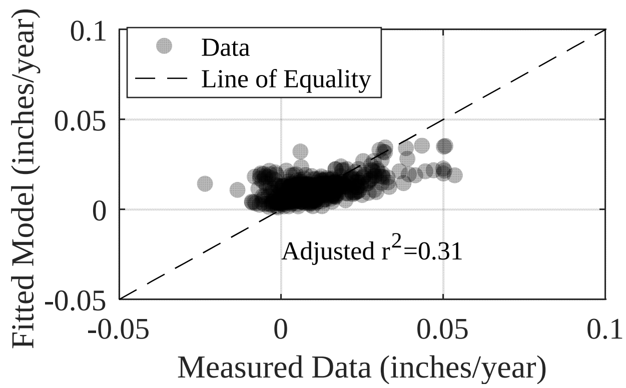


Figure 26. Model fit results for rut growth following a thin overlay.

$$RUT_{TO} = 1.88 + 0.104 \times RUT_{Pre}{}^{0.8} - 0.022 \times Log_{10}(AADT) - 0.903 \times Log_{10}(MR) + 1.54 \times 10^{-4} \times HiTemp - 1.75 \times 10^{-3} \times MAAT \times RUT_{Pre} + 8.98 \times 10^{-4} \times Log_{10}(AADT)^3 + 0.110 \times Log_{10}(MR)^2 \quad (7)$$

Where:
RUT_{TO} = Predicted rutting growth rate after thin overlay (inch/year)
RUT_{Pre} = Rutting before preservation (inch)
AADT = Average annual daily traffic
HiTemp = Count of the degree days above 90°F
MAAT = Mean annual air temperature in degrees Fahrenheit
MR = Subgrade resilient modulus (psi)

Next, the model was evaluated using simulation, and the results are shown in Figure 27; as can be seen that the results match well with measured growth rates shown in Figure 25. The sensitivity of the models to each of the inputs was assessed, and the results are shown in Figure

27. The results show that, as temperature, AADT, rutting before the overlay and the subgrade resilient modulus increases, the rut growth rate increases.

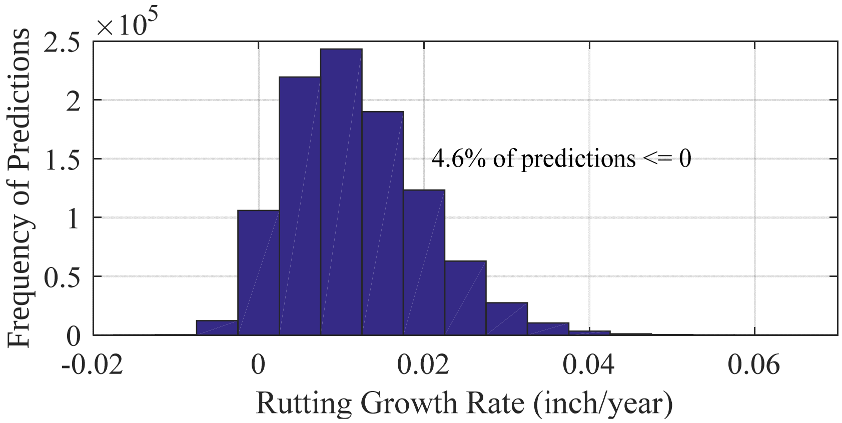


Figure 27. Range of predicted values for rut growth rate.

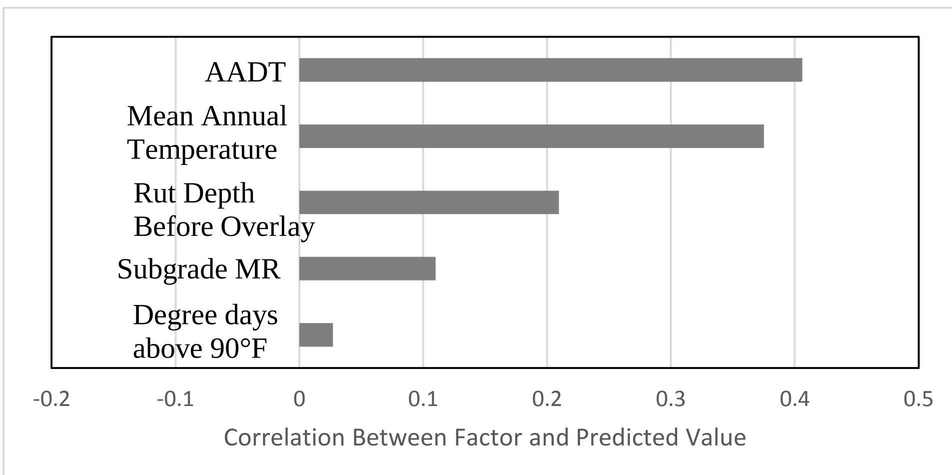


Figure 28. Sensitivity of factors in rutting prediction model following thin overlay.

Transverse Cracking

Transverse cracking data were gathered from sources which defined cracking in terms of length, which limited the data to the following sources: Virginia DOT, Louisiana DOTD and the LTPP database. Transverse cracking growth rates were divided by the segment length to normalize the results. Therefore, the growth rates are presented in terms of feet of transverse cracking per mile of pavement per year. The distributions of transverse cracking growth rates for control and treatment segments are shown in Figure 29. The mean growth rate for control segments is 12 feet/mile/year and the mean growth rate for treatment segments is 14 feet/mile/year. However, as can be seen in Figure 29, the control segments tend to have a higher growth rate for much of the range of data, and the mean growth rate for overlay segments is highly influenced by a few very high growth rates. The overlay segments do not have negative growth rates because they each start from zero cracking immediately after the overlay, and negative cracking length is not possible. However, the control segments do not begin at zero, and therefore measurement variability can cause an estimated negative cracking growth rate.

Next, a model was developed by regressing the growth rates to the available variables; the fit of the model is shown in Figure 30 and the model is shown in Equation 8. In this case, a binary variable that serves as an indicator for preservation was statistically significant.

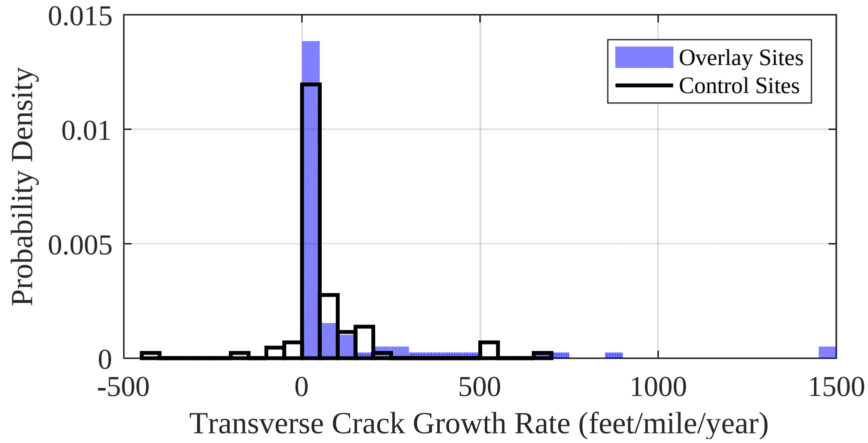


Figure 29. Distribution of transverse cracking growth rates following thin overlay.

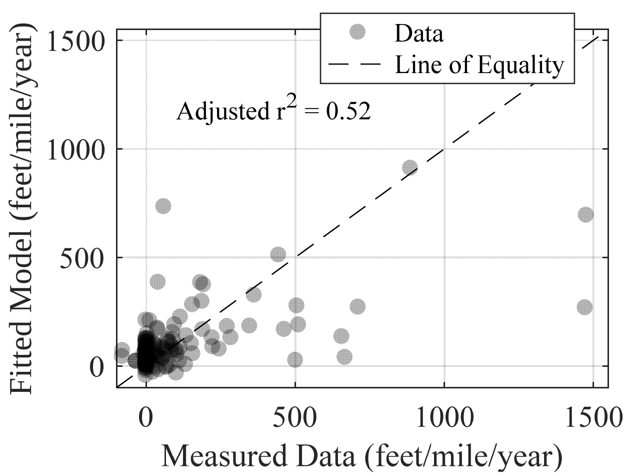


Figure 30. Model fit results for transverse cracking growth following a thin overlay.

$$TRCK_{TO} = 28.35 - 0.04 \times TRCK_{Pre} + 1.40 \times IRI_{Pre} - 2.08 \times MAAT - 8.26 \times TRCK_{Pre} \times IRI_{Pre} + 2.70 \times 10^{-3} \times TRCK_{Pre} \times MAAT - 0.051 \times TRCK_{Pre} \times Pres_{Ind} + 0.62 \times MAAT \times Pres_{Ind} \quad (8)$$

Where:
$TRCK_{TO}$ = Predicted transverse cracking growth rate after thin overlay (feet/mile/year)
$TRCK_{Pre}$ = Transverse cracking before preservation (feet/mile)
IRI_{Pre} = IRI before preservation (feet/mile)
MAAT = Mean annual air temperature in degrees Fahrenheit
$Pres_{Ind}$ = Binary variable (equals 1 if preservation applied and 0 otherwise)

Next, the model was evaluated using simulation, and the results are shown in Figure 31; approximately 87 percent of the simulated results are below 150 feet/mile/year. The sensitivity of the models to each of the inputs was assessed, and the results are shown in Figure 32. The results show that temperature, transverse cracking before overlay, IRI before the overlay and the application of the overlay affect the growth rate.

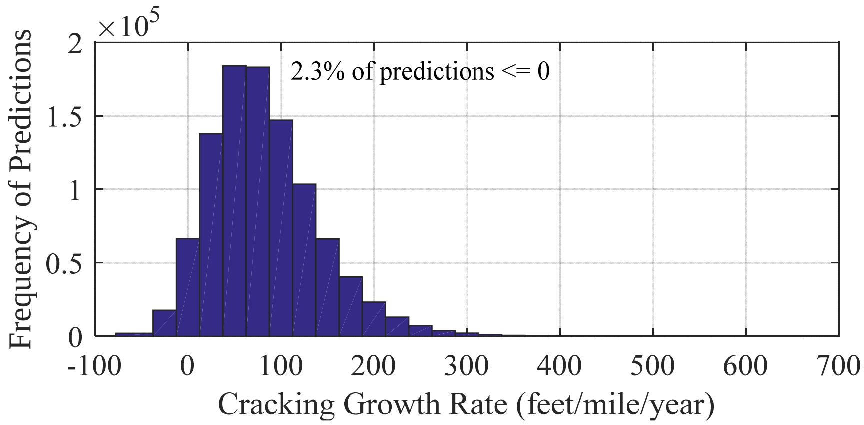


Figure 31. Range of predicted values for transverse cracking growth rate.

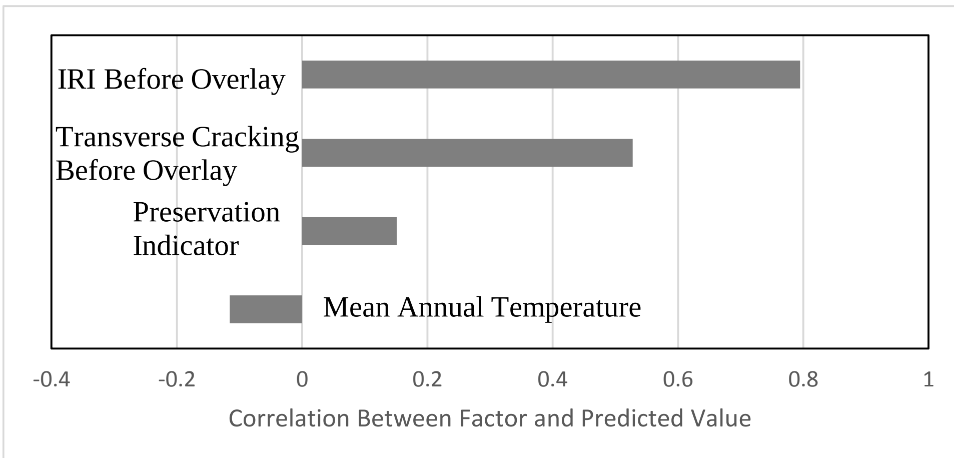


Figure 32. Sensitivity of factors in transverse cracking model following thin overlay.

Fatigue Cracking

Fatigue cracking data were gathered from sources that defined cracking in terms of area within the wheel path. The definition of the wheel path (i.e., width and location within the lane) were compared for agencies, and no consistent definition was found. The result of the comparison of fatigue cracking definitions was that only LTPP data were used to develop fatigue cracking models, and the growth rates are presented in terms of square feet of fatigue cracking per mile of pavement per year. The distributions of fatigue cracking growth rates for control and treatment segments are shown in Figure 33. The control segments have a higher growth rate, and the majority of overlay sites do not form fatigue cracking during the analysis period.

The next step was to develop a model; the fit of the resulting model is shown in Figure 34 and the model is shown in Equation 9. In this case, a binary variable that serves as an indicator for preservation was statistically significant to the model, and was included. Then, the model was evaluated using simulation, and the results are shown in Figure 35. The sensitivity of the models to each of the inputs was assessed, and the results are shown in Figure 36. The results show that the preservation indicator (i.e., noting that an overlay was applied) is the most significant factor affecting the fatigue cracking growth rate. This is largely driven by the large portion of overlay sites that do not have measurable fatigue cracking over the analysis period (see Figure 33).

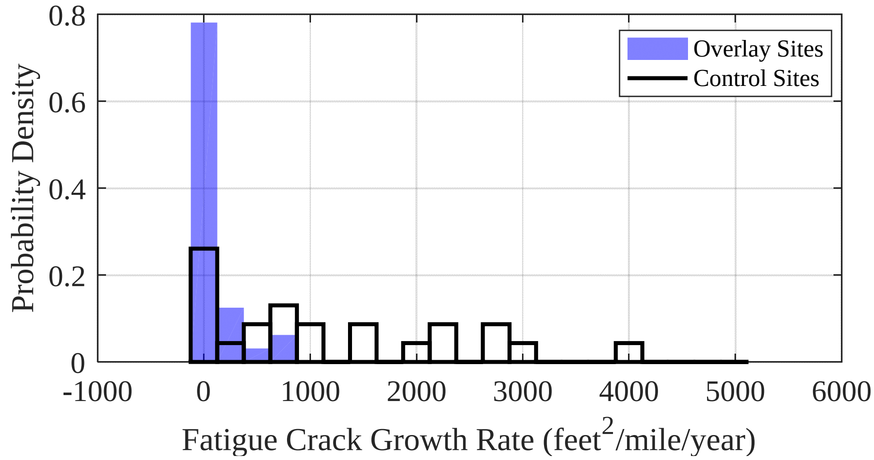


Figure 33. Distribution of fatigue cracking growth rates following thin overlay.

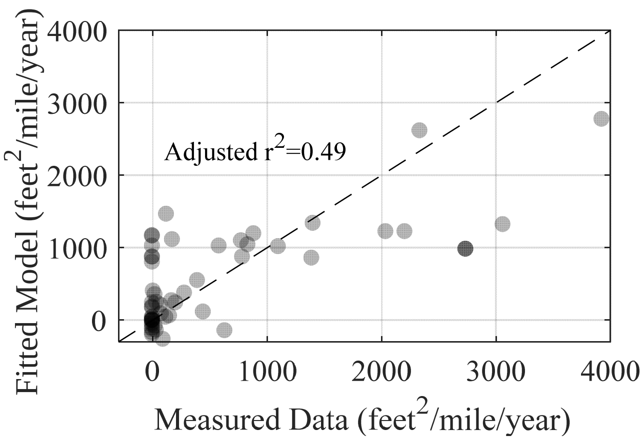


Figure 34. Model fit results for fatigue cracking growth for thin overlay.

$$FAT_{TO} = 2884 + 4.15 \times FAT_{Pre} - 166 \times Log_{10}(AADT) + 11.8 \times Thck - 983 \times Pres_{Ind} - 0.071 \times FAT_{Pre} \times MAAT + 3.29 \times 10^{-5} \times FAT_{Pre}{}^{2} - 82.3 \times Log_{10}(MR)^{2} \quad (9)$$

Where:
FAT_{TO} = Predicted fatigue cracking growth rate after thin overlay (feet^2/mile/year)
FAT_{Pre} = Fatigue cracking before preservation (feet^2/mile)
Thck = Total pavement thickness above subgrade (inch)
MAAT = Mean annual air temperature in degrees Fahrenheit
$Pres_{Ind}$ = Binary variable (equals 1 if preservation applied and 0 otherwise)
MR = Subgrade resilient modulus (psi)
AADT = Average annual daily traffic

Longitudinal Cracking

Longitudinal cracking data were gathered from sources which defined cracking in terms of length and did not consider construction joints or cracks in the wheel path in the longitudinal cracking definition. Using the aforementioned criteria limited the data sources to the following: the Virginia DOT, Louisiana DOTD and the LTPP. The distribution of growth rates on treatment and control segments is shown in Figure 37; no difference was found between the distributions.

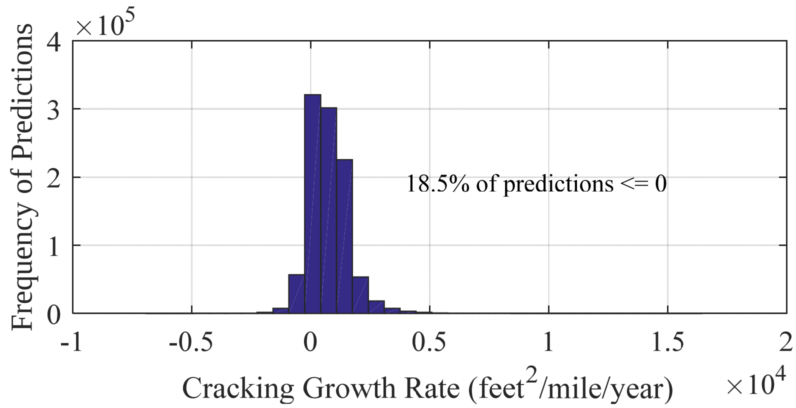


Figure 35. Range of predicted values for fatigue cracking growth rate for thin overlay.

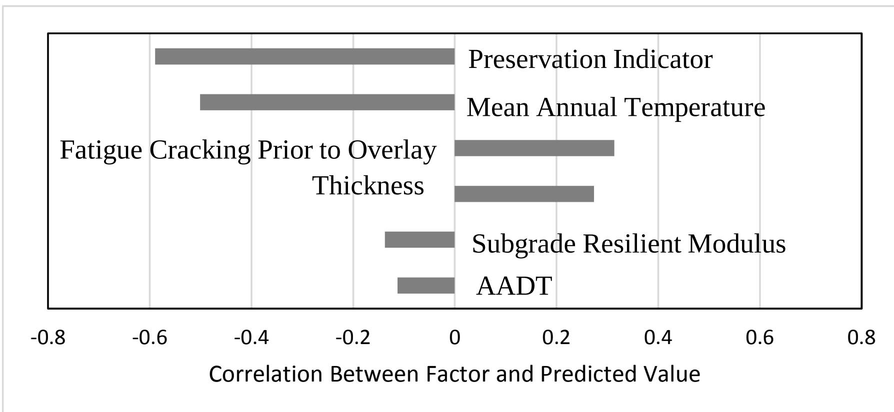


Figure 36. Sensitivity of factors in fatigue cracking prediction following thin overlay.

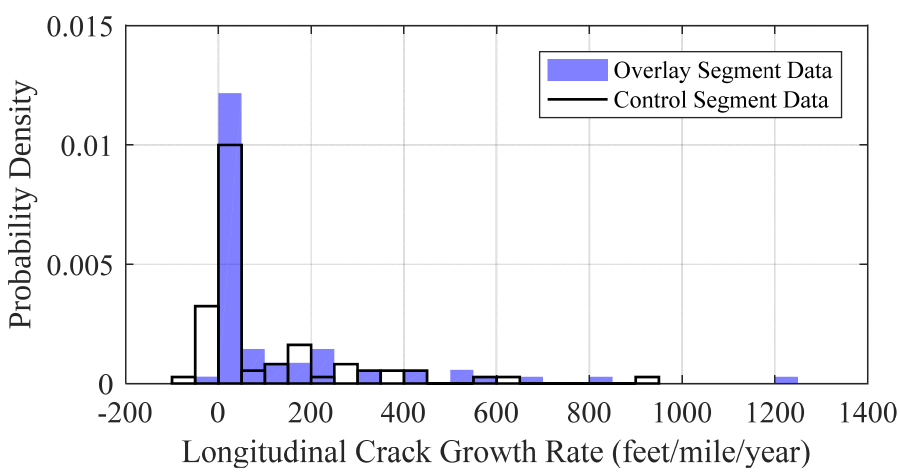


Figure 37. Distribution of longitudinal cracking growth rates following thin overlay.

Next, regression was performed; the model fit results are shown in Figure 38 and the model is shown as Equation 10. The predicted growth rates have significant variability (i.e., the model only loosely fits the measured data), which is a similar result to the rutting model. An investigation of the data showed that, in many cases, longitudinal cracking was not initiated and thus the growth rates on each of these segments is shown as zeros. These segments can be seen in the large density of values in Figure 38 where the measured growth rate is zero. Therefore,

this model estimates the average growth rate of longitudinal cracking assuming that some crack initiation is exhibited after the first year.

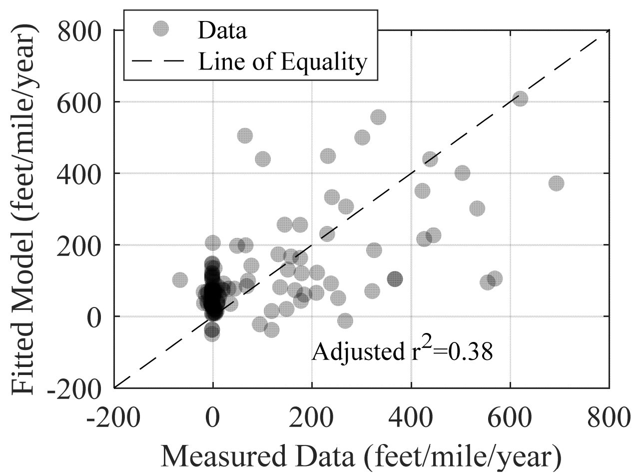


Figure 38. Longitudinal cracking prediction compared to measured values for thin overlay.

$$Long_{TO} = 954 - 0.858 \times Long_{Init} - 17.82 \times MAAT + 5.516 \times HiTemp + 0.025 \times Long_{Init} \times MAAT - 7.89 \times 10^{-4} \times Long_{Init} \times FTC - 0.013 \times Long_{Init} \times HiTemp + 9.49 \times 10^{-5} \times Long_{Init} \times FTC \times HiTemp - 7.39 \times 10^{-7} \times Long_{Init}{}^{2} \times MAAT \quad (10)$$

Where:
$Long_{TO}$ = Predicted longitudinal cracking growth rate after thin overlay (feet/mile/year)
$TRCK_{Pre}$ = Longitudinal cracking before preservation (feet/mile)
MAAT = Mean annual air temperature in degrees Fahrenheit
FTC = Mean annual number of freeze thaw cycles (count)
HiTemp = Count of the degree days above 90°F

The model was then evaluated using simulation, and the results are shown in Figure 39. The distribution shows that the model produces reasonable results that match well with Figure 37. The sensitivity of the model to each of the inputs was assessed, and the results are shown in Figure 40. The results show that the non-wheel path longitudinal cracking growth rate is primarily driven by temperature related variables and cracking before the overlay.

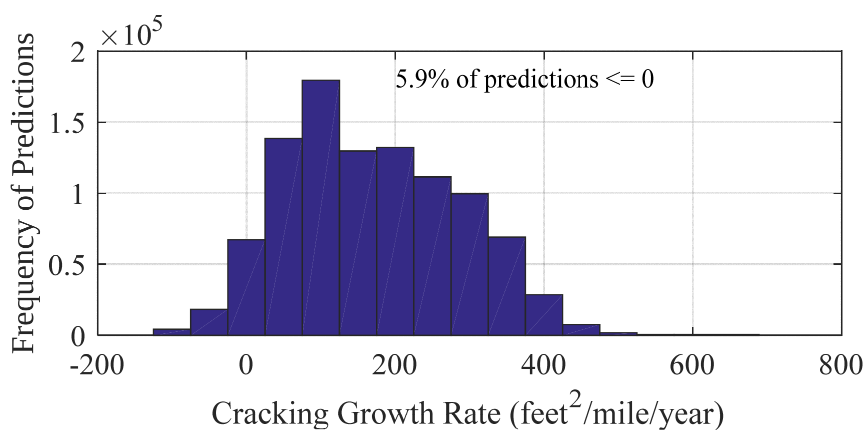


Figure 39. Results of extrapolating the longitudinal cracking growth model.

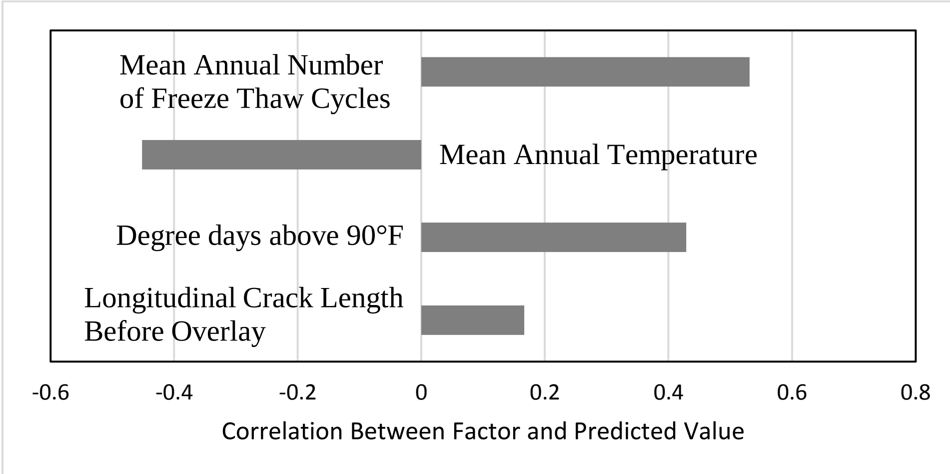


Figure 40. Sensitivity of factors in longitudinal cracking model following thin overlay.

CHIP SEAL ANALYSIS

Chip seal data were gathered to develop similar models as for thin overlays; however, only single layer chip seals that were not identified as polymer modified or co-applied with a secondary treatment (e.g., crack sealing) were studied. For example, multiple DOTs have chip seal treatments that are applied with patching, micro surfacing, crack sealing or other preservation treatments, and these were not considered

Immediate Change

Data for the immediate effect of chip seals on IRI were available from the following sources: Utah DOT, Kansas DOT, Virginia DOT, Louisiana DOTD, Ohio DOT and the LTPP database. The results indicated that no change in IRI or rutting can be expected following the application of a chip seal. However, this finding was not consistent across all DOTs. Kansas DOT data showed a consistent improvement in IRI and rutting following application of a chip seal, which is a conflicting result when compared to the other data sources. No explanation was found as to why the Kansas DOT data differed from the other data sources and findings from literature (e.g., see Mamlouk and Dosa [2014] and Carvalho et al. [2011]), and therefore those data were not combined with other data to develop chip seal models.

Data from the following sources were evaluated to assess the immediate effect of chip seals on rutting: Idaho DOT, Utah DOT, Kansas DOT, Virginia DOT, Louisiana DOTD and the LTPP database. However, similar to IRI, Kansas DOT data show an improvement in rutting, which conflicts with data from the other sources and literature (e.g., see Carvalho et al., 2011). Therefore Kansas DOT data were not combined with the other data for assessment purposes.

Transverse cracking was evaluated using data from the following sources: Virginia DOT and the LTPP database. Louisiana DOTD have available data, but those data were excluded from this analysis given that their data collection cycle is two years, and therefore the first available condition measurement following the chip seal cannot be assumed to be representative of the immediate effect. It was found that transverse cracking following a chip seal cannot be assumed to be completely eliminated. The histogram of transverse cracking following a chip seal is shown in Figure 41, and only 60 percent of the data show zero cracking following the chip seal.

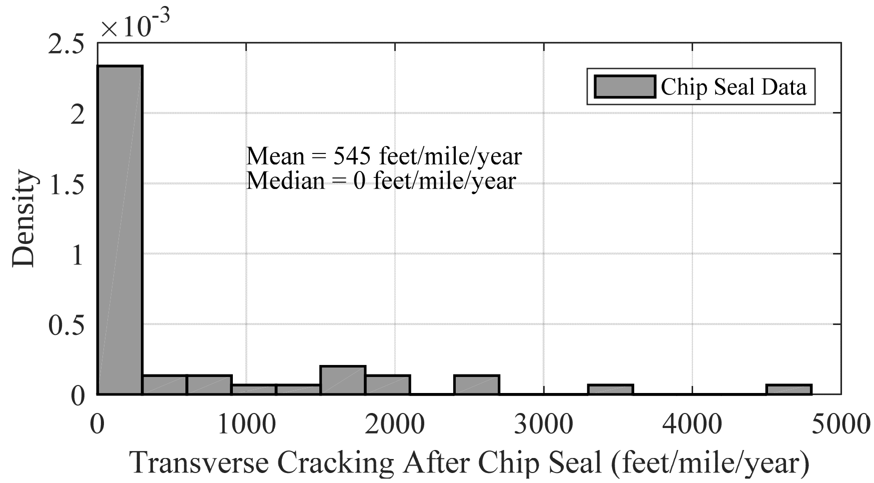


Figure 41. Histogram of transverse cracking after chip seal.

An additional assessment was performed to investigate whether the severity of cracking before the chip seal explained the cracking following the chip seal. This assessment was performed with only the LTPP data so that the cracking could be accurately disaggregated into the different levels of severity. The pre-treatment length of cracking in low, medium and high severities were treated as independent variables, and these were combined with the remainder of the variables. By disaggregating the cracking into different severities, a statistically significant model was found to predict the cracking after a chip seal. The model fit results are shown in Figure 42 with the model given in Equation 11.

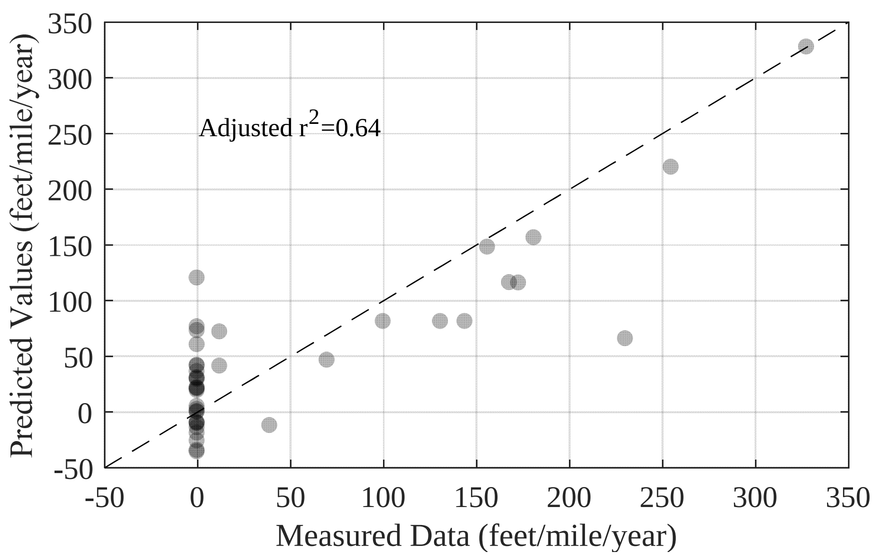


Figure 42. Model fit for predicting the transverse cracking length after chip seal.

$$TRCK_{L\,CS} = 199 + 0.227 \times TRCK_{Pre-LS} - 4.73 \times TRCK_{Pre-MS} - 55.2 \times TRCK_{Pre-HS} + 0.055 \times TRCK_{Pre-MS}^{\;2} - 4.10 \times Precip - 0.594 \times HiTemp \quad (11)$$

Where:

$TRCK_{L\,CS}$ = Predicted transverse cracking after chip seal (feet/mile)
$TRCK_{Pre\text{-}LS}$ = Length of low severity transverse cracking before chip seal (feet/mile)
$TRCK_{Pre\text{-}MS}$ = Length of medium severity transverse cracking before chip seal (feet/mile)

$TRCK_{Pre\text{-}HS}$ = Length of high severity transverse cracking before chip seal (feet/mile)
Precip = Mean annual precipitation (inches)
HiTemp = Count of the degree days above 90°F

An analysis of fatigue and non-wheel path longitudinal cracking revealed that the cracking was eliminated following the chip seal in 96 percent of the cases. Thus it can be concluded that the chip seal eliminates fatigue and non-wheel path longitudinal cracking.

Growth Rates

Roughness (IRI)

Data for evaluating the effect of chip seals on IRI growth rates were available from the following sources: Kansas DOT, Louisiana DOTD, Virginia DOT, Ohio DOT and the LTPP database. Figure 43 shows the growth rates for chip seal and control sites, and it can be seen that the chip seal segments have a lower average IRI growth rate when compared to control segments. The mean IRI growth rate on chip seal segments is 2.9 inches/mile/year, whereas the mean IRI growth rate on control segments is 5.2 inches/mile/year.

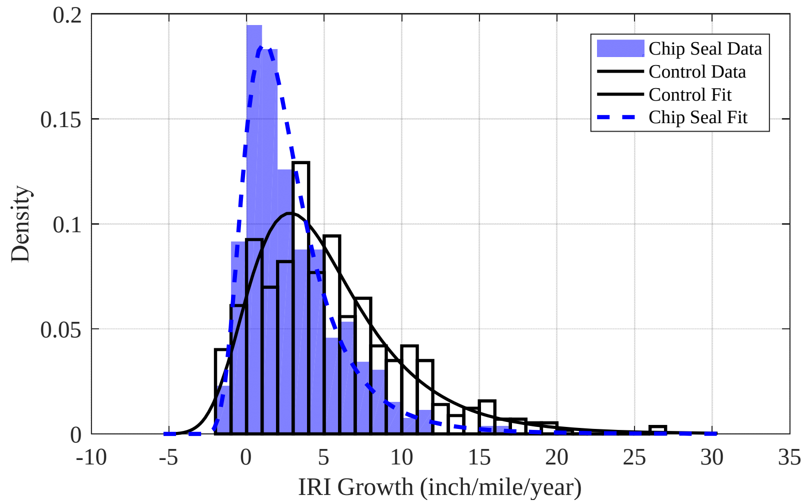


Figure 43. Comparison of chip seal and control IRI growth rates.

Next, a regression analysis was performed and the results (Figure 44) show little correlation between the developed model and the independent variables. Equation 12 presents the model; each variable showed to be statistically significant to the model at the 95 percent confidence level. A binary variable for indicating whether preservation had been applied was found to be statistically significant to the model. Given the tenuous relationship that could be developed from the available data (Figure 44), and the significant difference in growth rates between treatment and control segments (Figure 43), it is expected that there are factors not included in the data that are significantly influencing growth rates.

A simulation was performed and the results are shown in Figure 45; the results match well with the chip seal distribution in Figure 43. The sensitivity of the model to each of the inputs was assessed, and the results are shown in Figure 46. The results show that the preservation indicator and an increase in the subgrade resilient modulus are correlated with a reduction in IRI growth rates, whereas an increase in the IRI before the chip seal and an increase in the number of freeze thaw cycles correlates with an increase in IRI growth rate.

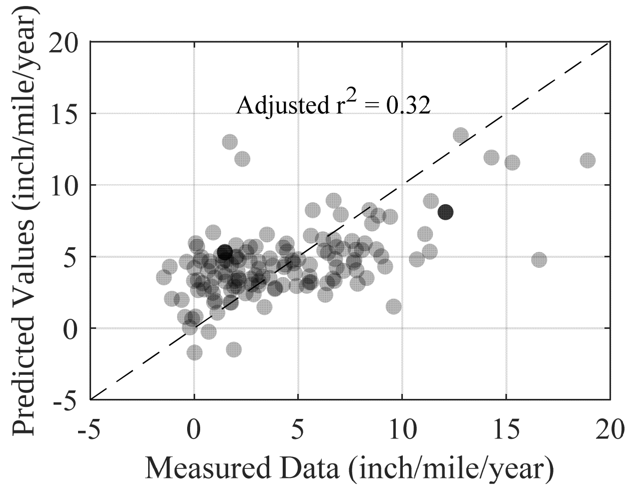


Figure 44. Model fit results for IRI growth following a chip seal.

$$IRI_{CS} = 29.9 + 0.151 \times IRI_{Pre} - 0.753 \times Log10(AADT) - 7.095 \times Log10(MR) + 2.957 \times Pres_{Ind} + 5.49 \times 10^{-4} \times FTC^2 - 1.96 \times 10^{-3} \times IRI_{Pre} \times MAAT - 0.083 \times FTC \times Pres_{Ind} + 0.058 \times Precip \times Pres_{Ind} \quad (12)$$

Where:
IRI_{CS} = Predicted IRI growth rate after chip seal (inch/mile/year)
IRI_{Pre} = IRI before preservation (inch/mile)
AADT = Average annual daily traffic
MR = Subgrade resilient modulus (psi)
FTC = Mean annual number of freeze thaw cycles (count)
Precip = Mean Annual Precipitation (inches)
MAAT = Mean annual air temperature in degrees Fahrenheit
$Pres_{Ind}$ = Binary variable (equals 1 if preservation applied and 0 otherwise)

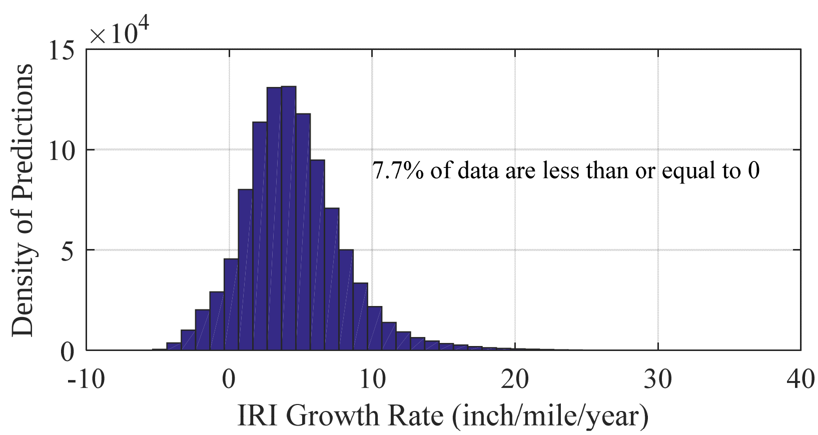


Figure 45. Results of extrapolating the IRI growth model for chip seals.

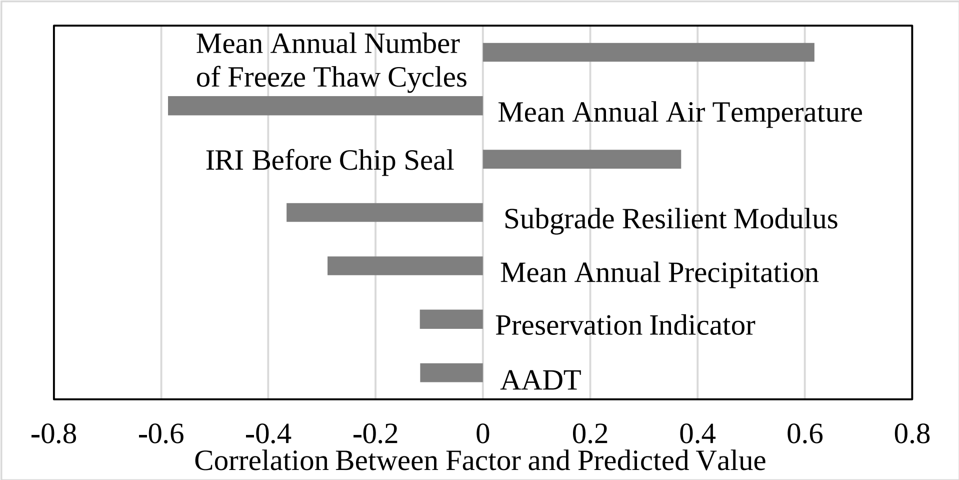


Figure 46. Sensitivity of factors in IRI prediction model following chip seal.

Rutting

Data for evaluating the long-term effect of chip seals on rutting were available from the following sources: Kansas DOT, Louisiana DOTD and the LTPP database. The distribution comparing rutting growth rates for chip seal and control segments is shown in Figure 47, and the difference in the growth rates is not statistically significantly different. Next, a regression was performed to develop a model; similar to the IRI growth model, the rut growth model shows little correlation between the developed model and the independent variables (Figure 48). The model is shown in Equation 13.

The results of the simulation check of the model are shown Figure 49, and they match well with the distribution in Figure 47. The sensitivity of the model to each of the inputs was assessed, and the results are shown in Figure 50. The results show that the rutting growth rate is primarily driven by high temperature, followed by the rut depth before chip seal, traffic and subgrade resilient modulus.

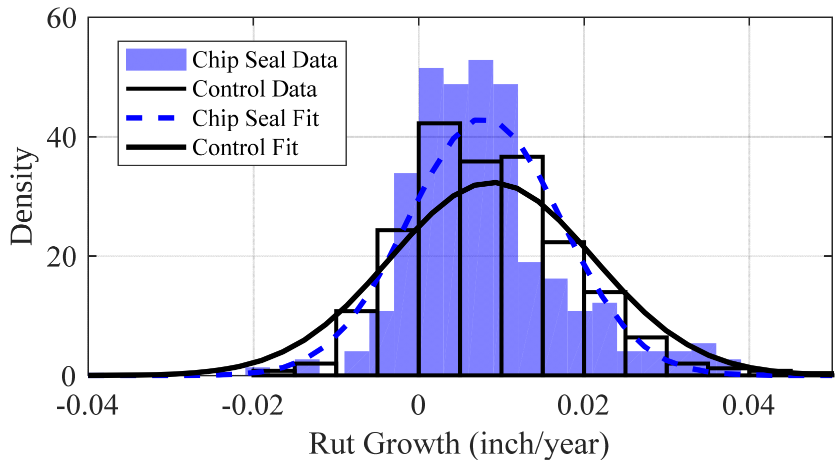


Figure 47. Comparison of chip seal and control rut growth rates.

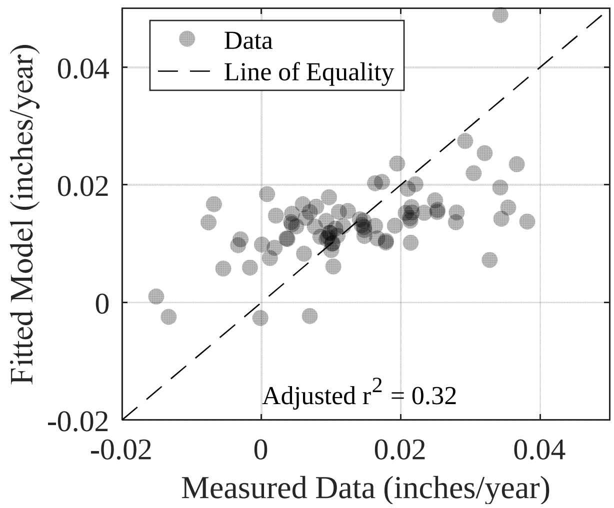


Figure 48. Model fit results for rutting growth following a chip seal.

$$RUT_{CS} = -0.136 + 0.523 \times RUT_{Pre} + 0.088 \times {RUT_{Pre}}^2 + 9.82 \times 10^{-3} \times Log10(AADT) + 2.48 \times 10^{-2} \times Log10(MR) - 0.127 \times Log10(MR) \times RUT_{Pre} - 5.65 \times 10^{-5} \times Log10(AADT) \times Log10(MR) \times HiTemp + 2.42 \times 10^{-4} \times Log10(MR) \times HiTemp \quad (13)$$

Where:
RUT_{CS} = Predicted rutting growth rate after chip seal (inch/year)
RUT_{Pre} = Rutting before preservation (inch)
AADT = Average annual daily traffic
HiTemp = Count of the degree days above 90°F
MAAT = Mean annual air temperature in degrees Fahrenheit
MR = Subgrade resilient modulus (psi)

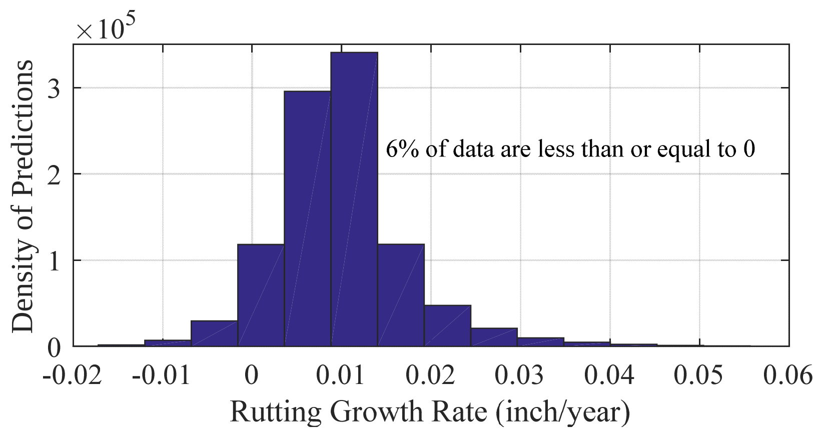


Figure 49. Results of extrapolating the rut growth model for chip seals.

Transverse Cracking

Transverse cracking data were gathered from sources which defined cracking in terms of length, which limited the data to the following sources: Louisiana DOTD, Virginia DOT and the LTPP database. The transverse cracking data were normalized by dividing the cracking length by the length of the pavement segment in the evaluation. Figure 51 shows the distributions of transverse cracking growth for chip seal and control segments; they are not statistically different.

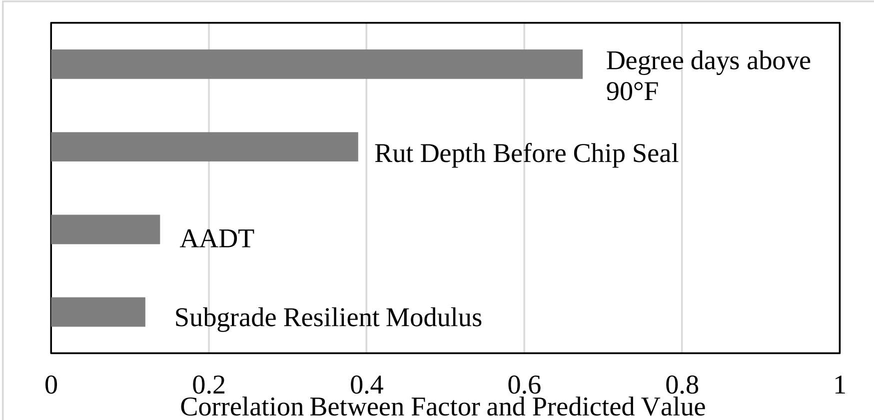


Figure 50. Sensitivity of factors in rutting prediction model following chip seal.

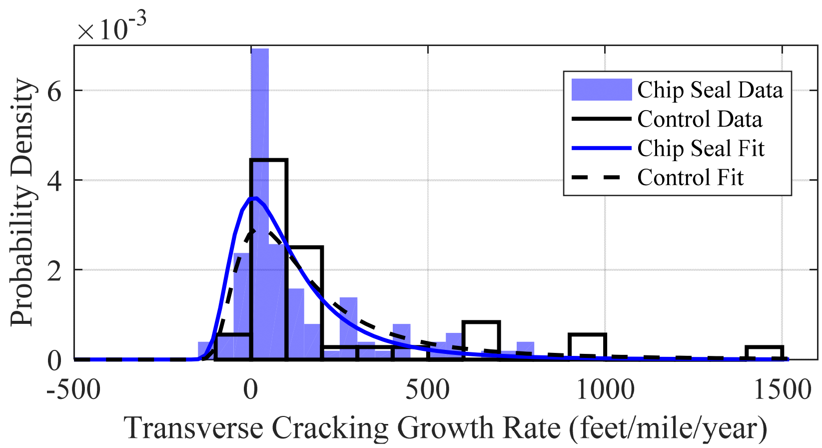


Figure 51. Comparison of transverse cracking growth rates.

A regression was performed, and the application of the chip seal is statistically significant. The growth rate reduction is more significant for higher values of initial transverse cracking. The resulting model fit is shown in Figure 52, and the model is in Equation 14.

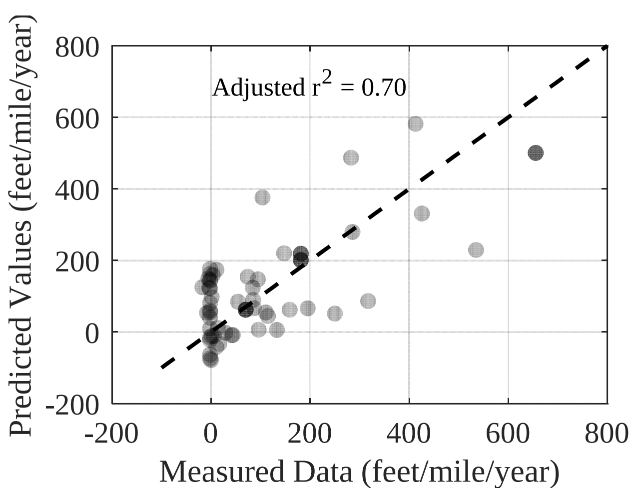


Figure 52. Model fit results for transverse cracking growth following a chip seal.

$$TRCK_{CS} = -234 + 3.74 \times 10^{-5} \times TRCK_{Pre}{}^{2} - 11.8 \times IRI_{Pre} + 0.106 \times IRI_{Pre}{}^{2} + 10.04 \times MAAT + 2.70 \times FTC - 7.57 \times HiTemp + 0.07 \times HiTemp^{2} - 0.118 \times TRCK_{Pre} \times Pres_{Ind} \quad (14)$$

Where:
$TRCK_{CS}$ = Predicted transverse cracking growth rate after chip seal (feet/mile/year)
$TRCK_{Pre}$ = Transverse cracking before preservation (feet/mile)
IRI_{Pre} = IRI before preservation (inch/mile)
HiTemp = Count of the degree days above 90°F
MAAT = Mean annual air temperature in degrees Fahrenheit
FTC = Mean annual number of freeze thaw cycles (count)
$Pres_{Ind}$ = Binary variable (equals 1 if preservation applied and 0 otherwise)

A simulation was performed and the results are shown in Figure 53; the results match well with the distribution in Figure 51. The sensitivity of the model to each of the inputs was assessed, and the results are shown in Figure 54.

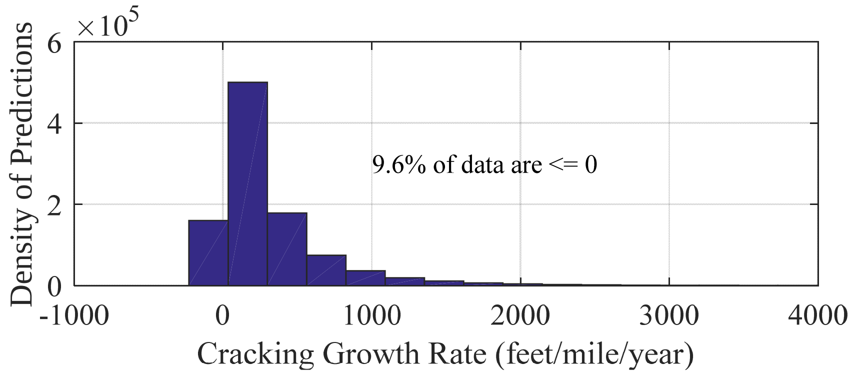


Figure 53. Results of extrapolating the transverse cracking growth model for chip seals.

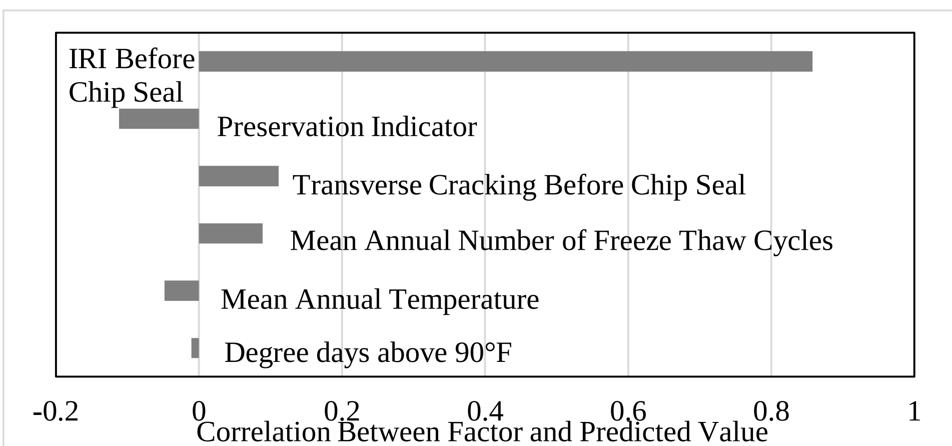


Figure 54. Sensitivity of factors in transverse cracking model following chip seals

Fatigue Cracking

Fatigue cracking performance following a chip seal was investigated. As before, only LTPP data were used for fatigue cracking because of inconsistent cracking definitions across agencies. Figure 55 shows the distribution of growth rates for fatigue cracking following a chip seal, and the majority of both preservation and control sites did not have fatigue cracking. A

regression was performed, but no significant model could be developed due to the very high number of sites with zero fatigue cracking growth rates.

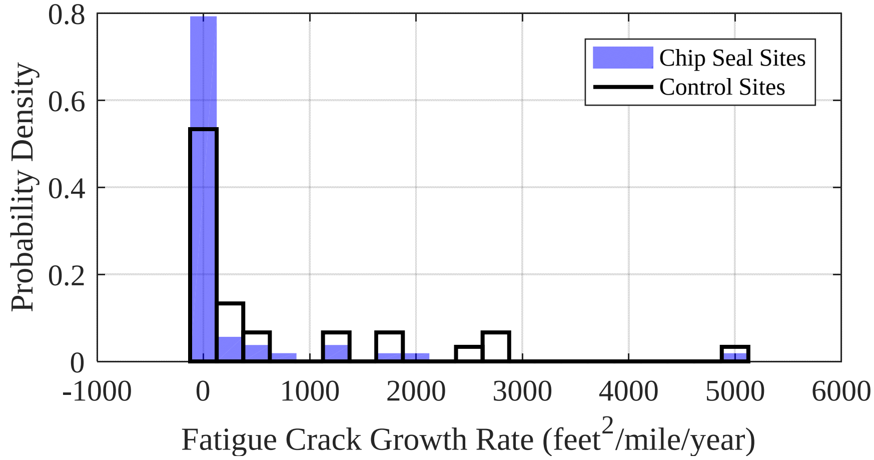


Figure 55. Comparison of fatigue cracking growth rates.

Longitudinal Cracking

Longitudinal cracking data were gathered from sources which defined cracking in terms of length and did not consider construction joints or cracks in the wheel path in the longitudinal cracking definition. Using the aforementioned criteria limited the data sources to the following sources: Virginia DOT, Louisiana DOTD and the LTPP database. A comparison of the longitudinal cracking growth rates for chip seal and control pavements is shown in Figure 56, and chip seal pavements have a lower growth rate. Much fewer data were available for control segments in this specific case (only 32 unique segments). However, the control segments were found to be comparable to the chip seal segments.

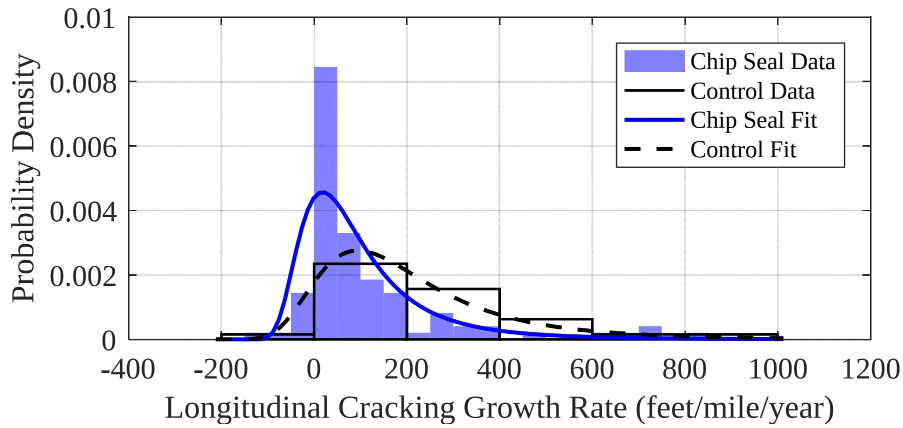


Figure 56. Comparison of longitudinal cracking growth rates.

Next, a regression was performed. The model fit is shown in Figure 57 and the model is provided as Equation 15. An indicator for preservation was found to be statistically significant related to several independent variables.

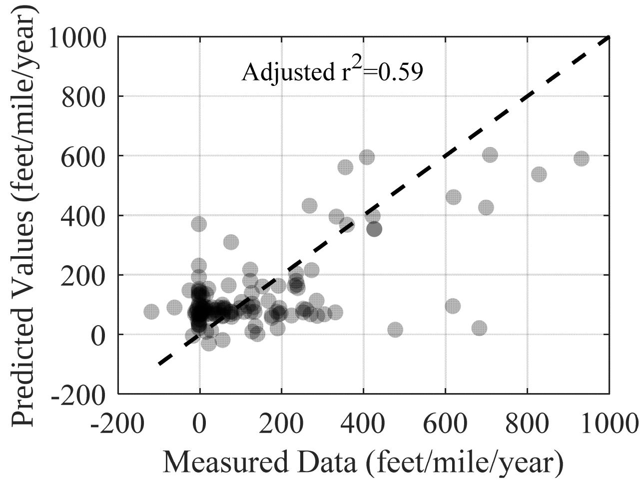


Figure 57. Model fit results for longitudinal cracking growth following a chip seal.

$$Long_{CS} = -2438 + 0.379 \times Long_{Init} + 39.3 \times MAAT + 9.9 \times FTC - 5 \times HiTemp + 3756 \times Pres_{Ind} - 7.05 \times 10^{-3} \times Long_{Init} \times MAAT + 1.75 \times 10^{-3} \times Long_{Init} \times HiTemp - 58.9 \times MAAT \times Pres_{Ind} - 13.1 \times FTC \times Pres_{Ind} + 9.04 \times HiTemp \times Pres_{Ind} - 5.28 \times 10^{-4} \times HiTemp^2 - 0.026 \times HiTemp^2 \times Pres_{Ind} \tag{15}$$

Where:
$Long_{CS}$ = Predicted longitudinal cracking growth rate after chip seal (feet/mile/year)
$Long_{Init}$ = Longitudinal cracking before preservation (feet/mile)
IRI_{Pre} = IRI before preservation (inch/mile)
HiTemp = Count of the degree days above 90°F
MAAT = Mean annual air temperature in degrees Fahrenheit
FTC = Mean annual number of freeze thaw cycles (count)
$Pres_{Ind}$ = Binary variable (equals 1 if preservation applied and 0 otherwise)

A simulation was performed and the results are shown in Figure 58; the results match well with the chip seal distribution in Figure 56. The sensitivity of the model to each of the inputs was assessed, and the results are shown in Figure 59.

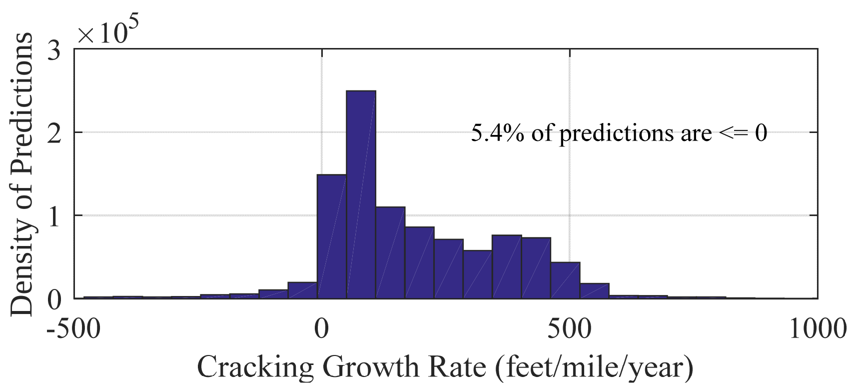


Figure 58. Results of extrapolating the longitudinal cracking growth for chip seals.

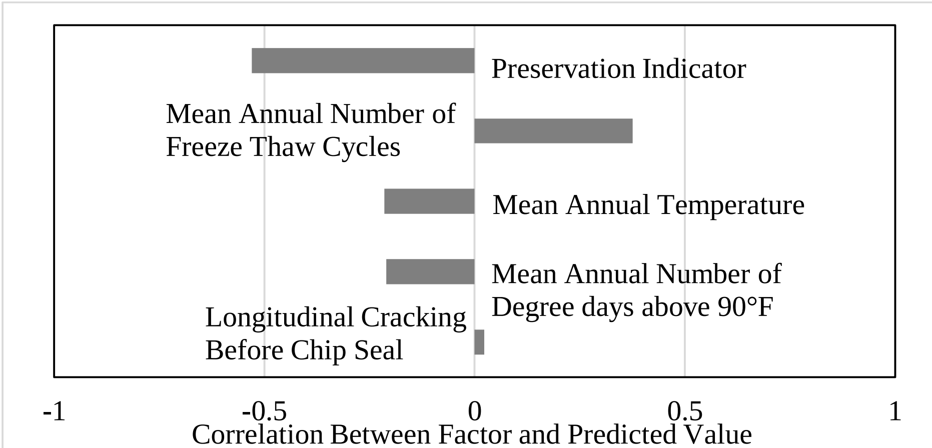


Figure 59. Sensitivity of factors in longitudinal cracking model following chip seals.

MICROSURFACING ANALYSIS

Data were gathered from each DOT that included microsurfacing in their data submittal. Only single layer microsurfacings that were not identified as polymer modified or co-applied with a secondary treatment (e.g., crack sealing) were considered.

Immediate Change

The immediate change in IRI and rutting was evaluated using data from the following sources: Louisiana DOTD, Virginia DOT, Maine DOT and the Utah DOT. It was found that microsurfacing did not have a significant effect on IRI or rutting in terms of an immediate change in condition. Only Louisiana DOTD and Virginia DOT data were used for evaluating transverse cracking because other sources had different cracking definitions. Similar to chip seals, it was found that transverse cracking following the application of microsurfacing cannot be assumed to be eliminated. The mean value for transverse cracking following microsurfacing is 260 feet/mile. Similarly (and using the same data sources), it was found that longitudinal cracking was not completely eliminated in every case, though the majority of segments (85 percent) showed no longitudinal cracking after microsurfacing. A further investigation found that longitudinal cracking can be assumed to be eliminated following microsurfacing. No fatigue cracking model was evaluated for microsurfacing due to inconsistent cracking definitions across agencies; the LTPP SPS-3 does not contain microsurfacing sites.

Growth Rates

Roughness (IRI)

Data for assessing the change in performance were available from the following sources: Louisiana DOTD, Virginia DOT and Maine DOT. Figure 60 shows the distribution for microsurfacing and control segments, and the means of the distributions are not statistically different. Next, a regression was performed; several model functional forms were assessed, and it was found that none adequately described that progression of roughness growth without significantly overfitting the model. However, it was found that the relationship between the IRI growth rate and some variables were statistically significant. Specifically, the IRI growth rate was positively correlated to the product of the IRI before microsurfacing and the base 10 logarithm of the AADT, as well as negatively correlated with the mean annual precipitation. In

other words, the IRI growth rate increases as the product of the pretreatment IRI and AADT increases, whereas the IRI growth rate decreases as the mean annual precipitation increases.

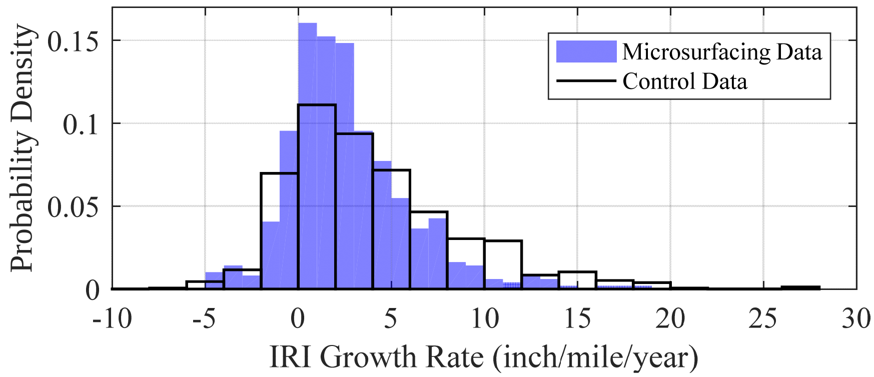


Figure 60. IRI growth rate for microsurfacing and control segments.

Rutting

Data for evaluating the long-term effects of microsurfacing on rutting were available from the following sources: Louisiana DOTD, Maine DOT and Maryland SHA. The distribution comparing rutting growth rates for microsurfacing segments and control segments is shown in Figure 61, and it can be seen that the two distributions overlap well. The mean growth rates between the treatment and control segments are not statistically different. The next step was to regress the growth rates to the independent variables to assess the significance of each factor. A binary variable indicating whether preservation had been applied was tested in the model, and it was found to be a significant variable. The model fit results are shown in Figure 62, and the model is provided in Equation 16.

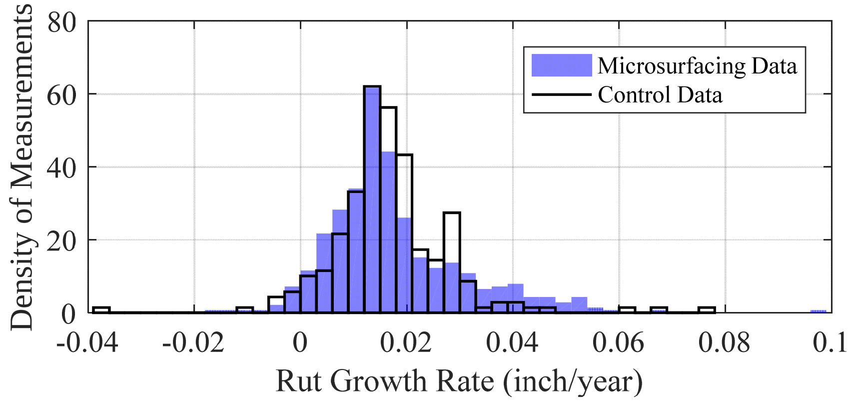


Figure 61. Rut growth rate for microsurfacing and control segments.

A simulation was performed and the results are shown in Figure 63. The results match well with the control distribution in Figure 61, though the range of predicted values is higher. The sensitivity of the model to each of the inputs was assessed, and the results are shown in Figure 64. The results show that many variables are significant, and the application of preservation is correlated with only a slight reduction in rutting growth rates.

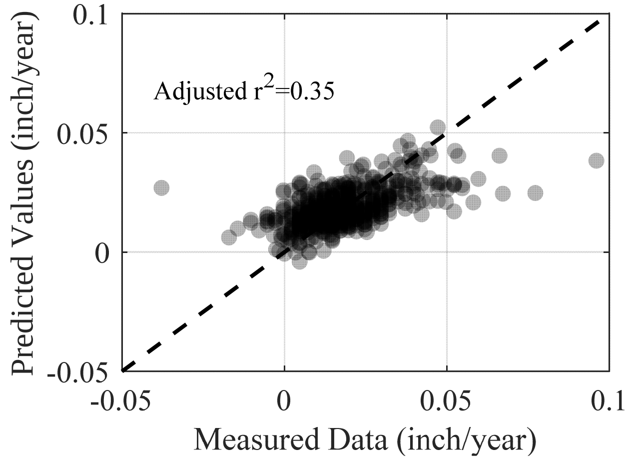


Figure 62. Model fit results for rut growth following microsurfacing.

$$Rut_{MS} = 0.349 + 2.33 \times 10^{-4} \times Rut_{Pre} \times IRI_{Pre} - 2.60 \times 10^{-6} \times IRI_{Pre} \times Precip + 0.937 \times Rut_{Pre} \times Log10(AADT) - 0.151 \times Rut_{Pre} \times MAAT + 4.68 \times 10^{-3} \times Rut_{Pre} \times FTC + 0.07 \times Rut_{Pre} \times Precip - 4.44 \times 10^{-3} \times Log10(AADT) \times Precip - 1.92 \times 10^{-5} \times MAAT \times Pres_{Ind} - 0.02 \times Rut_{Pre} \times Log10(AADT) \times Precip + 5.82 \times 10^{-4} \times {Rut_{Pre}}^{2} \times MAAT + 1.5 \times 10^{-3} \times Rut_{Pre} \times MAAT^{2} - 5.89 \times 10^{-3} \times Log10(AADT)^{2} \times Log10(MR) + 1.25 \times 10^{-3} \times Log10(AADT)^{2} \times Precip \quad (16)$$

Where:
Rut_{MS} = Predicted longitudinal cracking growth rate after microsurfacing (inch/year)
IRI_{Pre} = IRI before preservation (inch/mile)
AADT = Average annual daily traffic (count)
Precip = Mean annual precipitation (inches)
MR = Subgrade resilient modulus (psi)
HiTemp = Count of the degree days above 90°F
MAAT = Mean annual air temperature in degrees Fahrenheit
FTC = Mean annual number of freeze thaw cycles (count)
$Pres_{Ind}$ = Binary variable (equals 1 if preservation applied and 0 otherwise)

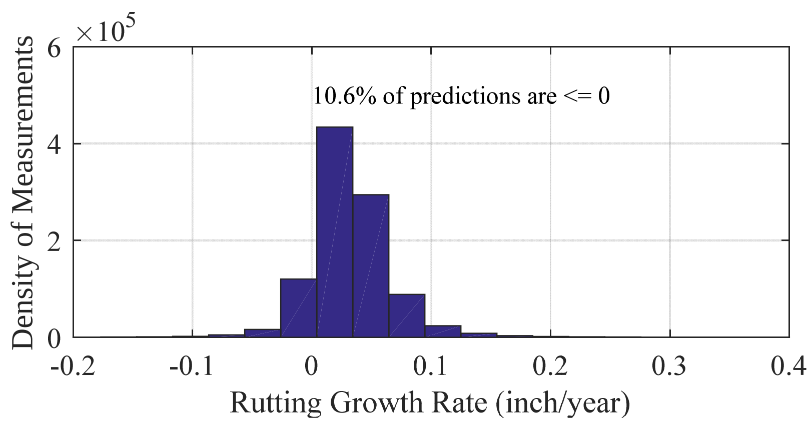


Figure 63. Results of extrapolating the rut growth for microsurfacing.

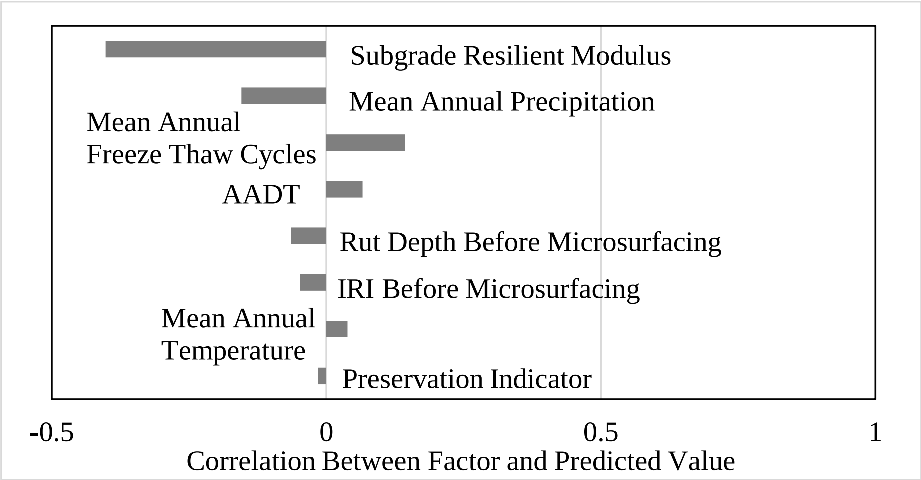


Figure 64. Sensitivity of factors in rutting prediction model following microsurfacing.

Transverse Cracking

Transverse cracking data were gathered from sources which defined cracking in terms of length, which limited the data to the Louisiana DOTD and Virginia DOT. Figure 65 shows the comparison of microsurfacing and control segments; transverse cracking growth rates on microsurfacing segments are higher on average than cracking on control segments.

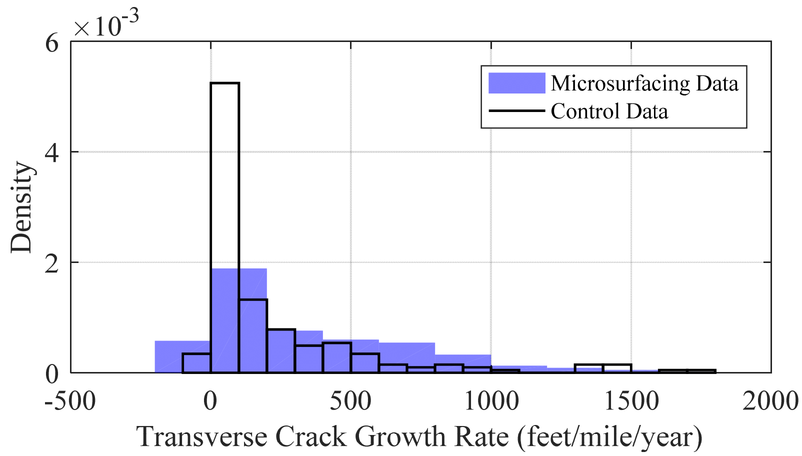


Figure 65. Transverse cracking growth rate for microsurfacing and control segments.

Next, a regression was performed; the model fit results are shown in Figure 66 and the model is provided in Equation 17. A simulation was performed to assess the applicability of the model over a broad set of conditions, and the results are shown in Figure 67. The shape of the distribution in Figure 67 is similar to the microsurfacing distribution in Figure 65, though the upper range of growth rates is much higher for the model results. The increase in the frequency of high cracking values for the extrapolated model results is directly related to an increase in the proportion of low mean annual temperatures in the simulated data.

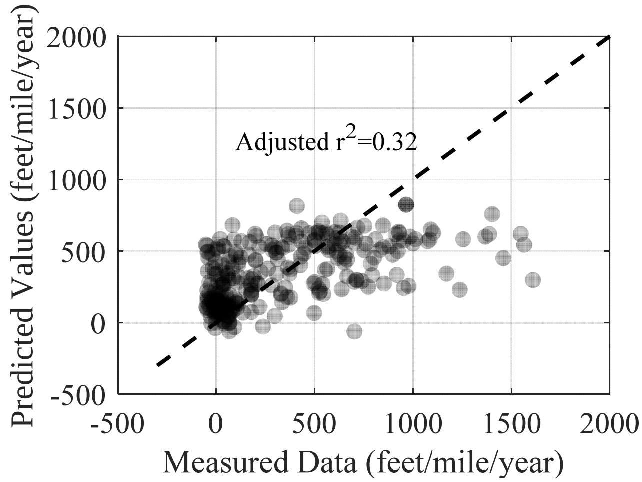


Figure 66. Model fit results for transverse crack growth following microsurfacing.

$$TRCK_{MS} = -201 + 0.977 \times TRCK_{Pre} - 2.56 \times FTC + 739 \times Pres_{Ind} - 0.176 \times TRCK_{Pre} \times Log10(MR) + 6.30 \times TRCK_{Pre} \times Pres_{Ind} + 1.11 \times IRI_{Pre} \times Log10(AADT) + 0.0458 \times IRI_{Pre} \times FTC - 10.95 \times IRI_{Pre} \times Pres_{Ind} - 0.773 \times Log10(AADT)^2 + 5.94 \times 10^{-3} \times TRCK_{Pre} \times IRI_{Pre} \times Pres_{Ind} - 9.17 \times 10^{-5} \times TRCK_{Pre} \times IRI_{Pre} \times MAAT + 1.85 \times 10^{-6} \times TRCK_{Pre}{}^2 \times MAAT - 1.29 \times 10^{-4} \times TRCK_{Pre}{}^2 \times Pres_{Ind} - 0.097 \times TRCK_{Pre} \times MAAT \times Pres_{Ind} + 3.49 \times 10^{-4} \times IRI_{Pre}{}^2 \times Precip \quad (17)$$

Where:
$TRCK_{MS}$ = Predicted transverse cracking growth rate after chip seal (feet/mile/year)
IRI_{Pre} = IRI before preservation (inch/mile)
AADT = Average annual daily traffic (count)
Precip = Mean annual precipitation (inches)
MR = Subgrade resilient modulus (psi)
MAAT = Mean annual air temperature in degrees Fahrenheit
FTC = Mean annual number of freeze thaw cycles (count)
$Pres_{Ind}$ = Binary variable (equals 1 if preservation applied and 0 otherwise)

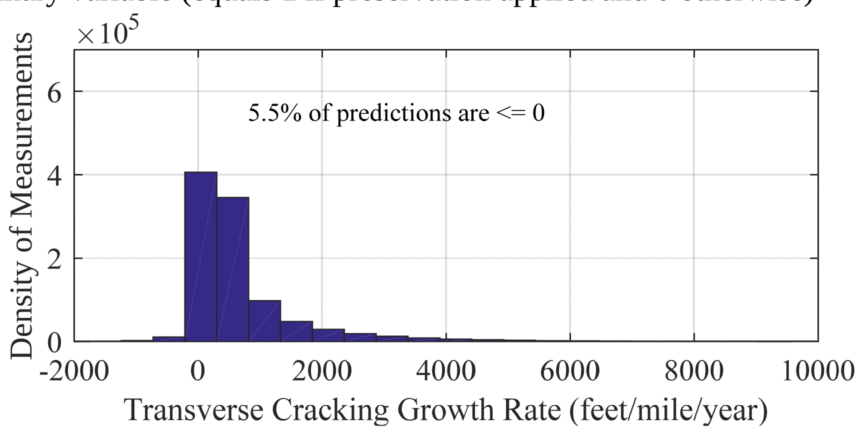


Figure 67. Results of extrapolating the transverse cracking growth for microsurfacing.

The sensitivity of the model to each of the inputs was assessed, and the results are shown in Figure 68. The results show that cracking before the microsurfacing, climatic variables and the application of preservation are the primary drivers of transverse cracking following the application of microsurfacing.

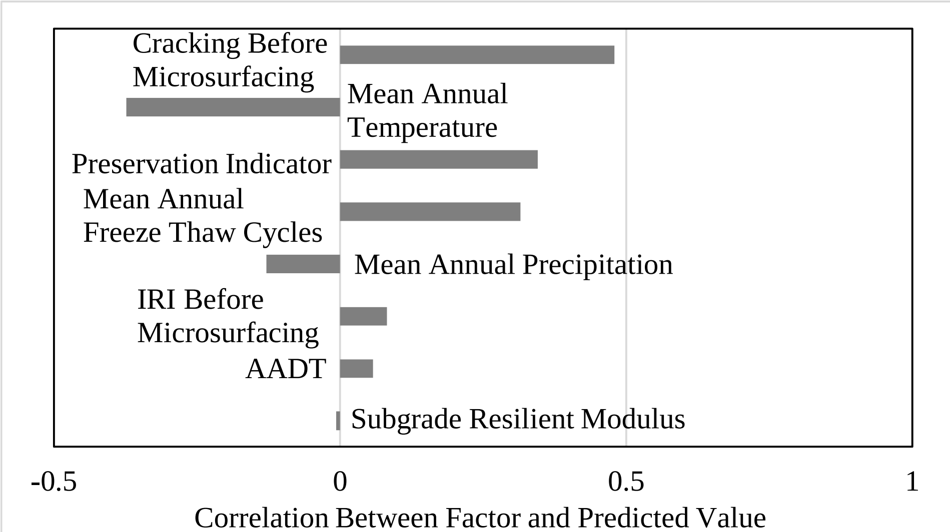


Figure 68. Sensitivity of factors in transverse cracking model following microsurfacing.

Longitudinal Cracking

Longitudinal cracking data were limited to two agencies: to the Louisiana DOTD and Virginia DOT. Figure 69 shows the distributions of growth rates for microsurfacing and control segments, and the means of the two distributions are not statistically different.

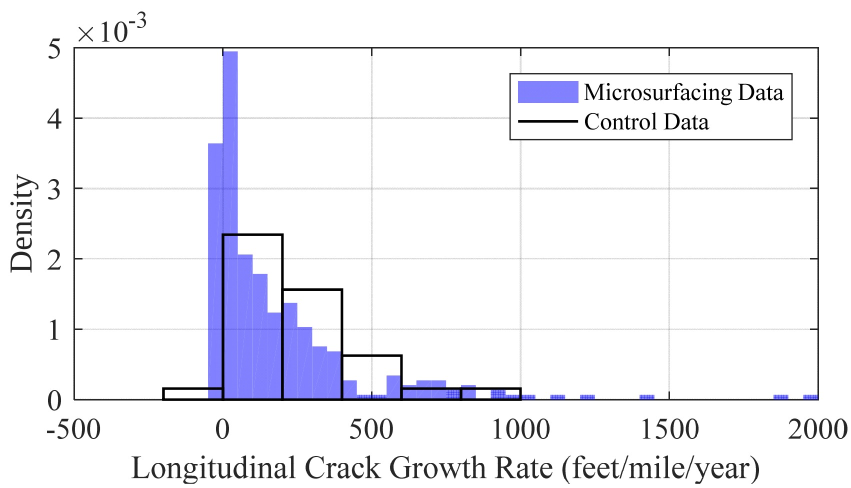


Figure 69. Longitudinal cracking growth rate for microsurfacing and control segments.

Next, regression was performed, and the preservation indicator was not statistically significant in any of the models investigated. The model fit results are shown in Figure 70 and the model is provided in Equation 18. A simulation was performed to assess the applicability of the model over a broad set of conditions, and the results are shown in Figure 71. The shape and range of the distribution in Figure 71 is similar to the microsurfacing distribution in Figure 69. The sensitivity of the model to each of the inputs was assessed, and the results are shown in

Figure 72. The results show that the non-wheel path longitudinal cracking growth rate is primarily driven by temperature related variables, as well as cracking and IRI before treatment.

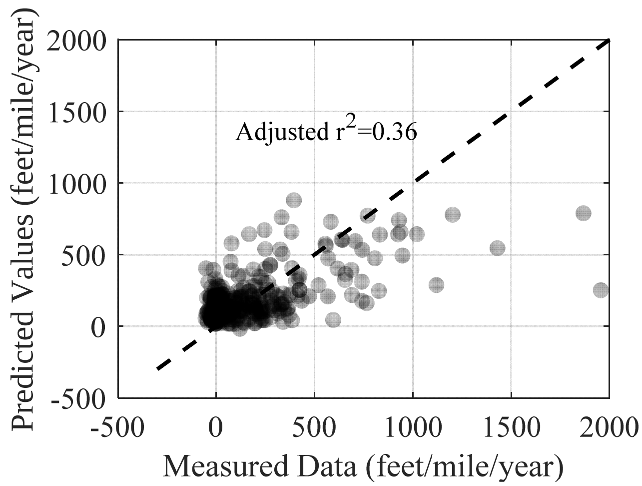


Figure 70. Model fit results for longitudinal crack growth following microsurfacing.

$$Long_{MS} = 495 + 0.324 \times Long_{Init} - 11.74 \times IRI_{Pre} + 2.546 \times FTC - 0.144 \times HiTemp + 0.081 \times {IRI_{Pre}}^2 - 6.24 \times 10^{-3} \times HiTemp^2 - 8.56 \times 10^{-10} \times {Long_{Init}}^3 - 1.62 \times 10^{-4} \times {IRI_{Pre}}^3 - 2.71 \times 10^{-3} \times Long_{Init} \times IRI - 8.88 \times 10^{-3} \times Long_{Init} \times HiTemp + 6.06 \times 10^{-6} \times Long_{Init} \times {IRI_{Pre}}^2 + 2.01 \times 10^{-4} \times Long_{Init} \times HiTemp^2 \quad (18)$$

Where:
$Long_{MS}$ = Predicted transverse cracking growth rate after chip seal (feet/mile/year)
$Long_{Init}$ = Longitudinal cracking before preservation (feet/mile)
IRI_{Pre} = IRI before preservation (inch/mile)
HiTemp = Count of the degree days above 90°F
FTC = Mean annual number of freeze thaw cycles (count)
$Pres_{Ind}$ = Binary variable (equals 1 if preservation applied and 0 otherwise)

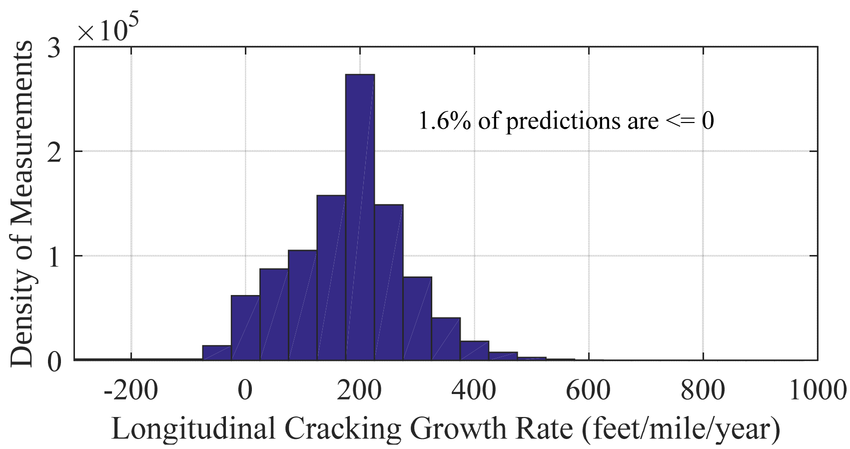


Figure 71. Results of extrapolating the longitudinal cracking growth for microsurfacing.

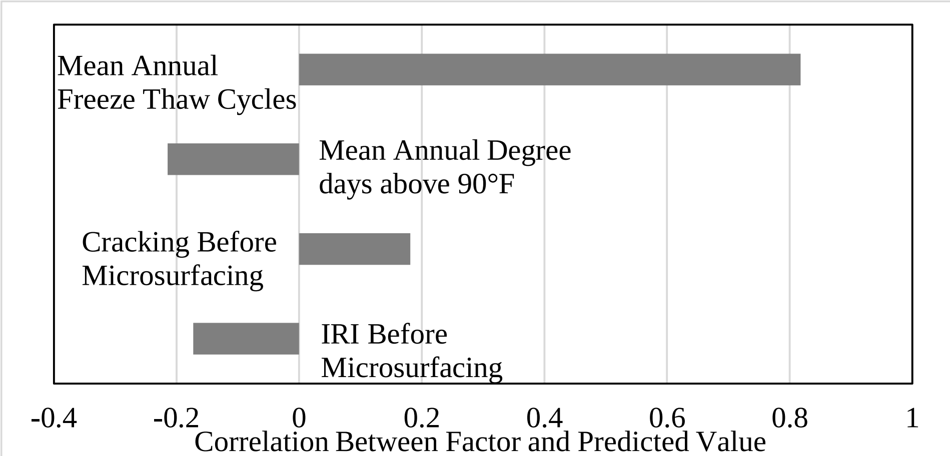


Figure 72. Sensitivity of factors in longitudinal cracking model following microsurfacing.

SLURRY SEAL ANALYSIS

Data for slurry seals were gathered from agencies and the LTPP. Multiple agencies had data for evaluating the immediate effect of slurry seals on performance measures. However, upon investigation of slurry seal data submitted by agencies, no agency had complete data sets that could be used for modeling changes in performance. The result of investigating all available data was that only LTPP data were used for developing the performance for slurry seals.

Immediate Change

Data for evaluating the immediate effect of slurry seals on IRI and rutting were obtained from the Kansas DOT, Idaho DOT and the LTPP database. It was found that slurry seals do not have an immediate effect on IRI or rutting. Due to inconsistent cracking definitions, only LTPP data were used to assess the effects of slurry seals on cracking. Similar to microsurfacing and chip seals, non-wheel path longitudinal cracking was eliminated but transverse cracking was not found to be zero following application of the slurry seal. Figure 73 shows the histogram of transverse cracking following the slurry seal using LTPP SPS3 data, and only 57 percent of the segments were found to have zero cracking following the slurry seal.

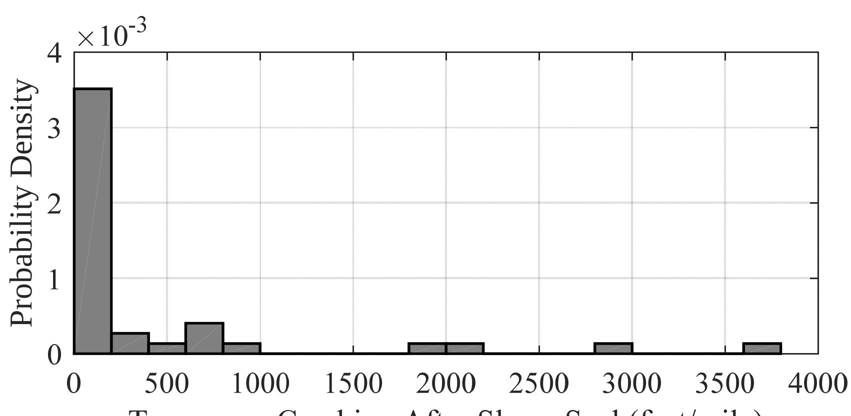


Figure 73. Histogram of transverse cracking following slurry seal.

An assessment was performed to investigate significant factors that may contribute to transverse cracking immediately following the application of a slurry seal. It was found that the

length of transverse cracking before the slurry seal and mean annual precipitation were the two variables that most significantly predicted the transverse cracking following the slurry seal; transverse cracking following the slurry seal is positively correlated with the length of cracking before the slurry seal and negatively correlated to the mean annual precipitation.

Growth Rates

Roughness (IRI)

Figure 74 shows the distribution of IRI growth rates on slurry seal and control segments. A regression was performed, and a binary variable indicating whether preservation had been performed was found to be statistically significant. The model fit resulting from the regression is shown in Figure 75, and the model is provided in Equation 19. A simulation was performed to assess the applicability of extrapolating the model over a set of conditions representative of the contiguous US, and the distribution of output values resulting from the simulation is shown in Figure 76. The results of the simulation indicate that the model is applicable to a wider range of conditions.

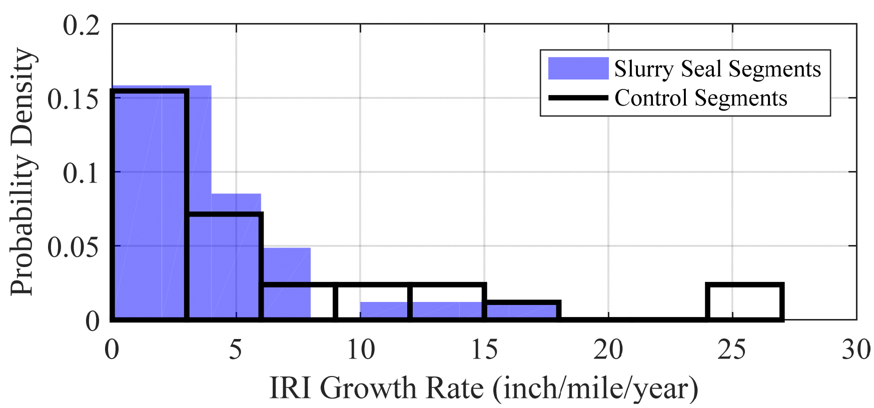


Figure 74. Comparison of IRI growth on slurry seal and control segments.

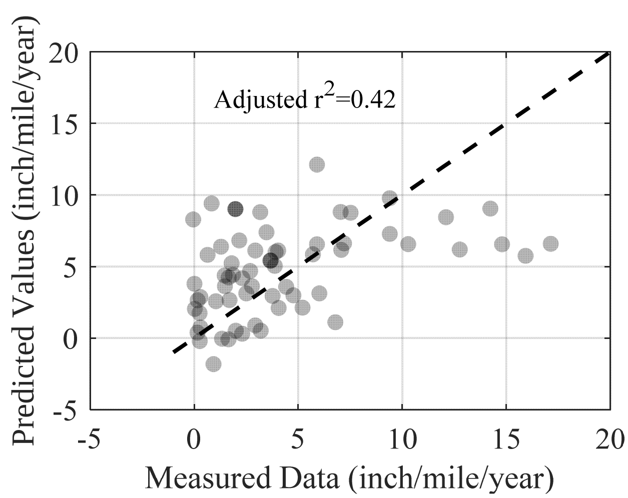


Figure 75. Model fit results for IRI growth after slurry seal.

$$IRI_{SS} = -91.5 + 29.4 \times Log10(MR) + 3.83 \times Precip + 0.156 \times HiTemp - 0.208 \times Log10(AADT) \times MAAT + 0.351 \times Log10(AADT) \times Precip - 1.14 \times Log10(MR) \times Precip - 0.036 \times FTC \times Pres_{Ind} \quad (19)$$

Where:
IRI_{SS} = Predicted IRI growth rate after slurry seal (inch/mile/year)
HiTemp = Count of the degree days above 90°F
Precip = Mean annual precipitation (inches)
AADT = Average annual daily traffic (count)
MAAT = Mean annual air temperature in degrees Fahrenheit
FTC = Mean annual number of freeze thaw cycles (count)
$Pres_{Ind}$ = Binary variable (equals 1 if preservation applied and 0 otherwise)

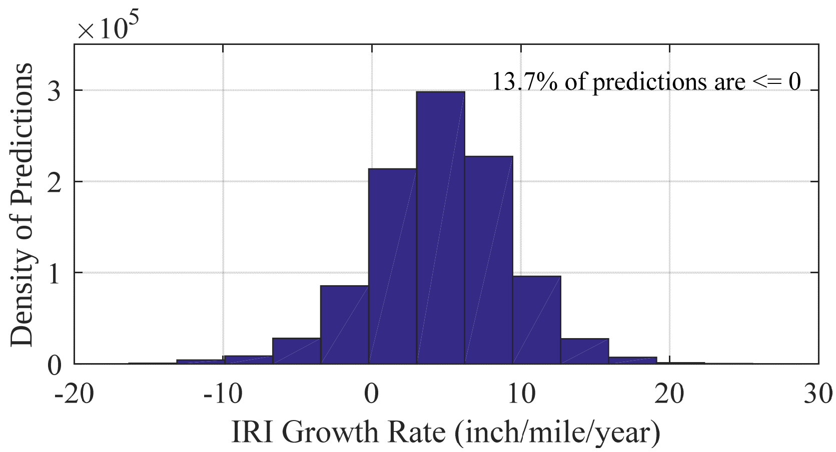


Figure 76. Results of extrapolating the IRI growth following slurry seals.

The sensitivity of the model to each of the inputs was assessed, and the results are shown in Figure 77. The results show that the non-wheel path longitudinal cracking growth rate is primarily driven by temperature related variables and cracking before the overlay.

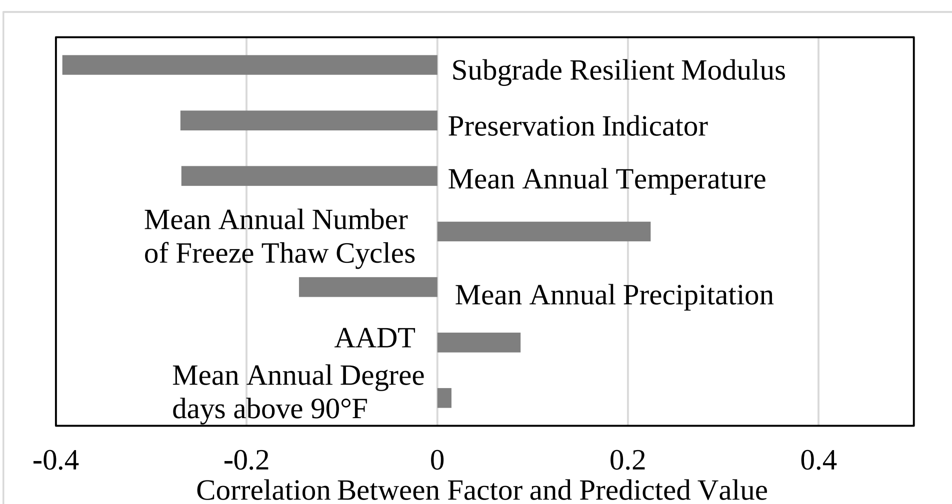


Figure 77. Sensitivity of factors in IRI prediction model following a slurry seal.

Rutting

The distribution comparing rutting growth rates for slurry seal and control segments is shown in Figure 78, and the means are not statistically different. A regression was performed, and a binary variable indicating whether preservation had been performed also was not found to be statistically significant. The results of the regression showed only traffic and mean annual temperature to be the significant variables towards predicting rut growth rates, though the regression model does not fit the data well. The model fit results are shown in Figure 79, and the model is provided in Equation 20.

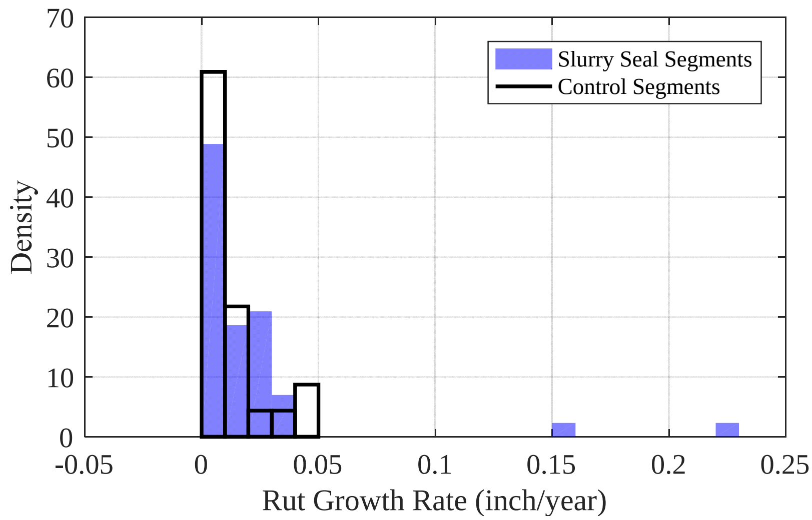


Figure 78. Comparison of rut growth on slurry seal and control segments.

A simulation was performed as detailed previously in this report to assess the applicability of extrapolating the model over a set of conditions representative of the contiguous US. The distribution of output values resulting from the simulation is shown in Figure 80. The results of the simulation indicate that the model is applicable to a wider range of conditions.

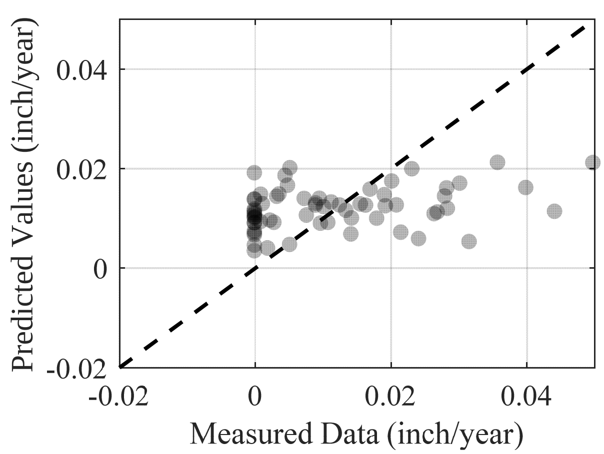


Figure 79. Rut growth following slurry seal.

$$Rut_{SS} = -1.08 \times 10^{-3} + 0.014 \times Log10(AADT) - 3.62 \times 10^{-4} \times MAAT \quad (20)$$

Where:

Rut_{SS} = Predicted rutting growth rate (inch/year)
AADT = Average annual daily traffic (count)
MAAT = Mean annual air temperature in degrees Fahrenheit

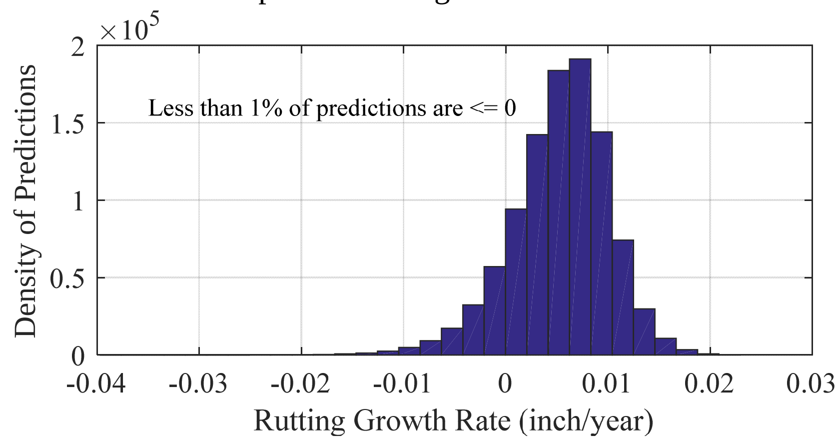


Figure 80. Results of extrapolating rut growth model for slurry seal.

Transverse Cracking

The distribution comparing transverse cracking growth rates for slurry seal and control segments is shown in Figure 81, and the means are not statistically different. The regression showed only transverse cracking before treatment and mean annual precipitation to be significant variables towards predicting growth rates. The model fit results are shown in Figure 82, and the model is provided in Equation 21.

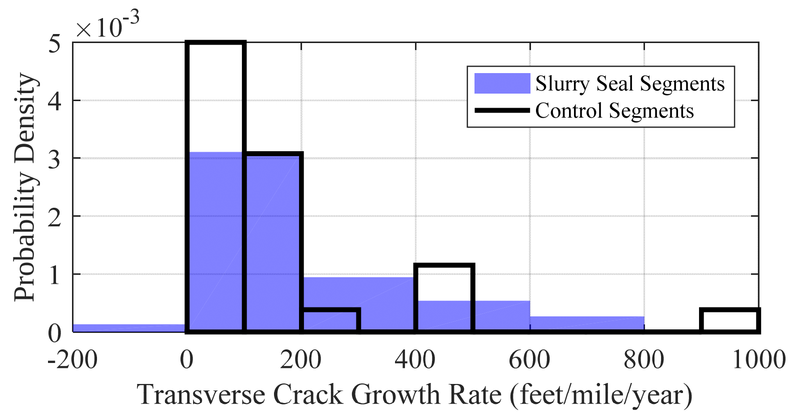


Figure 81. Comparison of transverse crack growth on slurry seal and control segments.

$$TRCK_{SS} = 334 - 0.276 \times TRCK_{Pre} - 2.41 \times 10^{-5} \times TRCK_{Pre}^{2} + 100 \times log10(AADT) - 147 \times log10(MR) + 0.132 \times TRCK_{Pre} \times log10(AADT) \quad (21)$$

Where:
$TRCK_{SS}$ = Predicted transverse crack growth rate after slurry seal (feet/mile/year)
$TRCK_{Pre}$ = Transverse cracking before preservation (feet/mile)
AADT = Average annual daily traffic (count)
MR = Subgrade resilient modulus (psi)

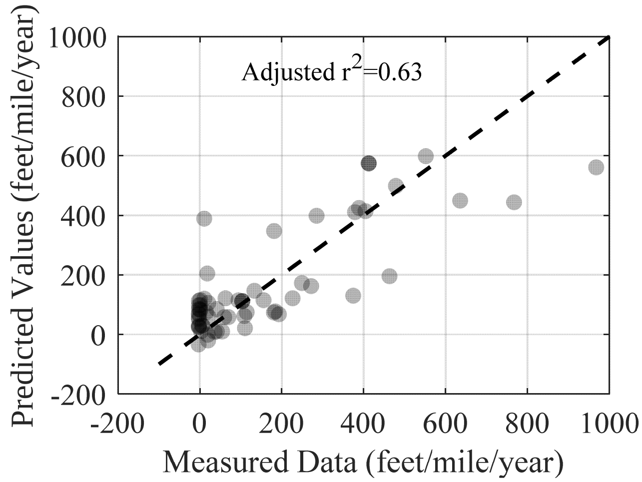


Figure 82. Transverse crack growth following slurry seal.

A simulation was performed and the distribution of output values resulting from the simulation is shown in Figure 83. The sensitivity of the model to each of the inputs was assessed, and the results are shown in Figure 84.

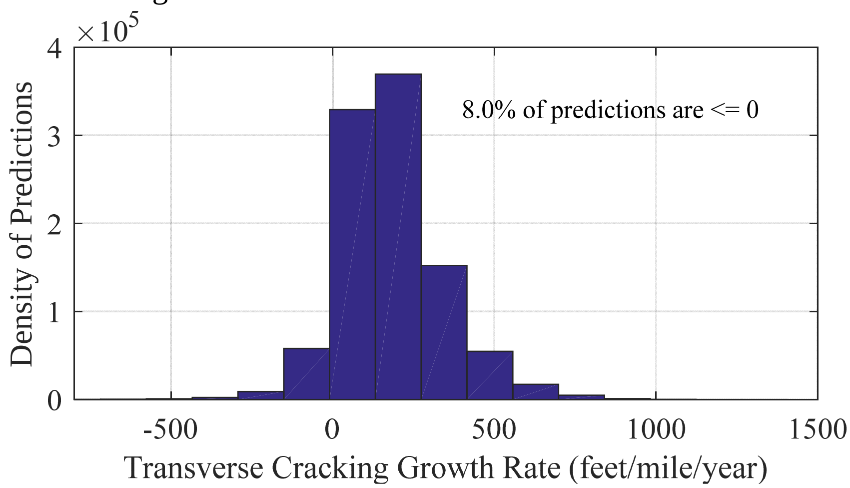


Figure 83. Results of extrapolating transverse cracking growth model for slurry seal.

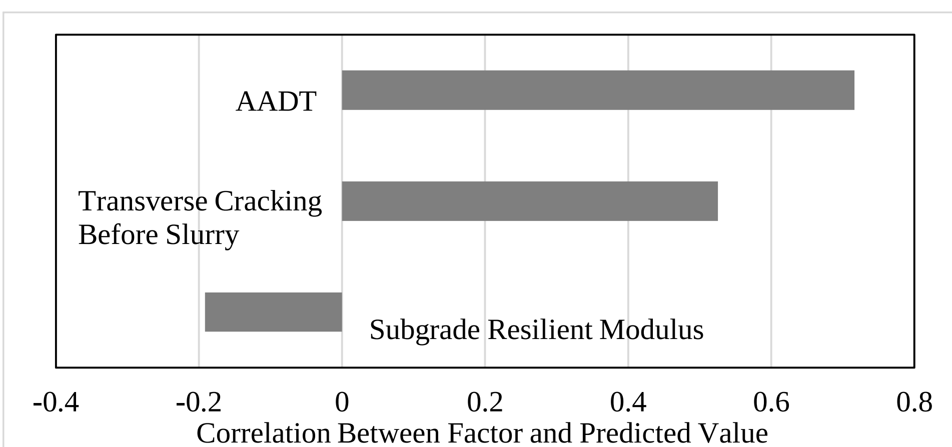


Figure 84. Sensitivity of factors in fatigue cracking prediction following slurry seal.

Fatigue Cracking

The distributions of fatigue cracking growth rates for control and treatment segments are shown in Figure 85, and the control segments tend to have a higher fatigue cracking growth rate. Next, a regression was performed. The fit of the resulting model is shown in Figure 86 and the model is given in Equation 22, where the estimated growth rate is the sum of the coefficients times the inputs. In this case, a binary variable that serves as an indicator for preservation was not statistically significant to the model.

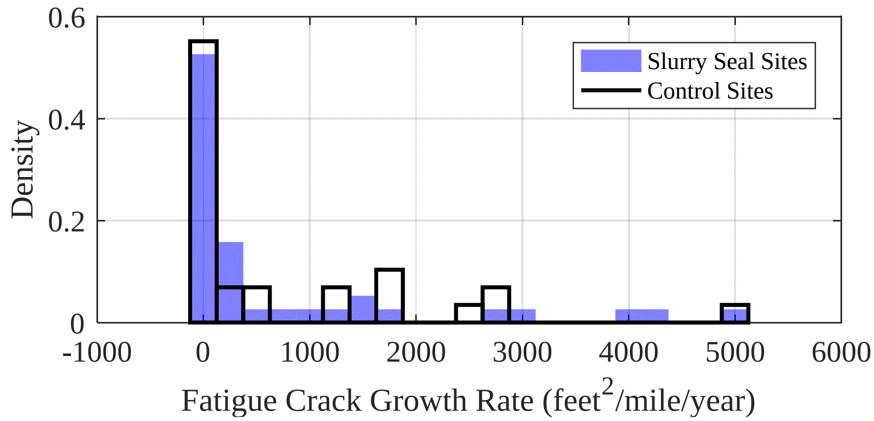


Figure 85. Comparison of fatigue crack growth on slurry seal and control segments.

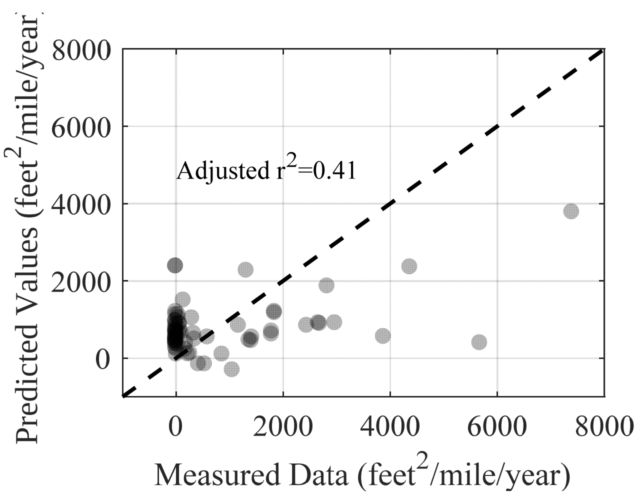


Figure 86. Fatigue crack growth following slurry seal.

$$Fat_{SS} = 5352 - 123 \times MAAT + 71.2 \times Precip + 29.6 \times HiTemp - 206 \times Thck + 6.75 \times Thck^2 \quad (22)$$

Where:
Precip = Mean annual precipitation (inches)
MAAT = Mean annual air temperature in degrees Fahrenheit
HiTemp = Count of the degree days above 90°F
Thck = Total pavement thickness above subgrade (inch)

To test its applicability to be used as a national level default model, the model was tested by extrapolating the results over a broad range of expected US conditions using simulation as detailed earlier in this report. The results of the simulation are shown in Figure 87. The

sensitivity of the model to each of the inputs was assessed, and the results are shown in Figure 88. The results show that fatigue cracking growth rate is primarily driven by pavement thickness and climate related variables.

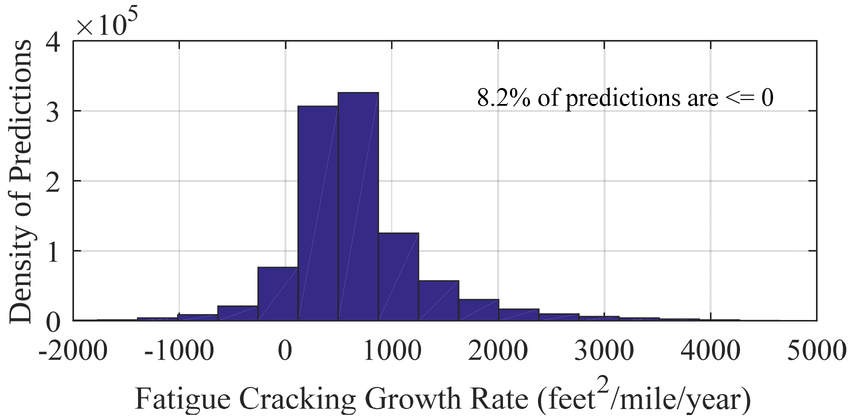


Figure 87. Results of extrapolating fatigue cracking growth model for slurry seal.

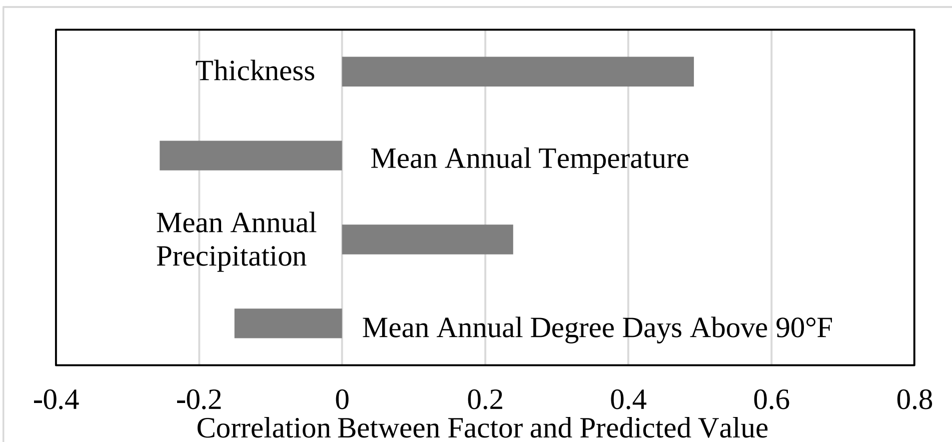


Figure 88. Sensitivity of factors in fatigue cracking prediction model following slurry seal.

Longitudinal Cracking

The distribution comparing longitudinal cracking growth rates for slurry seal and control segments is shown in Figure 89, and the means are not statistically different. A regression was performed, and a binary variable indicating whether preservation had been performed also was not found to be statistically significant. The results of the regression showed that the only significant variable towards predicting longitudinal cracking growth rate was the length of pretreatment longitudinal cracking. The model fit results are shown in Figure 90, and the model is provided in Equation 23.

A simulation was performed to assess the applicability of extrapolating the model over a set of conditions representative of the contiguous US. The distribution of output values resulting from the simulation is shown in Figure 91. The results of the simulation indicate that the model is applicable to a wider range of conditions.

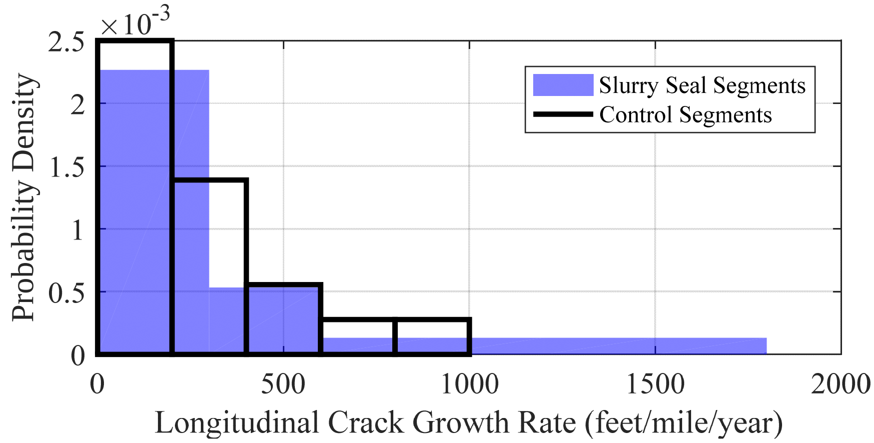


Figure 89. Longitudinal crack growth on slurry seal and control segments.

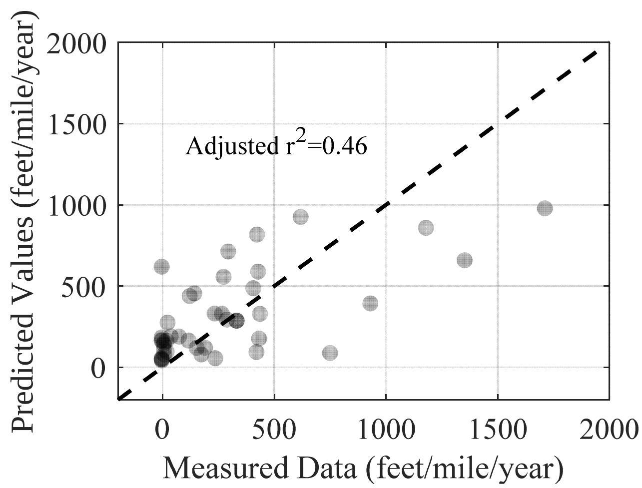


Figure 90. Longitudinal crack growth following slurry seal.

$$Long_{SS} = 2615 + 0.075 \times Long_{Init} - 581 \times Log10(MR) \quad (23)$$

Where:
$Long_{SS}$ = Predicted longitudinal crack growth rate after slurry seal (feet/mile/year)
$Long_{Init}$ = Longitudinal cracking before preservation (feet/mile)
MR = Subgrade resilient modulus (psi)

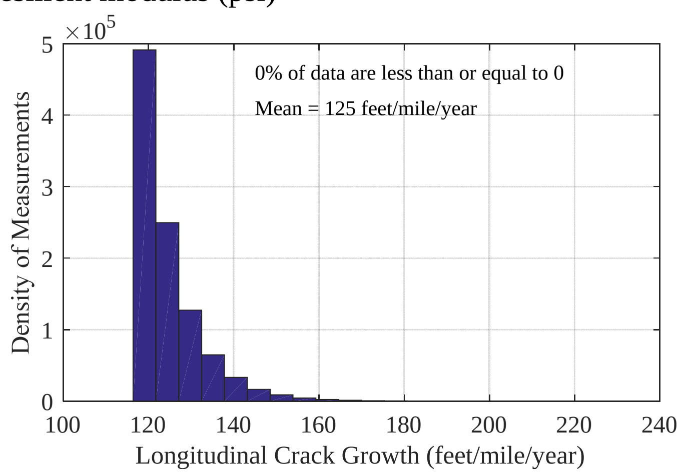
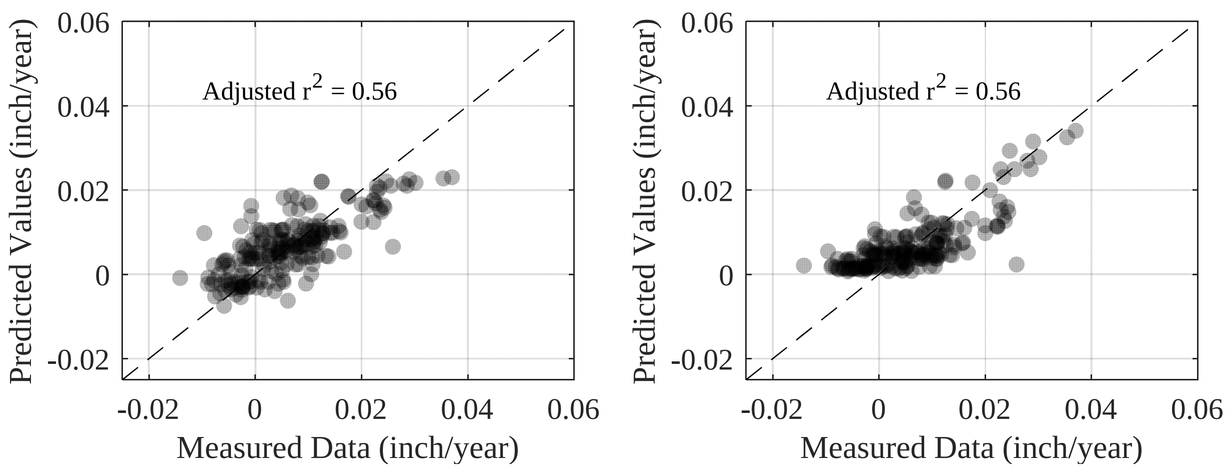


Figure 91. Results of extrapolating longitudinal cracking growth model for slurry seal.

ADDRESSING NEGATIVE GROWTH RATES

The performance measure growth rate models in this chapter will predict negative growth rates for performance measures in some cases (although the model form was developed to minimize those cases). Censored regression was not used to develop the models because the negative growth rates were informative for the interaction of variables, and thus understanding how those interactions influence timing. For example, some combination of condition and non-condition based factors were more likely to predict negative values than others, indicating that the growth rate on those segments is expected to be significantly smaller than the measurement variability.

The predicted negative growth rates were compared to the results from models that were constrained to not predict negative values, and a correction approach was developed based on those findings. For example, Figure 92 shows two sets of model fit results for the rut growth model shown in Chapter 4 of the Guide. Figure 92(a) shows the fit when negative values are allowed and Figure 92(b) shows the fit when the model was constrained to predict only positive values; the same terms were used in both models. In both cases, the data fit the model reasonably well. A comparison between the two cases is shown in Figure 93, and the results show that the negative growth rates in the model that allows for negative values (x-axis) are very low growth rates in the constrained model (y-axis). The model predictions are very comparable over the range of expected rutting growth (between 0 and 0.02 inches/year). The correction factors were selected to account for this trend in the data.



(a) **(b)**

Figure 92. Model fit results for rutting prediction when negative values are allowed (a), and when negative values are restricted (b).

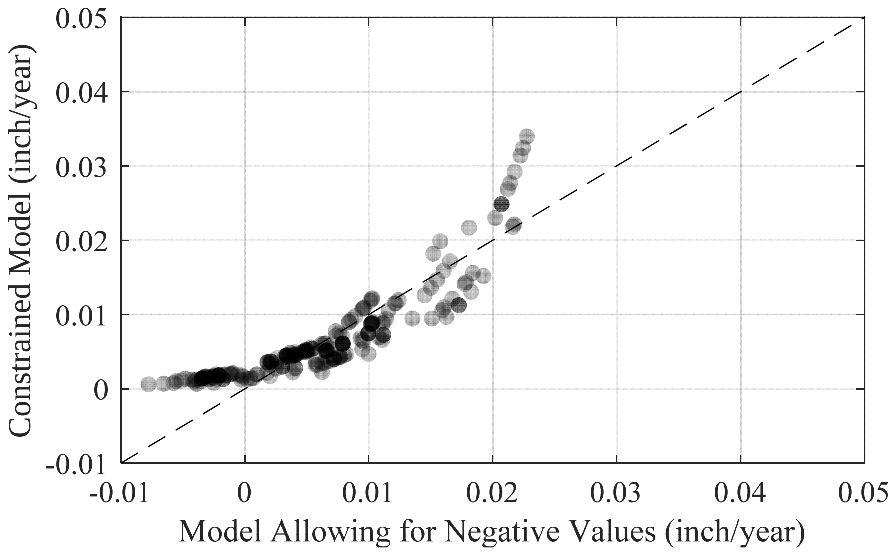


Figure 93. Comparing constrained model (i.e., no negative predictions allowed) to the model allowing for negative growth rates.

The correction factors are as follows:

For predicted IRI growth rates less than 1 inch/mile/year, Equation 24 should be applied:

$$IRIGrowth_{Corr} = 0.3 * e^{1.2*\mathrm{IRI}Growth} \quad (24)$$

Where:

IRIGrowth = the predicted IRI growth rate (inch/mile/year) from the models in this chapter

$IRIGrowth_{Corr}$ = the corrected IRI growth rate (inch/mile/year)

For predicted rutting growth rates less than 0.005 inch/year, Equation 25 should be applied:

$$RutGrowth_{Corr} = 0.0025 * e^{150*\mathrm{Rut}Growth} \quad (25)$$

Where:

RutGrowth = the predicted rutting growth rate (inch/year) from the models in this chapter

$RutGrowth_{Corr}$ = the corrected rutting growth rate (inch/year)

For predicted cracking growth rates less than 5 feet/mile/year for transverse or longitudinal cracking or 5 feet^2/mile/year for fatigue cracking, Equation 26 should be applied:

$$CrkGrowth_{Corr} = 2.2 * e^{0.15*\mathrm{Crk}Growth} \quad (26)$$

Where:

CrkGrowth = the predicted cracking growth rate from the models in this chapter

$CrkGrowth_{Corr}$ = the corrected cracking growth rate

CHAPTER 6. PAVEMENT PRESERVATION TIMING GUIDE

The previous chapters detailed the approach to developing a framework and methodologies for determining the timing of asphalt surface pavement preservation treatments. The framework and methodologies were used to develop a Guide for determining the timing of asphalt surfaced pavement preservation, which is attached to this report. The objective of the Guide is to present a set of detailed steps for determining the timing of asphalt surfaced pavement preservation treatments using the framework and methods detailed in this report.

The Guide presents the timing determination as a set of five primary activities, each of which are detailed in Figure 94.

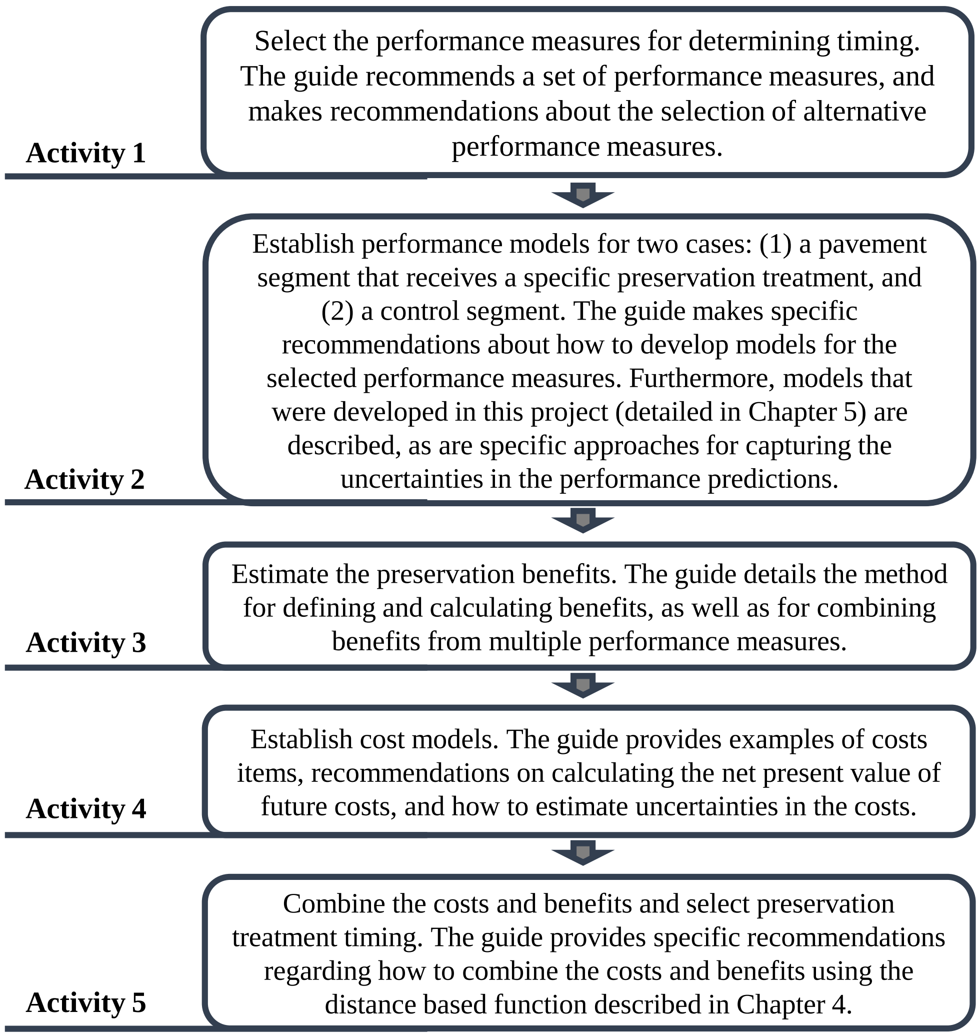


Figure 94. Primary activities for preservation timing

The most data intensive of the activities is expected to be Activity 2 (establish performance models), and thus it is broken into eight detailed steps beginning with the data required, and ending with a set of performance models.

Intended Audience

The Guide was written specifically for engineers and analysts that have a basic understanding of pavement condition data, as well as a basic understanding of statistics. Some topics in the Guide are more advanced than the basic engineer or analyst are familiar with, and those topics are explained in more detail and external references are cited. Additionally, many examples are detailed throughout the Guide to demonstrate clearly the important steps and concepts.

Guide Contents

The need to develop clear and informative supporting models is critical for determining the timing of preservation treatments. Therefore, the development of the Guide began with the details of model development (Chapter 3) and supporting example analyses (Chapter 4). The Guide contents are:

Chapter 1. Introduction – provides background information, Guide objective, overview of timing methodology and implementation process, and organization of the Guide.

Chapter 2. Preservation Timing Framework – details the components and many considerations of the framework needed for a clear understanding of pavement preservation timing selection.

Chapter 3. Implementation Process – provides step-by-step approaches for the five main activities for determining preservation treatment timing. The chapter begins with guidance on selecting performance measures, then details performance model development, and finally describes how to use the performance measures and models to determine timing. Examples are also provided in the form of stand-alone text boxes.

Chapter 4. Example Analyses – provides four example analyses. The first example demonstrates the development of performance models for control and preserved pavements. The second example demonstrates the development of the cost models. The third example demonstrates multiple cases of calculating preservation treatment benefits, and the final example demonstrates multiple cases of selecting preservation treatment timing.

Chapter 5. Summary and Other Considerations – provides a summary of the procedures discussed in the Guide with emphasis on the importance of data quality and how this can influence timing decisions. This chapter also emphasizes that the methodology presented in the Guide should not be a static procedure, but that data quality and models should be routinely improved.

The references cited throughout the Guide were included in a list at the end of the Guide.

CHAPTER 7. SUMMARY, CONCLUSIONS, AND RECOMMENDED RESEARCH

Determining the timing to apply pavement preservation to a specific pavement segment or a network of pavements is a problem that has been widely reported in the pavement literature. Many different analysis methodologies exist for determining preservation treatment timing, and each have benefits and drawbacks. This report detailed the results of a project that developed a framework and set of methodologies for determining the timing of asphalt pavement preservation treatments. The framework and methodologies were used to develop a detailed Guide for determining the timing of applying preservation treatments.

SUMMARY

Preservation treatment timing is based on the costs of applying the treatment and the benefits gained from application of that treatment. A review of current literature revealed that many approaches exist for determining preservation treatment timing. The majority of preservation treatment timing approaches detailed in literature are based on cost-benefit analysis, though some studies focus only on the benefits while others report the results of expert surveys. The primary differences between the approaches identified in literature are the specific methods for calculating preservation treatment benefits and costs.

Based on a critical review of the results found in literature, a general preservation timing framework was developed in this project. The framework is based on a comparison of costs and benefits, and includes the evaluation of uncertainties as an integral step in determining timing. The inclusion of uncertainties was a result of evaluating literature related to the effects of preservation treatments on pavement performance and noting the high values of uncertainties in the results of that literature. Detailed guidance on how to determining values for uncertainties in both costs and pavement performance (which defines the benefits) is provided in the Guide that is attached to this report.

The framework contains methodologies for defining pavement performance, calculating benefits, calculating costs and combining the costs and benefits to determine preservation treatment timing. This project explored specific approaches for each methodology, and then developed recommendations for the steps required in each methodology. The framework and methodologies were then used as the foundation for the development of the Guide.

CONCLUSIONS

The results of this project demonstrated that using a cost-benefit based approach that takes into consideration uncertainties is an effective way to determine the timing of preservation treatments. Basing the timing on costs and benefits reflects business practices within many agencies, and the inclusion of uncertainties allows for risk to be considered in the decision making process. Additionally, a cost-benefit based approach leverages existing practices for estimating costs and existing data for defining benefits.

The benefits (positive or negative) of pavement preservation are derived from two effects; the immediate change in condition and the change in performance (i.e., long-term changes in condition over time). An example of the immediate change in condition is cracking being eliminated when a chip seal is applied, and an example of changes in performance is the reduction in the rate of cracking growth following application of a chip seal. Therefore, the benefits of preservation are maximized when the marginal benefits from the two effects are jointly maximized. If the effect resulting from the immediate change in condition causes the

largest increase in benefits, the benefits are maximized if preservation is applied in the last possible year before the pavement is in too poor of condition for preservation to be a consideration. Conversely, if the effect resulting from the change in performance causes the largest increase in benefits, the benefits are maximized if preservation is applied earlier in time. For example, the following was found during the conduct of this project:

- If evaluating the timing to place a chip seal and IRI is the performance measure, the timing would likely be recommended early in the analysis period. This is because the chip seal has no immediate effect on IRI, but reduces the rate of growth of IRI. Maximum benefits occur when the chip seal is placed in the earliest possible year when using IRI as the performance measure.
- If evaluating the timing to place a chip seal and transverse cracking is the performance measure, the timing will likely be recommended further into the future than if using IRI as the measure. This is because the largest marginal benefit is added due to the immediate reduction in cracking – the marginal benefit resulting from the reduction in the cracking growth rate is much lower on average.
- If evaluating the timing to place a chip seal and using both IRI and transverse cracking as the performance measures, the timing would likely be recommended sometime between the timing recommended using the measures individually. This is because the immediate effect is only seen in cracking, and both cracking and IRI experience a reduction in growth rates.

An evaluation of expected cost data provided by State DOTs revealed many differences in how costs are estimated. This finding parallels a finding from the literature that cost information is inconsistent among agencies (Zimmerman et al., 2017). Finally, this project included an assessment of pavement condition data across multiple sources (i.e., 10 State DOTs and the LTPP database). The IRI data were comparable across the data sources, but rutting and cracking measures were not defined or collected in the same way across each of the data sources. The lack of standard data collection and reporting protocols for rutting and cracking limited the ability to compare across the sources of data, which limits extrapolating conclusions across multiple agencies.

RECOMMENDED RESEARCH

The conduct of this project resulted in a timing framework and set of methods supporting the framework, and also included a significant number of analyses performed on pavement preservation performance data provided by ten agencies and contained in the LTPP database. The following recommendations are made for future research:

- Agencies that are seeking to implement the framework and methods recommended in this report for determining the timing of pavement preservation should develop a set of performance models instead of using those found in literature. The example models developed during this project (detailed in Chapter 5) can be used as a first step. However, this project found consistent differences in the performance of preservation treatment across different data sources that could not be described in terms of the variables collected and reported in this report. The Guide attached to this report presents a detailed set of steps that agencies can use to develop performance models for implementing the framework and methods.

- Standard rutting and cracking definitions should be developed to facilitate the comparison of results obtained by different agencies. At present, the comparison of preservation performance across multiple agencies is limited because many define cracking and/or collect rutting differently.

- The results of this study should be expanded to preservation activities on Portland cement concrete (PCC) pavements, as well as other asphalt pavement treatments that were not considered during the development of this project. The approach recommended in the Guide is not pavement type specific, and many different pavement preservation treatment types can be evaluated using the framework.

The Guide attached to this report also contains many recommendations directly related to the implementation of the preservation treatment timing approach detailed in this report.

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ATTACHMENT A

GUIDE FOR TIMING OF ASPHALT-SURFACED PAVEMENT PRESERVATION

Project No. 14-38 COPY NO. 1

GUIDE FOR TIMING OF ASPHALT-SURFACED PAVEMENT PRESERVATION

Final Guide

Prepared for
NCHRP
Transportation Research Board
of
The National Academies

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☐ Pipeline and Hazardous Materials Safety Administration and was conducted in the **Hazardous Materials Cooperative Research Program,**

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which is administered by the Transportation Research Board of the National Academies of Sciences, Engineering, and Medicine.

DISCLAIMER

GUIDE FOR TIMING OF ASPHALT-SURFACED PAVEMENT PRESERVATION

Final Guide

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CHAPTER 1. INTRODUCTION

1.1. Background.

Preservation is employed by highway agencies to maintain and improve a pavement's functional condition at a relatively low cost. Preservation treatments are applied to pavements with the expectation of improving functional performance, increasing service lives, and reducing life cycle costs (LCC) without significantly increasing the structural load carrying capacity of the pavement. However, the relationships between factors such as climate and traffic, and changes in performance and LCC are not well defined. Therefore, the timing at which preservation treatment should be applied to achieve maximum improvements in performance and LCC is not well defined.

The timing of preservation is determined by following a process to identify when the performance or service life of a pavement is maximized, while minimizing the costs associated with treatment placement. Such a process will evaluate the extent to which a preservation treatment affects pavement performance and costs associated with the treatment as detailed in this guide.

Pavement preservation is designed to address many pavement characteristics, such as:

- Slowing the age hardening of the asphalt pavement surface material.
- Sealing the surface to reduce water intrusion.
- Correct surface distress such as minor rutting and raveling.
- Restore surface friction characteristics.

Examples of pavement preservation treatments include chip seals, slurry seals, thin asphalt overlays, fog seals, and cape seals.

1.2. Effects of Preservation Treatments on Pavement Performance

Pavement performance describes the condition of the pavement over time with respect to a single or combined set of performance measures. The most common performance measures for asphalt concrete pavements (hereafter referred to as asphalt pavements) are roughness (as measured by the International Roughness Index (IRI)), rutting, and cracking. Other measures of pavement condition include raveling, flushing, polishing, stripping, shoving, and delamination. Each measure relates change in condition to the time after construction or the cumulative traffic loading, along with many other variables. A combined pavement performance measure (e.g. pavement condition index (PCI)) combines two or more performance measures into a single value to represent the overall condition of the pavement.

Pavement performance is affected by traffic loading, the structure of the pavement (including the subgrade), the materials used to construct the pavement, climate, quality of construction, type and time of maintenance, preservation, and rehabilitation, and other factors. Traffic loading is dominated by the axle weights of trucks and vehicle speed. In addition to layer thicknesses, properties of a pavement structure includes the stiffness of the subgrade, base, and asphalt pavement which change with the degree of moisture (for subgrade) and material temperature. Asphalt pavement stiffness also changes as the asphalt binder ages over time. The predominant climate features that influence pavement performance are air temperature, precipitation, and solar exposure. Quality of construction, specifically application rates and material compaction, bond between asphalt layers, and surface roughness, will affect pavement

performance. When a pavement is properly maintained and preserved, the performance of the pavement is likely improved.

The performance measures used to describe pavement condition vary by highway agency. The performance measures used in this guide are roughness, rutting and cracking, and the assessment of these measures can be found in NCHRP Report 858 (Rada et al., 2018). Pavement performance can be illustrated using either measures that decrease with worsening condition (e.g., the PCI) or measures that increase with worsening pavement condition (e.g., cracking), as shown in Figure 1.

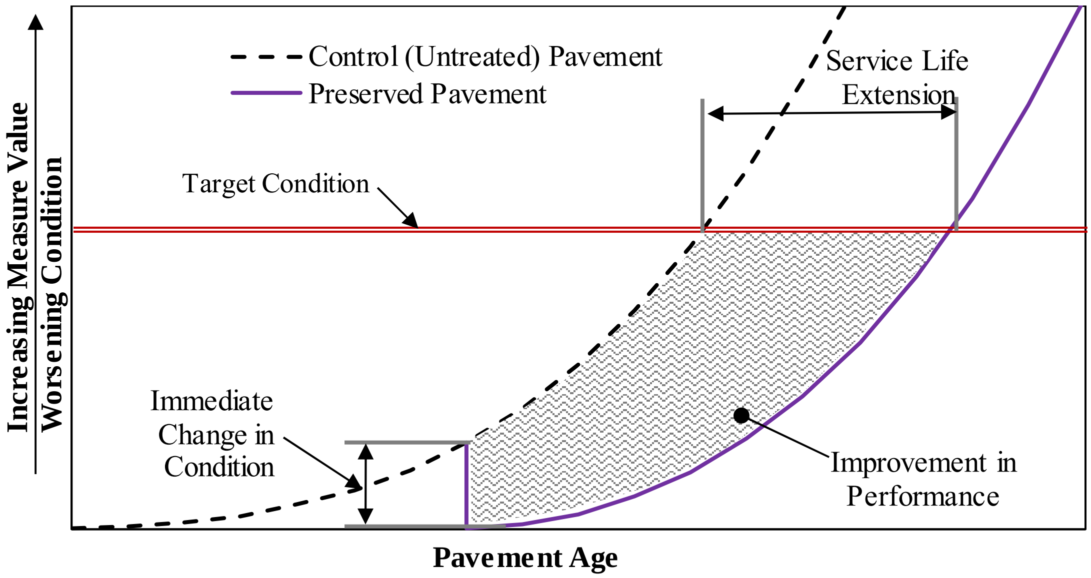


Figure 1. General performance prediction components.

Figure 1 also shows the change in pavement performance when a preservation treatment is placed. It is generally expected that an immediate change in condition will occur at the time of treatment placement, although some treatments will not result in a change in the value of certain measures (e.g., chip or slurry seals will not immediately change IRI). Over time, the pavement condition will change under the influence of traffic loading and climate. The rate of this change is also influenced by the pre-treatment condition of the pavement and the type and properties of the treatment.

As an example, when considering individual pavement conditions separately, both a slurry seal and thin overlay preservation treatments will cover-up existing transverse cracks. However, the slurry seal may not cause an immediate change in roughness or rutting, but the thin overlay may result in an immediate change. Similarly, a chip seal may not cause an immediate change in IRI, but may reduce its long-term growth rate of IRI.

1.3. Pavement Preservation Timing

This guide presents a detailed approach for defining the timing of a preservation treatment. The framework in this guide demonstrates how the timing of preservation is affected by the measured pavement condition, climate variables, and relative weight assigned to each performance measure and the interpretation of the uncertainties. Therefore, the recommended timing will depend on these factors.

The first step to establish the timing for pavement preservation is defining how benefits will be measured. A common measure of benefits is the life extension achieved by the treatment, generally expressed in years, which is illustrated in Figure 1. The predicted performance of the preservation treatment is composed of the immediate change in condition followed by the change in performance. The life extension is measured as the difference between the time the do-nothing condition and the preservation condition at the target terminal condition. One drawback of using service life extension is that it does not account for the non-linearity in the pavement performance. Another measure of benefits is quantified as the area bound by the do-nothing performance curve, the preservation performance curve and the target threshold condition. As detailed in Chapter 3, the area calculation, not the service life extension, is used to measure preservation benefits in this guide.

The expected benefits associated with the preservation treatment is one of the two primary inputs to determine the time to place a preservation treatment, with the other input being cost. A common cost-benefit approach divides the cost of the treatment by the value of the performance to obtain a unit cost per unit of performance, such as dollars per lane-mile per years of service. The added cost component helps define the time to place the preservation treatment. Examples of types of costs are project cost and preservation construction unit cost. Project costs also include items such as mobilization, traffic control, and construction safety among many other items. Preservation construction unit cost includes items such as labor, equipment and materials. With measures for benefits and cost, an agency can determine the timing of specific preservation treatments. As detailed throughout this guide (e.g., see the examples in Chapter 4), not all preservation treatments affect pavements the same.

1.4. Objective and Audience of Guide

The objective of NCHRP Project 14-38 "Guide for Timing of Asphalt-Surfaced Pavements Preservation" is to develop a guide for identifying the timing for preservation of asphalt pavements considering condition (e.g., IRI, rutting, and cracking) and non-condition-based factors (e.g., climate, subgrade soil and traffic). For this guide, preservation treatments are defined as treatments applied to preserve an existing roadway, slow future deterioration, and maintain and improve its functional condition without substantially increasing structural capacity.

The timing of asphalt pavement preservation treatments is a question of when the performance or service life of a pavement is maximized, while also minimizing the costs associated with placing the treatment. The change in pavement condition over time (i.e., performance) is not well documented for many preservation treatments. Additionally, relationships between the performance of preservation treatments and many factors that are expected to affect performance, such as traffic, structure, initial pavement condition, workmanship, and climate, have not been adequately developed. These relationships are essential for identifying the most appropriate timing that a preservation treatment should be applied to a pavement.

This guide is designed to be used by engineers or analysts for defining the time that preservation treatments should be applied to specific pavements. Some basic knowledge of general pavement engineering, pavement condition data collection and data analysis is required prior to implementing this guide.

1.5. Organization of guide.

This Guide is divided into five chapters. Chapter 1 provides an introduction and the objectives of the guide, and presents an overview of important pavement preservation concepts. Chapter 2 presents a description of the preservation timing framework developed and used in this guide. Chapter 3 presents steps for agencies to implement the recommended timing framework. Chapter 4 presents examples of using the Chapter 2 framework and Chapter 3 methods. Chapter 5 presents a general summary and recommendations for implementing the timing approach. The list of references used throughout the guide is presented following Chapter 5.

CHAPTER 2. GENERAL PRESERVATION TIMING FRAMEWORK

This chapter details the recommended general preservation treatment timing framework. The framework defines a set of steps and required data for inputs, and then links the data and calculations into a timing approach. The recommended framework is based on cost-benefit calculations, and includes an evaluation of uncertainties. Specific methods within the framework presented in this chapter are detailed in Chapter 3, and Chapter 4 shows examples that link the methods to the overall timing framework.

2.1. Common Preservation Timing Approaches

Twenty-two approaches that are applicable for determining pavement preservation treatment timing were identified in the literature for use in project- and network-level applications (Bryce et al., 2018). A review of the approaches considered at the project- and network-levels showed many similarities; the network-level timing was generally based on the same type of approach as the project-level timing evaluation. A more detailed review of the 22 approaches showed that 15 of them are based on cost-benefit analysis, three only consider effectiveness (i.e., benefits), two are based on changes in material properties, and two are based on expert judgement (Bryce et al., 2018). Although expert judgment is a vital part of engineering practice, the approach in this guide does not recommend it as the basis for preservation timing. Instead, expert judgment is recommended during the development and interpretation of required pavement and preservation performance models and for implementation of the guide. Similarly, the results of the two approaches that evaluated changes in material properties did not form the basis for the framework.

A detailed review of the remaining approaches showed many similarities. Figure 2 is a schematic of pavement performance when considering a preservation treatment, and it illustrates many concepts identified in the approaches considered for the framework. Preservation treatment benefits are defined as some measure of treatment effectiveness (as opposed to being monetized), defined as one of the following:

- As the preservation treatment life shown in Figure 2. This definition requires an estimation of the time it takes for the pavement condition subject to the ‘do-nothing’ and ‘preserved’ scenarios to reach a defined threshold. The threshold was generally defined as the value for any performance measure that indicates when pavement preservation is or is not considered a feasible treatment.
- As the benefit area shown in figure 2. This definition requires an equation that defines the performance curve of the pavement subject to the ‘do-nothing’ and ‘preserved’ scenarios, as well as a defined condition threshold.
- A ratio of the benefit area to some portion of the do-nothing area shown in figure 2.

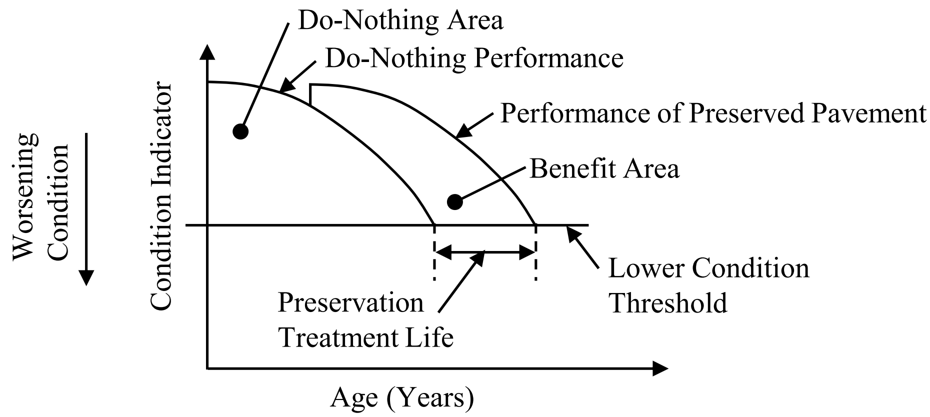


Figure 2. Schematic of pavement performance definitions.

Preservation treatment timing approaches follow a common set of steps defined as:

Step 1: Select the performance measure that will be assessed. The recommended preservation treatment timing is directly related to the performance measure under consideration. In some cases, the combination of performance measures and preservation treatments considered can result in counterintuitive results. For example, it was found that when considering only IRI, treatment effectiveness of a chip seal is maximized if the treatment is placed on a pavement at the lowest possible IRI value. However, if using cracking as the performance measure, the effectiveness from applying a chip seal is maximized when the cracking is near its threshold value. The reason for this can be described using the illustration in Figure 3, where the benefit area and treatment life are shown as they relate to the immediate change in condition and long-term changes in the rate of deterioration. If the benefits from the immediate change in condition are much greater than the benefits from the long-term changes in performance, then the preservation treatment effectiveness is maximized when the immediate change in condition is maximized (e.g., when cracking has become significant prior to a chip seal).

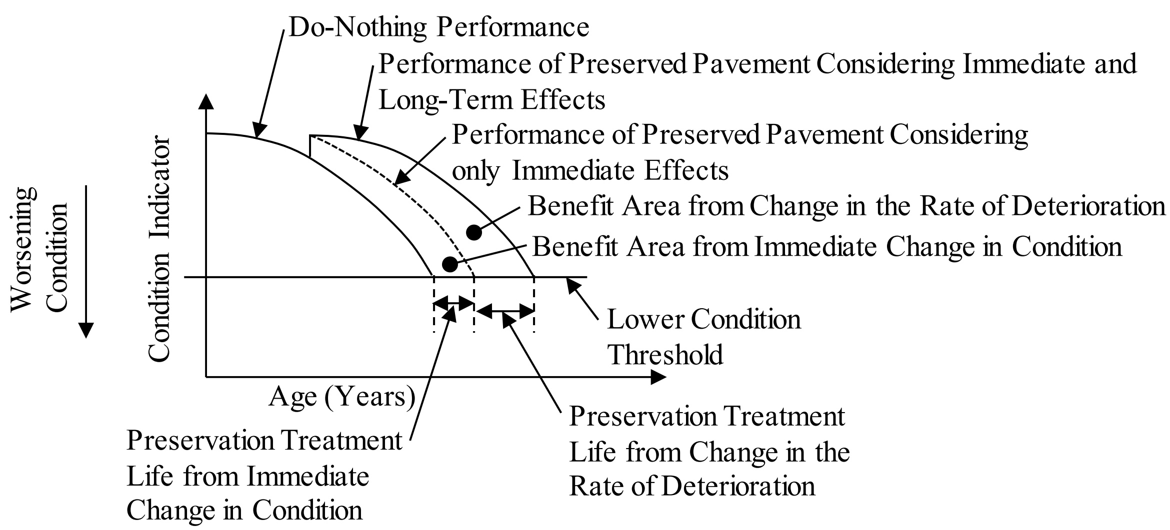


Figure 3. Schematic showing preservation treatment effectiveness from immediate and long-term changes in condition.

Step 2: **Select the preservation treatment under consideration.** This guide specifically evaluated thin overlays, chip seals, microsurfacing and slurry seals.

Step 3: **Define a set of rules for when the treatment should no longer be considered**. This includes defining a set of condition thresholds beyond which specific preservation treatments are no longer a consideration; thresholds are generally provided in agency pavement preservation guidance.

Step 4: **Calculate the costs and the benefits of applying the preservation treatment.** This should be done in the first year under consideration, and each year beyond that as defined in step 6. For example, if the project development process requires two years, then the first year of consideration should be three years in the future.

Step 5: **Using a defined equation, combine the costs and benefits into a single value**. The specific function is recommended in Chapter 3.

Step 6: Repeat steps 4 and 5 for each year in consideration.

Step 7: **Select timing as the year when the equation from Step 5 is best satisfied**. For example, if the objective is to minimize costs divided by benefits, select the timing as the year in the analysis when the costs divided by the benefits result in the lowest value.

The recommended treatment timing framework is detailed in the next section. An evaluation of the literature and of data submitted by ten Departments of Transportation (DOTs) showed that agencies should have the required data to support each of the steps. However, it was found that cost data are not consistent across agencies, and therefore the recommended method for defining costs were made flexible to account for multiple approaches.

One important component that is missing in the preservation treatment timing approaches from literature is an assessment of uncertainties associated with preservation treatment costs and benefits. In each of the seven steps, the values required for inputs have historically been defined deterministically. However, models describing the effects of preservation treatments on pavements have a significant amount of uncertainties, and therefore the recommended framework includes consideration of uncertainties using a probabilistic approach.

2.2. Recommended Preservation Timing Framework

The recommended framework is shown in Figure 4, and the major framework steps are detailed over the remainder of this section.

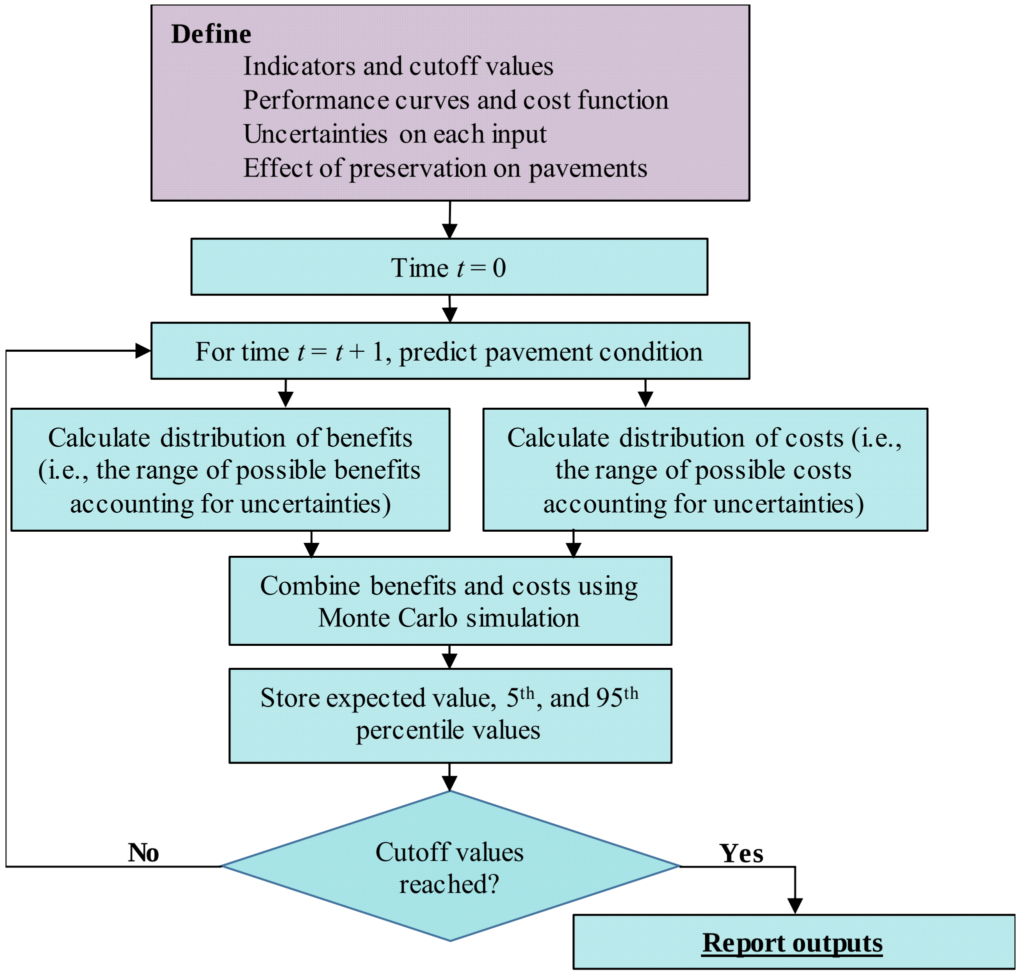


Figure 4. Framework for defining the timing of preservation treatments.

2.2.1. Framework Elements

The first element of the framework is where each input is defined, including:

- Selected performance measures.
- Cutoff values, which are the thresholds beyond which pavement preservation is no longer considered an option. For example, if cracking is the indicator selected in the analysis, the cutoff value should be the level of cracking beyond which the preservation treatment being considered will no longer be applied to the pavement.
- Performance equations that describe the pavement condition as a function of time and other variables (e.g., traffic, climate, etc.). These performance functions are required for preservation treatment and control segments, and Chapter 3 details approaches for developing them.
- Equations that describe pavement preservation costs for different timing scenarios.
- Uncertainties associated with the costs and performance over time. Chapter 3 defines approaches for estimating these uncertainties quantitatively and qualitatively, and

Chapter 4 provides multiple examples to demonstrate uncertainties in the calculations.

The second element of the framework is to calculate the future pavement condition for the control and preservation treatment case for each step in time. Then, the pavement condition is used to estimate the benefits of the preservation treatments using the methods in Chapter 3.

An important aspect of calculating preservation treatment benefits is the combination of the benefits estimated for each performance measure. For example, Figure 5 illustrates the expected benefits for a chip seal using IRI and cracking as performance measures. In both cases the chip seal is applied in the same year, but the final years in the benefits calculation are different for each measure. Accordingly, no single benefit can be directly calculated when using multiple different performance measures, and the recommendation in this guide is to calculate the individual benefits for each performance measure, and then weight and sum the benefit values from each measure. Details for how to calculate the weighted benefits are provided in Chapter 3.

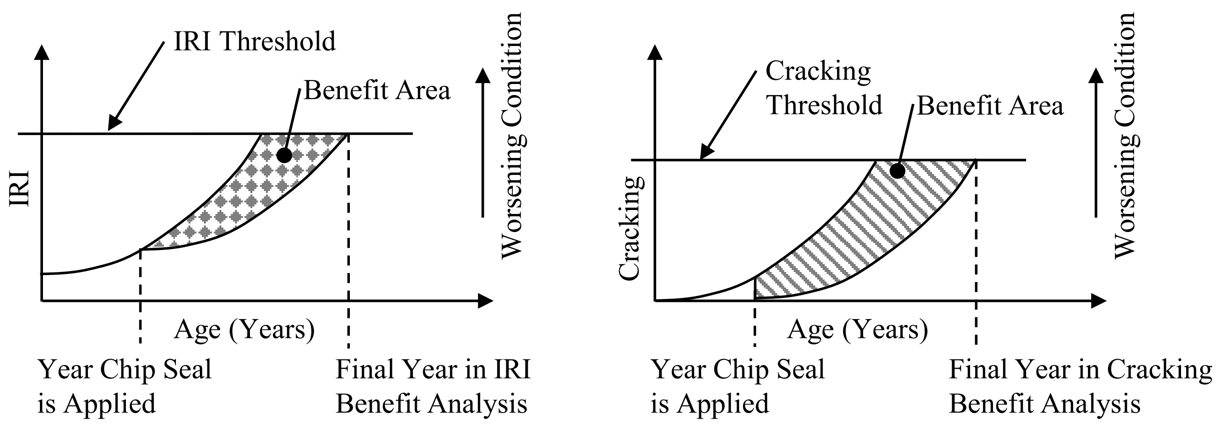


Figure 5. Illustration of IRI and cracking benefits following a chip seal.

Another important consideration for calculating the benefits is the uncertainty in their estimation. Methods for including uncertainty in the timing calculation are detailed in Chapter 3 and illustrated using examples in Chapter 4. An example of the impact of uncertainties on the calculation of preservation treatment effectiveness is presented in Example 2.1.

The third element in the framework is the calculation of costs. Defining preservation treatment timing includes predictions of costs that must be compared for different times, requiring that the costs be presented in comparable terms. Chapter 3 recommends the calculation of the net present value of future costs, and demonstrates how to calculate the values.

Example 2.1 – Evaluating the impact of uncertainties on effectiveness calculations

To demonstrate how uncertainties affect the calculation of the benefit area, an example of the performance of a thin overlay measured using IRI was developed. The thin overlay models in Chapter 5 of the final report were used to calculate the benefit area when the treatment is applied on a pavement with an IRI of 110 inches/mile and another with an IRI of 120 inches/mile. The rest of the factors were the same for both cases; an AADT of 2,000, average annual precipitation of 35 inches, mean annual air temperature of 44 degrees Fahrenheit and an annual average of 10 degree days exceeding 90 degrees Fahrenheit. Figure 6 shows the case of the initial IRI equal to 110 inches/mile, and the benefit area equals 631 inches/mile – years. Figure 7 shows the case of the initial IRI equal to 120 inches/mile, and the benefit area equates to 590 inches/mile – years. It is more beneficial to apply the overlay when the IRI is 110 inches/mile if only using a deterministic evaluation (i.e. no uncertainties).

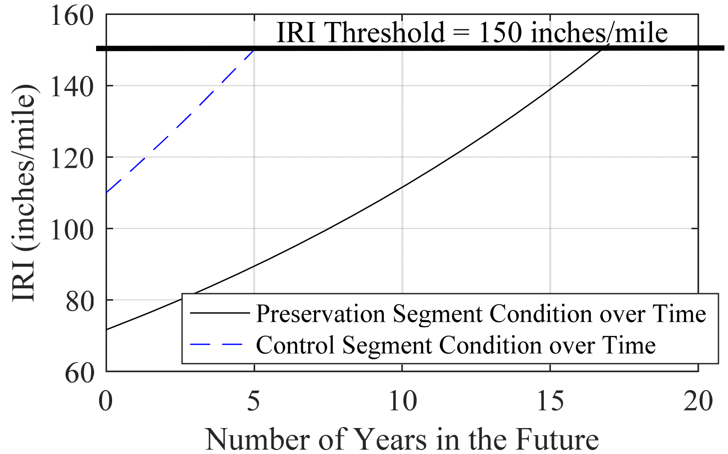


Figure 6. IRI prediction for control and treatment segments when thin overlay is placed at an initial IRI of 110 inches/mile.

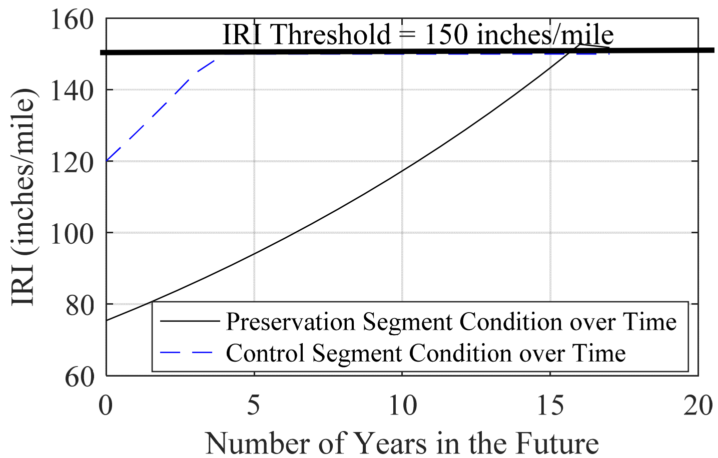


Figure 7. IRI prediction for control and treatment segments when thin overlay is placed at an initial IRI of 120 inches/mile.

To demonstrate the uncertainties associated with the performance prediction and benefits calculations, the benefit area for both cases were calculated using the uncertainties in the performance prediction (see Chapter 5 of the final report) and Monte Carlo simulation. The distribution of possible values for the benefit area calculation is shown in Figure 8, and it demonstrates the significant variability that can exist due to uncertainties. When calculating the benefit area with the uncertainties, the mean difference in the benefits area for the two cases are not considerably different from each other (see the overlap in the distributions). Chapter 4 demonstrates how these uncertainties propagate through the timing calculation, as well as how the range of uncertainties can be interpreted.

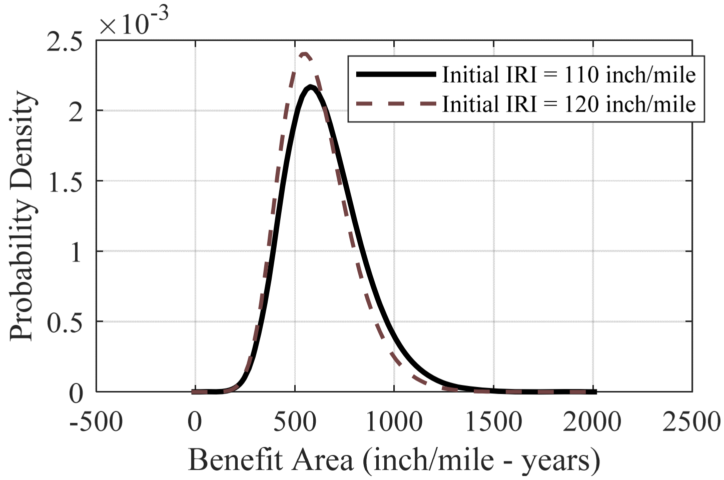


Figure 8. Distribution of possible benefits calculations.

The pavement condition may also affect the expected cost of specific preservation treatments. For example, cost data were collected from DOTs during the development of this guide, and multiple DOTs described how pavement surface preparation (e.g., rut leveling, etc.) is directly related to the pretreatment surface condition and is a part of the overall cost of applying the preservation treatment. However, the cost data obtained during the development of this guide were not consistent (e.g., some agencies included total historical contract costs, whereas others provided expected future costs, etc.), and no general conclusions about the relationship of pavement condition and preservation treatment costs could be reached during the development of this guide. The literature review conducted during the development of this guide also revealed many differences in the cost items that are considered during pavement preservation timing (Bryce et al., 2018). Because of the differences in the definition of costs throughout literature and the databases submitted during the development of this guide, the cost element in the timing framework was made to be flexible.

The fourth element is the combination of costs and benefits into a single value that can be used to define preservation treatment timing. Many methods for combining costs and benefits were identified, including:

- Translating the benefits into monetary value (e.g., by considering user costs) and subtracting the costs from the monetized value of benefits to arrive at a single net cost associated with preservation treatment timing scenarios. Similarly, the costs of applying the treatment can be divided by the monetized benefits to calculate a cost-

benefit ratio. In both cases, the minimum value of the calculation corresponds to the most effective preservation treatment timing.

- Dividing the costs by the benefits (without monetization) to develop a scaled cost. The resulting ratio defines the cost per unit of benefit, and the minimum value corresponds to the most cost effective preservation treatment timing.
- Many more techniques typically used in decision analysis, such as Matter Element Analysis (Li et al., 2010), Reference Point Programming (Romero et al., 1998).

Chapter 3 presents the recommended approach for combining costs and benefits, which is based on the Reference Point Programming approach.

The fifth and final element of the timing framework is the storage and presentation of results. At a minimum, the output resulting from combining costs and benefits should be stored for each year to compare different timing scenarios. The uncertainties associated with the calculation of the results are also required, and Chapter 4 demonstrates how the results and uncertainties can be displayed and interpreted.

CHAPTER 3. IMPLEMENTATION PROCESS

3.1. Overview

This chapter details the process required to determine preservation treatment timing, including the data and modeling necessary to define benefits for selected performance measures, costs, and how to combine the costs and benefits. This chapter outlines five activities for selecting preservation timing. The largest portion of the chapter is spent on detailing how to establish the performance models and estimate the preservation treatment benefits because this is seen as the most resource intensive activity.

3.2. Implementation Activities

The first two implementation activities, selecting performance measures and establishing performance models, follow the recommendations in NCHRP Report 858 "Quantifying the Effects of Preservation Treatments on Pavement Performance", as well as the guide accompanying that report. Therefore, significant reference is made to NCHRP Report 858 to avoid unnecessary duplication and to provide a source of additional detail.

Many of the approaches detailed in this chapter are accompanied by examples, and these examples are set apart from the text in boxes to separate them from the guidance. In addition, Chapter 4 presents detailed examples using data gathered from DOTs in support of the development of this guide.

3.2.1. Activity 1. Select pavement performance measures to be used in determining timing

The first activity in the implementation process is to select the performance measures that will be used to determine preservation timing. NCHRP Report 858 details how to select pavement performance measures for assessing the effectiveness of preservation, and the same guidance is recommended for use in this case (Rada et al., 2018). The chosen performance measures should link directly to the decision making processes and pavement management objectives within an agency. Some objectives, and hence measures, will be common among many agencies, such as those related to maintaining an acceptable level of ride quality, whereas some agencies have objectives that are not in widespread use, such as safety or environmental objectives.

According to NCHRP Report 858, the following factors should be considered when selecting performance measures for pavement preservation:

- **Number of measures** – All objectives should be adequately reflected in the set of measures. In general, the fewer the performance measures used by highway agencies the better. The reason for fewer measures include: elimination of measures that duplicate the same outcomes, easier implementation and maintenance of measures within agency's pavement and/or asset management tools, and lower data demands. At the same time, the selected performance measures must address the full range of pavement types and the full range of preservation treatments used.
- **Data availability** – performance measures must have the necessary data to support development (as well as periodic updates) of the performance prediction models.

- **Data quality** –the two most important criteria for data quality in this guide are accuracy and precision. Accuracy is the condition or quality of being 'true' – i.e., representing the actual condition measured without errors. Precision is the condition or quality of able to repeatedly measure the same quantity with little random error.
- **Risk impacts** – the ability to capture risk associated with application of preservation treatments is a key consideration in selecting performance measures.
- **Quantifiable** – if performance measures are to accurately reflect the effect of preservation, they must be capable of generating initial and long-term effects resulting from the application of preservation treatments.
- **Ease of use and implementation** – the performance measures should be familiar to the agency and have a clear meaning.

Data availability is central to assessing the timing of preservation, thus data must also be central to the selection of performance measures. The creation of this guide included the development of performance models based on a set of performance measures that are common across many agencies, and the model development in this chapter will be discussed in terms of those measures. However, the same process can be followed regardless of the chosen performance measures, if adequate data are available to support the models.

3.2.1.1.Recommended performance measures

Based on the research conducted to develop this guide, as well as the guidance provided in NCHRP Report 858, the recommended performance measures are: ride quality (IRI), cracking, and rutting. The recommended measures provide many advantages, including:

- They are used by most State DOTs in their day-to-day pavement management related activities, and therefore the agencies are familiar with them.
- DOTs are required to submit these same measures as part of their Highway Performance Monitoring System (HPMS) data submittals, and thus data are likely available for these measures.
- They include distresses that typically trigger preservation treatments.

The recommended measures were used to develop performance models, and it was shown that different preservation treatments affect each performance measure in different ways. For example, chip seals do not affect rutting, whereas thin overlays reduce rutting.

3.2.1.2.Using other performance measures

The recommended performance measures capture the effects of preservation, but they are not the only measures that can be used. NCHRP Report 858 details additional performance measures that can be used, as well as the criteria for assessing those measures. For example, surface friction measurements can be used as a performance measure. A number of agencies do collect and use friction measurements within their decision-making process (Speir et al. 2009; De Leon Izeppi et al. 2016), and a number of preservation treatments such as chip seals and microsurfacing have a significant effect on pavement surface friction.

Another type of performance measure that can be considered are composite measures, such as the Virginia DOT critical condition index (McGhee, 2002) or the Maryland State Highway Administration (SHA) functional cracking and structural cracking indexes (Rada et al., 2016). The values for composite indexes are bound, typically on a 100-point scale, with 100 being the best possible score and 0 being the worst possible score. Composite indexes are typically developed by calculating deduct values using the severity of specific distresses, summing the deduct values and then subtracting the summed values from an upper limit value.

Caution should be taken when modeling the effects of preservation using composite indexes. The two effects of preservation – the immediate change in condition and long-term change in performance – vary by distress type as well as the type of preservation treatment. For example, a chip seal does not reduce rutting, but does have an immediate measured effect on cracking. A composite index that includes both rutting and cracking, such as the Virginia DOT critical condition index, will show significantly different effects of preservation than one that only considers cracking, such as the Maryland SHA cracking indexes. Therefore, no generalizations should be made when comparing composite performance on preservation treatment effect models between agencies.

3.2.2. Activity 2. Establish pavement performance prediction models quantifying effects of preservation treatments on pavement performance

Pavement performance models are the primary driver of preservation timing, and are used directly to calculate the benefits of preservation application. Two sets of models are required: a model to predict the immediate change in the performance measure, and a model to estimate the changes in the rate of deterioration of the performance measure following preservation.

The immediate change in a performance measure is estimated using performance measure values before and after the application of preservation. Although it is preferable for those values to be measured within short succession (e.g., within weeks) of the application of a preservation treatment, many agencies collect data on an annual or biannual basis. Consequently, the immediate change in condition describes the expected change in the performance measures between two data collection cycles instead of the change in condition directly following (i.e., prior to opening the road to traffic) preservation.

Some of the approaches that can be taken to model changes in the rate of deterioration due to the application of preservation include the following:

- If a full set of time history condition data are available for a pavement, beginning with construction, or another significant rehabilitation, and covering a long enough time period to include the time it takes a preservation treatment to deteriorate to poor condition, then the effect of preservation can be directly estimated using the performance before and after preservation application. However, it is unlikely that agencies will have the same performance measures collected on the same pavement segments using the same data collection protocols for that long of a time period.
- The effects of preservation can be estimated by comparing the deterioration of a set of preservation projects to another set of projects that have the same characteristics but did not receive preservation (e.g., projects that were not included in the preservation program due to a limited budget).

The second approach is recommended in this guide, and the methods detailed in this section reflect that approach. The primary reason for recommending the second approach is that more data are available to support it. The following section details eight steps used to develop the pavement performance models for both immediate change and change in rate of deterioration.

Step 2.1 – Gather Preservation Segment Data

The first step is to compile all relevant data for pavement segments that received preservation. The data should be in terms of the performance measures that are being considered, and consist of the following required and optional elements:

Required Data

- Pavement segment characteristics, including:
  - Pavement type.
  - Functional class.
  - Beginning and ending mileposts of the pavement segment.
- Construction history data that defines the type, timing and location of preservation treatments on the pavement network.
  - Type of preservation treatment (e.g., microsurfacing).
  - Date that preservation was applied.
  - If additional work was conducted on the segment (e.g., rut leveling).
  - Beginning and ending mileposts of the application of the treatment.
- Pavement condition measurements immediately prior to and following the application of preservation treatments. Multiple years of measurements following the year of preservation are required to assess the effect of preservation on pavement performance.
- If mileposts are not the same for each year of condition data, then the data should be aggregated to the least common denominator of length so that only preserved pavement segments are evaluated. Changes in linear reference systems (e.g. mileposts) present a potential complication to compilation of pavement performance time history data, as discussed in NCHRP Report 858.

The number of years of data required following the application of preservation is directly related to the variability in the performance measures; performance measures with high variability require more data. In general, Bryce et al. (2018) found that between 6 and 10 years of data are adequate for modeling the effects of preservation.

Optional Data

Optional data include the information on independent variables used to describe some of the variability in the models. The optional data elements listed below are representative of data that have been shown to affect pavement performance, either during the development of this guide or from other literature sources. However, additional variables that affect pavement performance can also be used in the modeling.

- Structural data, including:
  - Pavement layer thicknesses.

  - Structural number of the pavement.
  - Deflection data (e.g., center deflection from falling weight deflectometer data).

- Climatic data, including:
  - Mean annual air temperature.
  - Mean annual number of freeze thaw cycles.
  - Mean annual count of the degree days above 90 degrees Fahrenheit.
  - Mean annual precipitation.

- Traffic data, including:
  - Average annual daily traffic (AADT).
  - Average daily equivalent single axle loads (ESALs).
  - Axle load spectra.

- Subgrade soil data, including:
  - Subgrade resilient modulus.
  - Subgrade moisture content.

Step 2.2 – Select Control Segments

The next step is to identify a set of representative segments that can provide information about the deterioration of a pavement when no preservation is applied, which are referred to as control or do-nothing segments throughout this guide. Control segments are defined as pavement segments that were candidates for preservation, but did not receive preservation. The approach used for defining control segments during the development of this guide was to use the agency's treatment selection criteria (e.g., condition ranges for specific treatments) to identify pavement segments that had been a candidate for preservation in past years. This approach is recommended in the cases that past decisions on specific pavements are not stored in a database.

The control segments should have similar characteristics as the preserved segments. For example, if the preserved segments are all along low traffic routes, then the control segments should also be gathered from routes with similar traffic volumes or loads. Similarly, the condition, as measured by the performance measures being modeled, and the age of the control segment should be similar to that of the treatment segments.

The same data detailed in Step 2.1 above should be gathered for each control segment identified, with the exception of the following: preservation type, timing of preservation application and mileposts defining the preserved section within the pavement segment.

Step 2.3 – Assess the Data

Following the gathering of the preservation and control segment data, effort should be spent to assess the data for the quality and any potential anomalies. For example, the following issues should be investigated:

- Presence of unrecorded maintenance.
- Biases caused by high pavement ages.
- Errors caused by variable pavement beginning and ending reference locations.

Identifying Unrecorded Maintenance

Unrecorded maintenance may cause an improvement in pavement condition when one is not expected. A significant number of references to variability in pavement condition measurements in literature have alluded to the possibility of unrecorded maintenance (e.g., Hunt and Bunker, 2004; Byrne and Parry, 2009; Susanna et al., 2017). However, these sources generally identify unrecorded maintenance through evaluating changes in a single performance measure, which is not as robust as when multiple measures are evaluated.

The recommended approach is to evaluate changes in each performance measure in each measurement cycle. Ideally, the different performance measures being used to identify unrecorded maintenance should be measured using different sensors or equipment types so that the errors in the measurements are mostly independent of each other. For example, IRI and cracking have traditionally been measured with two types of equipment that are calibrated independently, and the correlation of the errors in their measurements are expected be relatively small. However, this does not preclude the use of data for multiple performance measures gathered from single sensors. When using the data from single sensors, it should be noted that added correlation between the errors in the performance measures will exist, and that the results may not as clearly show unrecorded maintenance events. Additionally, the data used to identify unrecorded maintenance is not required to be the same performance measures that are selected for modeling the effects of preservation.

The approach to objectively identifying unrecorded maintenance can be implemented using some of the same data collected in the first two steps detailed above (i.e., identifying preservation and control segments).

The following actions are recommended for identifying unrecorded maintenance:

- Identify pavement segments that received preservation, as well as segments that received rehabilitation. Extract the following variables for each segment:
  - The condition before the preservation or rehabilitation for each measure.
  - The condition following the preservation or rehabilitation for each measure.
  - The time (in months) between data collection cycles.
- Identify pavement segments where it is known no work (i.e., maintenance or rehabilitation) was performed between two data collection cycles, and gather the same variables listed in the previous bullet. One option for identifying data with no maintenance is to use the condition data on the same segments from the previous bullets from two and three years prior to the preservation or rehabilitation and two and three years following the preservation or rehabilitation. This option assumes no maintenance was performed between years two and three before and after application of preservation or rehabilitation, and it is the approach used in this guide.
- Assign a value of 1 for each segment that received preservation, and a value of 2 for the segments that received no work.
- Perform logistic regression; the dependent variable is the indicator of whether work occurred, and the independent variables are:
  - Time between condition measurement cycles.

  - Change in performance measure divided by the previous value of the measure; each measure is used as an independent variable.
- Use the logistic regression results to assess whether the changes in each segment for each year is random or potentially due to unrecorded maintenance.

The recommended approach for identifying unrecorded maintenance is demonstrated in example 3.1. It was found throughout the development of this guide that variability in condition measures significantly differed between DOTs, and therefore it is not recommended to use results from other agencies when assessing unrecorded maintenance.

Biases from High Pavement Ages

A second issue found during the development of this guide is bias caused by high pavement ages. For example, when identifying control segments for some agencies, some pavements were found to be 15 years old or more, yet they had zero rutting, minimal cracking and very low values for IRI. These segments were checked for the presence of unrecorded maintenance, and many were found to likely not have unrecorded maintenance performed on them.

Pavements with high ages that are in very good condition should not be included when developing the models to identify pavement timing because they can potentially bias the models. Fundamentally, asphalt pavements that reach ages over 15 years without maintenance are not necessarily representative of candidates for preservation. Including pavements with very high ages as control segments will bias the models to lessen the expected benefits of preservation, and pavements with very high ages as preservation segments will bias the models to show an increase in expected benefits. Therefore, the recommended approach, which was used in the development of this guide, is to not include pavements above a certain age (e.g., 15 years) in either the control or preservation segments.

Example 3.1 – Assessing Data for Unrecorded Maintenance

To demonstrate an example, data were gathered from a State DOT, and Table 1 shows an example subset of those data. Three measures were selected for assessing unrecorded maintenance, although only two of those measures (IRI and rutting) were used to develop performance models. The variability in the rutting and IRI data in the example set is relatively high. For example, pavement segment 3 shows a 21 inch/mile decrease in IRI with no work performed, and pavement segment 2 shows a 0.1 inch decrease in rutting with no work performed.

For the example in question, an analysis program was used to develop a multinomial logistic regression with the data provided by the State DOT, and the result is shown in Equation 3-1. The time between measurements was not included in the model because it remains the same in the database – i.e., always 1 year. The multinomial logistic regression can be performed using one of several programs available, including Microsoft Excel. Equation 3-1 results in a ratio of the likelihood of no work to work being performed, and can be reformulated as the probability that work occurred (Equation 3-2).

Equation 3-2 can be used to assess the probability that work (i.e., maintenance or rehabilitation) occurred on a given pavement segment between the two years. For example, Table 2 shows values for IRI, rutting and equivalent transverse cracking for two years (labelled year 1 and year 2), and shows the probability of work occurring between the two years calculated using Equation 3-2. The only segment with a high likelihood of work is segment 5, which experienced a significant decrease in each measure. Segment 1 experienced a decrease in IRI and rutting, but no decrease in cracking. The probability of work shown for segment 1 is less than 0.5, which indicates that it is slightly more likely than not that the changes in IRI and rutting are due to measurement variability.

Table 1. Example data for IRI, rutting and equivalent cracking.

Pavement Segment	IRI in Year 1 (in/mile)	IRI in Year 2 (in/mile)	Rutting in Year 1 (in)	Rutting in Year 2 (in)	Equivalent Cracking[a] in Year 1	Equivalent Cracking[a] in Year 2	Time Between Measurements	Work Indicator[b]
1	63	62	0.19	0.17	0	0.53	12 Months	1
2	72	63	0.19	0.08	0	0	12 Months	1
3	148	127	0.11	0.15	0.89	0	12 Months	1
4	106	40	0.12	0.07	0.12	0	12 Months	2
5	112	59	0.11	0.06	0.4	0	12 Months	2
6	106	54	0.14	0.13	0	0	12 Months	2

a. Equivalent cracking is a unitless value that combines different severities and extents of transverse cracking into a single continuous number.

b. A value of 1 indicates no work performed between years 1 and 2, whereas a value of 2 indicates work was performed between the two years.

$$\frac{\pi_{No\,Work}}{\pi_{Work}} = e^{1.8-9.3\times\left(\frac{\Delta IRI}{IRI_{Initial}}\right)-1.6\times\left(\frac{\Delta Rut}{Rut_{Initial}}\right)-2.3\times\left(\frac{\Delta EqCRK}{EqCRK_{Initial}}\right)} \quad (3\text{-}1)$$

Where:

$\pi_{No\ Work}$ = relative likelihood that no work occurred given the changes in the measures

π_{Work} = relative likelihood that some work occurred given the changes in the measures

ΔIRI = change in IRI (inches/mile) between the two condition measurements

$IRI_{Initial}$ = value of the IRI (inches/mile) for the first measurement

ΔRut = change in rutting (inches) between the two condition measurements

$Rut_{Initial}$ = value of rutting (inches) for the first measurement

$\Delta EqCRK$ = change in equivalent transverse cracking (unitless)

$EqCRK_{Initial}$ = value of equivalent transverse cracking (unitless) for the first measurement

$$p_{work} = \frac{1}{1+e^{1.8-9.3\times\left(\frac{\Delta IRI}{IRI_{Initial}}\right)-1.6\times\left(\frac{\Delta Rut}{Rut_{Initial}}\right)-2.3\times\left(\frac{\Delta EqCRK}{EqCRK_{Initial}}\right)}} \quad (3\text{-}2)$$

Where:

p_{work} = the probability of some work occurring on the segment

Table 2. Probability of work between years 1 and 2 using Equation 3-2.

Segment Number	IRI Year 1	IRI Year 2	Rut Year 1	Rut Year 2	Equivalent Cracking Year 1	Equivalent Cracking Year 2	Probability of Work
1	125	115	0.1	0.05	0.1	0.1	0.44
2	200	170	0.15	0.16	1.5	1.5	0.37
3	75	82	0.05	0.08	1	0.8	0.04
4	150	155	0.1	0.05	1.2	1	0.28
5	164	130	0.15	0.1	0.8	0	0.95

Variability from Changing Beginning and Ending Mileposts

A third issue that needs to be reconciled with the data prior to modeling is to address the increase in measurement variability due to changes in linear referencing standards, such as mileposts. For example, when evaluating the data collected in support of this guide, some data showed pavement segments with the same identifier but with slightly differing beginning and ending mileposts. To partially overcome this issue, multiple unique fields were identified in the data set, and strict filtering was performed so that only segments with the same unique fields over time were included in the models. Examples of unique fields used in this research include: unique segment identifiers, beginning and ending milepost values, Global Positioning System (GPS) coordinates and directional information. Therefore, it is recommended that, as pavement segments are assembled from pavement management systems to develop the required models, additional checks should be employed to gain higher confidence that the same segments are reported in each year. It is recognized that some of the variability due to changes in milepost

station data are incurred during the data collection (e.g., beginning data collection before or after the recorded beginning milepost), and these errors cannot be resolved by filtering on unique identifiers.

The result of the data assessment should be a subset of pavement condition data that has be cleaned of segments with likely unrecorded maintenance, very high ages and variable mileposts. This subset of data is what will be used to model the effects of preservation, which is required for the timing determination.

Step 2.4 – Calculate Immediate Change in Condition

Following the data gathering and assessment, equations to calculate the immediate change in condition following the application of preservation are needed. The model development is detailed in NCHRP Report 858 (Rada et al., 2018), and the same approach is recommended in this guide. The initial change in condition is defined as the change in pavement condition immediately following application of preservation. In most cases, agencies will not have condition measurements immediately prior to (e.g., within the month before) and immediately following (e.g., within the month after) application of preservation. If the condition data are collected relatively frequently (e.g., on an annual or biannual basis), and the rate of deterioration following preservation is not high, then using the agency condition measurements prior to and following preservation is expected to be adequate. However, if an agency collects data on a relatively infrequent basis, the data will not be adequate to support development of the immediate change models.

It was found that the initial change in condition resulting from pavement preservation for a given agency is primarily related to the specific treatment type and the pavement condition prior to applying preservation. This is because the condition measurements used to calculate the immediate change in condition are generally supplied in close enough succession so the pavement deterioration in the time between the measurements is minimal. The approach for calculating the initial change in condition resulting from the application of a preservation treatment can be obtained by the following sequence:

1. Identify the condition measurements just prior to and immediately following the application of preservation treatment, by type of treatment, for each of the pavement segments.
2. Calculate the difference in the two condition measurements such that an improvement in pavement condition reflects a positive value.
   - If the selected performance measure decreases with decreasing pavement condition (e.g., most composite indexes), then calculate the difference as the measurement after preservation minus the measurement before preservation.
   - If the selected performance measure increases with decreasing pavement condition (e.g., IRI), then calculate the difference as the measurement before preservation minus the measurement after preservation.
   - It is expected that measurement variability will lead to differences that are both positive and negative, and the sign of the difference should be kept as is.
3. Perform a regression where the independent variable is the performance measure value before the application of preservation, and the dependent variable is the calculated difference. This sequence is performed for each performance measure for

each treatment type to become a catalog of equations for initial change in condition. Given that the independent variable will contain variability, a technique such as Deming regression or orthogonal regression should be used (see Carroll et al. (2006) among other sources for details of these techniques).

Example 3.2 demonstrates the calculation of the immediate change in condition, as well as the differences when using orthogonal regression and ordinary least squares regression.

Example 3.2 – Calculating the Initial Change in Condition

Figure 9 shows the change in IRI following application of a thin overlay on LTPP SPS-3 experiment test sections. To establish the IRI change, data for thin overlays on the referenced test sections were first identified. Then, the IRI measurements immediately before and after the overlay were identified. The change in IRI was calculated as the IRI before the overlay minus the IRI after the overlay. Finally, a regression was performed where the dependent variable is the change in IRI and the independent variable is the IRI before the overlay. Figure 9 shows the results of two regression analysis, Deming and Ordinary Least Squares (OLS) regression. Deming regression is used to account for variability in both measurements The OLS regression assumes only errors in the dependent variable, which is a traditional assumption, but is not valid in this case. Figure 9 demonstrates the different results that can be obtained based on assumptions made in the analysis, and these are discussed in more detail in the guide accompanying NCHRP Report 858.

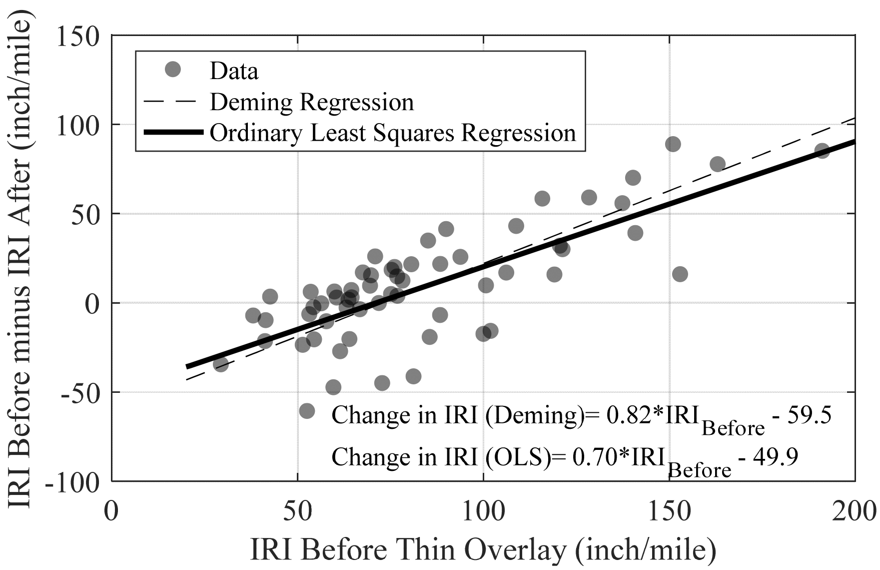


Figure 9. Change in IRI following a thin overlay – LTPP SPS-3 data.

Step 2.5 – Estimate Growth Rates

The step estimates the changes in growth rates of the performance measures following application of preservation. The recommended approach is to estimate the growth rate of each performance measure using a robust linear model with the condition data as a function of time. This approach is recommended for many reasons, including:

- It is a simple and easily implementable approach for estimating growth rates.
- Over relatively short time durations (e.g., 5 to 8 years), distress growth can be approximated as linear.
- The results of the model produce a single coefficient that can be directly related to the rate of growth of the distresses, unlike non-linear estimates or duration models.

NCHRP Report 858 details the approach that should be taken for estimating the growth rates for calculating the changes in performance related to the application of preservation, and that approach is recommended in this guide. The approach for estimating the growth rates of each performance measure is given below:

1. For preservation segments, identify all condition measurements following the application of preservation until another maintenance or rehabilitation action occurred on the segment.
2. For control segments, identify the start of the analysis period as the time when the segment is first considered a candidate for preservation, and the end of the analysis period as either the time until another maintenance or rehabilitation action occurred, or the average length of the analysis period for preservation segments, whichever is less.
3. For both control and preservation segments, perform a robust linear regression with the condition measurements as the dependent variable and time as the independent variable. Robust regression is used to reduce the influence of data that significantly deviates from the expected trend (e.g., those data that have very high errors). A regression is performed for each segment independently.
4. For both control and preservation segments, store the slope of the regression as the expected growth rate of the performance measure following preservation.

Example 3.3 demonstrates the results of calculating growth rates for both control and treatment pavement segments using LTPP data.

After the growth rates are estimated for each segment, the distributions of the growth rates should be compared to assess whether significant differences exist. This step is a check of the data to validate the growth rates calculated in Step 2.5, and is not required to develop the timing models. However, it is recommended that this check be performed to assess the ranges in the data and ranges of differences, and to better interpret the results of the regression performed in the final step (Step 2.7).

Detailing approaches for fitting a distribution to data is outside of the scope of this guide, but more information can be found in Gelman and Hill (2007) among other sources. The research that led to this guide found that a normal distribution was generally acceptable for modeling distributions in rutting growth rates, whereas generalized extreme value distributions were better for fitting IRI and cracking data. In all cases for rutting and IRI, a percentage of negative growth rates were found, and these were not removed from the data as to not bias the results. Example 3.4 demonstrates the comparison between control and preservation segment growth rate distributions for two distresses.

Example 3.3 – Estimate the Growth Rate of the Distresses

To demonstrate the estimation of growth rates, IRI data from the LTPP SPS 3 experiment were gathered for Illinois site A310. The LTPP SPS 3 experiment sites have control sites paired with each preservation site, and therefore the condition data for preservation and control sites covered the same time frame. A robust linear model was fit to the control and preservation sites, and the results are shown in Figure 10. The results in this case show a significant reduction in IRI growth following the application of an overlay, though this is only one of many results that will be used to develop the models. Additionally, the results show that a linear approximation is reasonable over the 13 years of data available for the site.

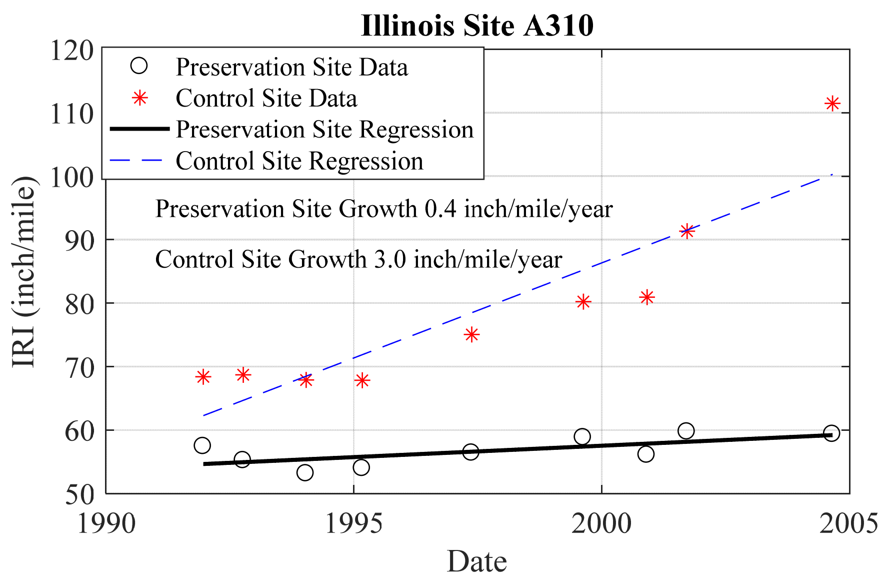


Figure 10. Growth rate estimate from a thin overlay site – LTPP SPS 3 data.

Step 2.6 – Compare Overall Distributions of Growth Rates

After the growth rates are estimated for each segment, the distributions of the growth rates should be compared to assess whether significant differences exist. This step is a check of the data to validate the growth rates calculated in Step 2.5, and is not required to develop the timing models. However, it is recommended that this check be performed to assess the ranges in the data and ranges of differences, and to better interpret the results of the regression performed in the final step (Step 2.7).

Detailing approaches for fitting a distribution to data is outside of the scope of this guide, but more information can be found in Gelman and Hill (2007) among other sources. The research that led to this guide found that a normal distribution was generally acceptable for modeling distributions in rutting growth rates, whereas generalized extreme value distributions were better for fitting IRI and cracking data. In all cases for rutting and IRI, a percentage of negative growth rates were found, and these were not removed from the data as to not bias the results. Example 3.4 demonstrates the comparison between control and preservation segment growth rate distributions for two distresses.

Example 3.4 – Comparing the Growth Rate Distributions

Figure 11 shows the comparison of IRI growth rates following a chip seal for the data used in the development of this guide (composed of State DOT and LTPP data). Figure 12 shows the comparison of rutting growth rates following application of a chip seal for the data used in this research. A comparison of the distributions in Figure 11 and Figure 12 shows that a difference in IRI growth rates can be expected following a chip seal, whereas no difference is expected in rutting growth rates (i.e., the distributions completely overlap). This result was verified by developing a stepwise regression model, which is described in step 2.7.

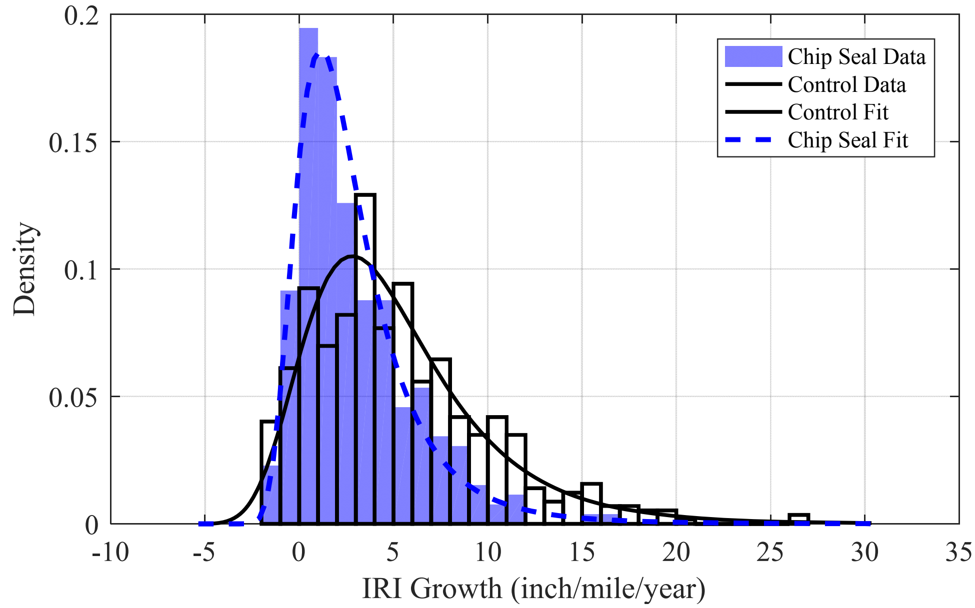


Figure 11. Comparison of IRI growth rates using State agency and LTPP data.

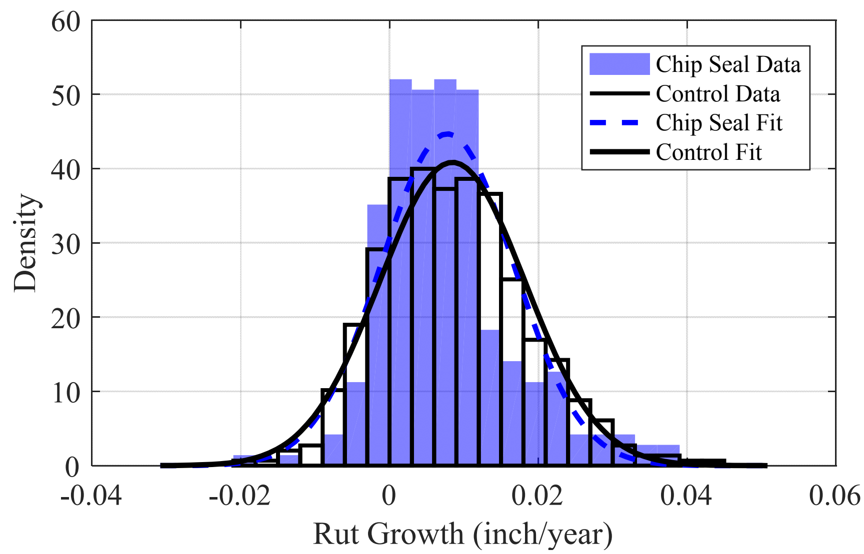


Figure 12. Comparison of rutting growth rates using State agency and LTPP Data.

Step 2.7 – Develop Regression Models for Growth Rates

The next step in developing the performance models is to perform a regression to relate the growth rates of preservation and control segments to the independent variables. The independent variables include condition and non-condition based factors, such as:

- Climate variables.
- Subgrade soil characteristics.
- Traffic data.
- Pavement structure.
- Pre-existing pavement condition.

There are two options for capturing the effect of preservation in the models:

- Develop two separate models, one for the control pavements and one for the preserved pavements.
- Combine the data for control and preservation segments, and add a variable to indicate whether preservation has occurred. The added variable would be binary, such that a value of zero indicates preservation and a value of one indicates no preservation.

The 'combined' approach is used in this guide, and is advantageous because it provides a direct indication of whether preservation has a significant effect on the growth rates of the distresses. However, the 'separate models' approach has the benefit of not assuming the same variables affect a preserved and non-preserved pavement.

The approach that is recommended for developing the regression models, which was used during the development of this guide, is to use regression for relating the independent variables to the calculated growth rates. It is strongly recommended that a rigorous statistical analysis program be used to perform the regression; although spreadsheet programs with basic statistical methods can be used. The advantage of employing a statistical program for developing the models is to automate the many steps and checks in the model development process. Gelman and Hill (2007) among other sources provides details for regression techniques that can be used for developing the models

The development of a regression model will result in a combination of independent variables that predict the growth rate of the distresses. Furthermore, the results of the regression analysis provide many important insights into the performance of a pavement following the application of specific preservation treatments, including:

- The variables that are most significant to the model are those that are most affecting the performance of the preserved pavement, and the sign of the coefficient indicates the direction of the effect. For example, if the mean annual air temperature (MAAT) is significant to the transverse cracking growth rate, a negative coefficient will indicate that decreasing MAAT is expected to lead to increases in transverse cracking growth rates.
- If the approach for performing the regression includes an indicator for preservation, the statistical significance of the indicator variable provides a direct indication of whether preservation affects distress growth rates.

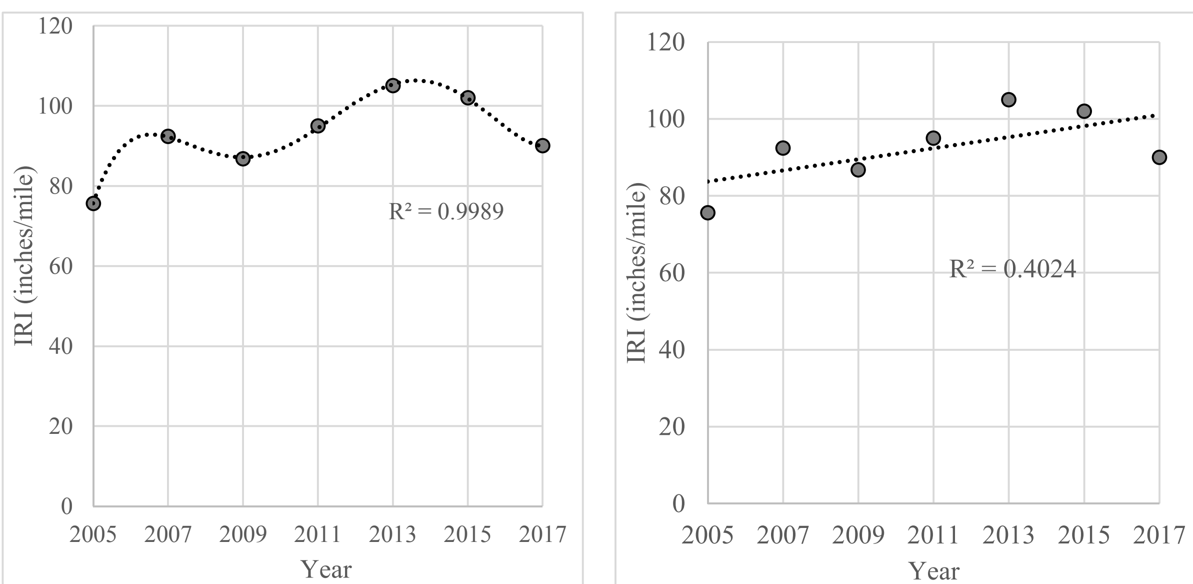
The result of this step will be a set of models that describe the expected performance of a pavement with and without preservation. These models, as well as the uncertainties in the model predictions should be documented and stored for use in calculating the preservation effects. The uncertainties in model predictions will be used when calculating the benefits and assessing the timing.

It is important to assess the models before accepting them, which is the final step in this process (described next). A very good model may be the result of overfitting the model, which is the result of estimating too many parameters (i.e., model coefficients) with too little data. Example 3.5 demonstrates the basic case of an overfit model compared to a properly fit model with a lower coefficient of determination.

Example 3.5 – Overfit and Properly Fit Model

An overfit model is the case where too many model parameters are being estimated for a given data set, or where the model fits the data so closely as to not facilitate future predictions. For example, Figure 13 shows IRI data with time as the only independent variable, and demonstrates two cases:

- The first case results from trying to estimate a model that maximizes the coefficient of determination (R^2) of the model by fitting too many parameters. This model cannot be used to extrapolate results (e.g., it cannot be used to estimate IRI values beyond 2017), and does a poor job of describing the effect of the independent variable on the dependent variable.
- The second case results from a simple estimation, assuming that the growth of the IRI is linear as a function of time. This model has a poor coefficient of determination, but can be used to predict future IRI values.



(a) (b)

Figure 13. Example of (a) overfit model with a very good coefficient of determination, and (b) properly fit model with a poor coefficient of determination.

Step 2.8 – Assess Regression Models

A final important step is to assess the results of the regression to understand the reasonableness of the results and the ability of the models to predict future values. Many approaches are acceptable for this, but the recommended approach is to perform a sensitivity analysis using Monte Carlo simulation. This is the same approach that was used in the development of this guide. The sequence of actions to performing this sensitivity analysis are:

1. Gather data for each independent variable that demonstrates the value and frequency of the variables. For example, if a regression model includes mean annual air temperature as a variable, then gather information about the range and frequency of the temperature for the area over which the model may be applied (e.g., the entire State).
2. Fit a probability distribution to each of the variables using the data gathered in the previous action. The approach to fitting probability distributions is outside the scope of this guide, though many resources (e.g., Karian and Dudewicz, 2000) are available to guide analysts on fitting probability distributions.
3. Estimate the correlation matrix between the independent variables.
4. Define the number of iterations for the simulation, and develop an array of random numbers for each independent variable, where the length of the number array equals the length of the number of iterations.
5. For each set of random numbers, develop a set of sampling variables that accounts for the correlations between the independent variables.
6. Using the set of sampling variables as inputs to the probability distributions, estimate inputs to the regression model, and calculate the outputs of the model (i.e., the growth rates) for each iteration.

It is critically important at this action to make sure that the simulation is not producing scenarios that are outside of realistic scenarios. For example, applying a very large traffic load to a very thin pavements is not realistic, so constraints should be set in the simulation to make sure that these scenarios are removed.

The results of the simulation will provide a direct indication of the quality of fit of the model. For example:

- The range of the predictions will provide a direct indication of how useful the regression models are for extrapolating over a range of conditions; e.g., if a model to predict the IRI growth rate results in many values exceeding 20 inches/mile/year, then the model is not acceptable.
- The correlation between the input variables and outputs provides one measure of the sensitivity of the models to each independent variable, and the sensitivity values can be used to assess the reasonableness of the model.

If the assessment resulting from the simulation demonstrates results that are not acceptable, then a new model should be fit to the data (Step 2.7). On the other hand, if the previous actions result in a model that produces acceptable results, then it can be used to estimate the preservation effects, which are required to assess the timing of preservation.

3.2.2.1. Using national performance models

A set of models were developed as part of the research that led to the development of this guide, and those models can be used as inputs for assessing the timing of preservation. The main purpose of the models developed as part of this guide was to describe the effect of condition and non-condition based factors on the timing of preservation, and so two important notes should be considered when using the provided models:

- The example models will predict negative growth rates for performance measures in some cases (although the model form was developed to minimize those cases). Censored regression was not used to develop the models because the negative growth rates were informative for the interaction of variables, and thus understanding how those interactions influence timing. For example, some combination of condition and non-condition based factors were more likely to predict negative values than others, indicating that the growth rate on those segments is expected to be significantly smaller than the measurement variability. Correction factors are discussed for accounting for negative predictions using the default models.
- The example models were not optimized across treatments. This is described in more detail in the last example in Chapter 4 of this guide.

The combination of performance measures and preservation treatments modeled as part of the research that led to this guide is summarized in Table 3, and the details of the models are provided in the NCHRP Project 14-38 final report.

Table 3. Treatments and Performance Measures Modelled in this Research

	IRI	Rutting	Transverse Cracking	Fatigue Cracking	Non-Wheel Path Longitudinal Cracking
Thin Overlay	✓	✓	✓	✓	✓
Chip Seal	✓	✓	✓	X	✓
Microsurfacing	X	✓	✓	X	✓
Slurry Seal	✓	✓	✓	✓	✓

✓ = models were developed for these treatment / performance measure combinations
X = the data did not support the development of a model

Although the models created as part of the study were assessed using the steps in this guide and were found to produce reasonable and acceptable results, it is recommended that agencies develop their own models. It was found throughout the development of this guide that some significant differences in performance exist between agencies, and these differences could not be explained with the independent variables available during the development of this guide. Therefore, it is strongly recommended that agencies develop their own models in support of preservation timing.

3.2.3. Activity 3. Calculate pavement performance and benefits as a function of time

The next activity is to calculate benefit values. The recommendation in this guide is to define preservation benefits as the Area A divided by the sum of Area A and Area B shown in Figure 14 for two cases. Time zero represents the time the preservation treatment is placed. This

calculation will result in a value between zero and one for each performance measure, with a value of zero indicating no benefit and a value of one indicating highest benefit.

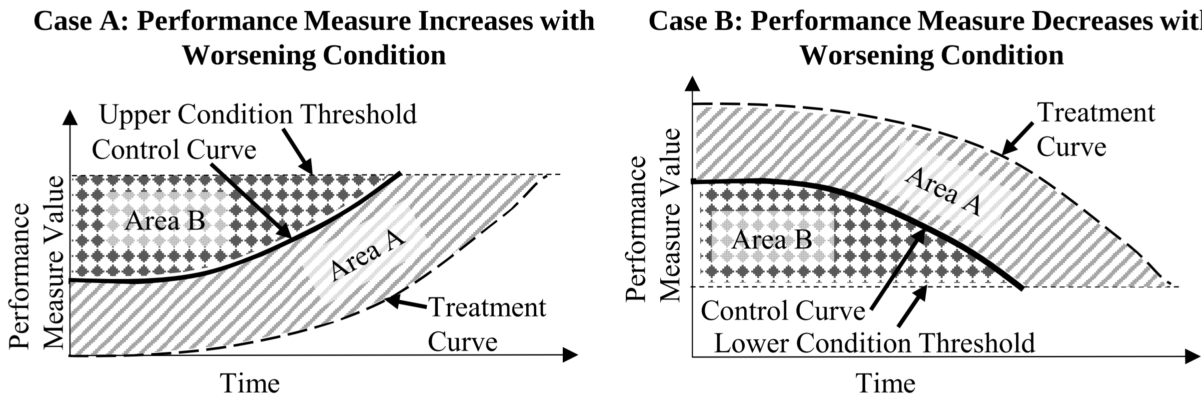


Figure 14. Recommended approach for defining preservation benefits.

The benefit calculation should be performed for each year in the analysis period. If using multiple performance measures, then an approach to combining the results is necessary. The approach recommended in this guide is to apply relative weighting factors to each benefit, and sum the product of the benefits and weights to derive a weighted benefit. The following steps are recommended for calculating weighted benefits:

- Derive weights for each performance measure that express their relative importance, and such that the sum of the weights equals one. For example, if IRI and friction are the measures, and friction is perceived as twice as important, then the weight for friction is 0.67, and the weight for IRI is 0.33. If IRI and friction are equally important, then their weights are both equal to 0.5.
- Calculate the weighted benefit by summing the product of the weights and benefits. The result will be a value between zero and one, with a value of one reflecting maximum benefits.

Next, estimate the uncertainties associated with the benefits calculation. This can be done analytically (i.e., by using probability distributions to calculate the weighted benefits) or via Monte Carlo simulation. The weighted benefit and uncertainty values will be a direct input to the timing methodology.

The result of Activity 3 will be a benefit value and associated uncertainties (expressed as a range or probability distribution) for each year in the analysis period. The benefit values will be used as one of the two primary inputs for assessing preservation timing. The second input, cost, is described next in this chapter.

3.2.4. Activity 4. Establish cost models

The timing framework is based on a cost-benefit analysis. Whereas the benefits are based on an engineering and statistical analysis of the performance of pavements, the cost assessment is much more specific to each agency business practice. It was found throughout the development of this study that many different agencies have different practices for estimating preservation costs, and few similarities could be found between each agency.

Regardless of the specific components and approaches for estimating the cost of preservation, it is recommended that the costs for input into the preservation timing framework be the net present value (NPV) normalized to the analysis year. Fundamentally, this requires three components:

1. The expected costs for applying the preservation in a given year.
2. The discount or inflation rate to apply to those costs.
3. Uncertainties associates with each value.

The expected costs for applying preservation can be estimated using agency specific practices. The total cost should account for any additional costs associated with surface preparation or any increase in costs due to worsening pavement condition. Additional cost elements include:

- Material costs.
- Transportation and mobilization costs.
- Temporary signage, barricades, markings and other construction related item costs.
- Construction and traffic management costs.
- Vehicle operating costs and user delay time costs.

The inclusion of user costs was not specifically evaluated as part of the study that led to this guide, but is a topic that should be agency specific. If an agency has appropriate procedures in place for how to combine agency and user costs into a single value, those procedures can be used to generate a total expected cost.

The discount or inflation of the costs over time is also an agency specific choice. Traditionally, discount values have been incorporated into engineering calculations to reflect the reduction in the value of money over time. One agency that submitted data for this guide inflates costs over time to account for anticipated future increases in material and construction costs. The choice whether to inflate or discount future costs will affect preservation timing. For example, if the preservation benefits are maximized in the first year of the analysis period and decrease in subsequent years, inflating the costs will result in preservation recommended in the first year, whereas discounting costs may result in preservation recommended in future years if the rate of decrease in costs is higher than the rate of decrease in benefits.

The uncertainties in cost data can either be the result of quantitative analysis or qualitative assessments. Walls and Smith (1998) provide comprehensive details and approaches for uncertainties in estimating costs associated with pavements, and readers are referred there for details of how to estimate cost uncertainties.

Assessing preservation timing requires that the costs and benefits of applying a specific treatment be compared over multiple potential times, and therefore the costs should be a function of time. The change in costs over time is expected to be a result of inflation and/or discount rates, changes in surface preparation costs (due to worsening pavement condition), anticipated changes in material and labor costs, and potentially many other factors. This guide recommends the use of the net present value as the cost input for the preservation timing model, which can be calculated using Equation 3-3.

$$Cost_{Future} = Cost_{PresentWorth} \times (1 + i)^n \tag{3-3}$$

Where:

$Cost_{PresentWorth}$ = present worth cost of the preservation treatment

$Cost_{Future}$ = expected future cost of the preservation treatment accounting for factors such as the cost of surface preparation, etc.

i = discount or interest rate: i is negative if using inflation rate and positive if using discount rate

n = number of years in the future the evaluation is occurring

The result of this activity will be a cost with associated uncertainties (expressed as a range or probability distribution) for each year in the analysis period. The cost values will be used as the second of the two primary inputs for assessing preservation timing (with the benefit being the other input).

3.2.5. Activity 5. Calculate cost-benefit equation as a function of time and select best treatment timing

This activity combines the costs and benefits into a single value that can be used to select timing. The approach recommended in this guide is based on reference point programming, which is widely used in decision analysis settings (e.g., Romero et al. (1998), Eiselt and Sandblom (2007), and Bryce et al. (2014)). The equation for combining costs and benefits using the recommended approach is shown in Equation 3-4 below, and it is based on a vector distance calculation that is illustrated in Figure 15.

$$Z = \left[w_b(1 - WB_i)^2 + w_c\left(\frac{Cost_i}{\max(Cost)}\right)^2\right]^{\frac{1}{2}} \tag{3-4}$$

Where:

Z = value that is being minimized

WB_i = weighted benefits associated with applying preservation in year i

$Cost_i$ = net present cost associated with applying preservation in year i

w_b = weight assigned to reflect the relative importance of benefits

w_c = weight assigned to reflect the relative importance of costs

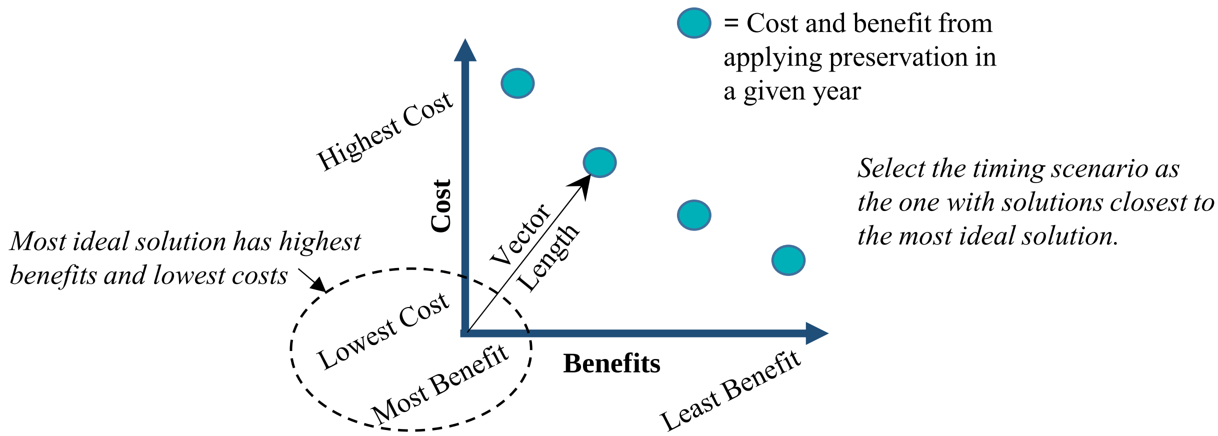


Figure 15. Schematic of reference point based approach.

The vector distance shown in Figure 15 estimates how far each potential preservation timing scenario is from the most ideal point – i.e., the origin on the plot where the lowest costs and maximum benefits are observed. The point on the plot that is closest to the origin is selected as the best outcome, and the timing associated with that point is selected as the best preservation timing.

Uncertainties should be used in the calculation, and two approaches can be taken to include those into Equation 3-4:

1. If the uncertainties result in simple distributions for the costs and benefits (e.g., normal), then Equation 3-4 can be solved using analytical techniques.
2. Monte Carlo simulation can be used to estimate the outcomes (and resulting distributions) of Equation 3-4.

The output of this activity will be a set of values that represent the relative cost and benefit to apply preservation in each year. The year that corresponds to the minimum output from Equation 3-4 is the optimum year that should be selected for preservation timing. The development of timing models using State DOT data, along with sample timing solutions are detailed in Chapter 4 of this guide.

After the timing is developed, it is important to test the sensitivity of the results to some values to better understand what is driving the timing. It is recommended that the following assumptions and inputs are checked:

- The influence of the discount or inflation rate. This can be done by varying the value of the discount or inflation rate and evaluating the change of the timing results against those variations.
- The influence of the relative weights applied to costs and benefits (w_b and w_c in Equation 3-4). Similar to the discount rate, the influence of these weights can be assessed by checking the change in outputs against variations in the values for each weight.

The above procedure selects the timing for a single preservation treatment, but the same process can be used to compare timing across multiple treatments. The approach to achieve a normalized benefit is based on the same do-nothing control area, so various treatments can be

compared directly. The primary difference when comparing multiple treatments is to normalize the cost component of Equation 3-4 (i.e., cost in a given year divided by maximum overall cost) by the maximum overall cost for all treatments in consideration.

3.3. Other Considerations

This study, as well as the research conducted and reported in NCHRP Report 858 on the same topic highlighted several considerations. First, pavement performance data can be highly variable, and even show slight improvements over time when degradation is expected. This variability is related to errors in condition data collection, errors in the data reporting (e.g., errors in segment labeling and naming), or many other potential sources.

Experience with statistical software or other modeling software can greatly enhance the development of the required models for supporting preservation timing. Much of the available software will have integrated functions for items such as simulation, distribution fitting, orthogonal regression and stepwise linear regression, each of which were described throughout this chapter. In addition, many statistical or modeling software options have automated data checking algorithms that can result in greater confidence in the models.

A significant consideration, particularly if selecting cracking as a performance measure, is the changes in cracking type labels as pavement condition becomes worse. For example, non-wheelpath longitudinal cracking was investigated during the development of this guide. In some cases it was found that, as fatigue cracking increased, the longitudinal cracking measures decreases, which could be indicative of the fatigue cracking connecting with the longitudinal cracking. A similar result was seen with a reduction in block cracking as fatigue cracking increased.

It is recommended that the personnel who are tasked with developing the supporting models be experienced with some fundamental statistical knowledge. Although many of the required concepts are described in simple terms within this guide and the guide that accompanies NCHRP Report 858, an understanding of the nuances and underlying concepts in statistical modeling will prove to be valuable when interpreting the results. Finally, the models and approaches that are described throughout this chapter can also be integrated within an agency's pavement management system (PMS) or other asset management practices.

CHAPTER 4. EXAMPLE ANALYSES

This chapter presents detailed example analyses developed using data provided by DOTs. The analyses are example calculations and demonstrations of how to apply the process activities detailed in Chapter 3 to determine preservation timing. First, the development of performance models for thin overlays using data from a single agency is presented. Next, the development of cost models for microsurfacing is presented. Then, the approach to calculating performance using performance models with the uncertainties for thin overlays is detailed. Finally, the approach for using the cost and benefit models to calculate timing is presented for a single and for multiple treatments.

4.1. Example 1 – Developing Performance Models

This example demonstrates the development of performance models for thin AC overlays using data provided by a DOT. The initial step is to gather all data related to the variables that are being modeled. Chapter 3 of this guide details the data that should be gathered for this effort, and specific to this example, the agency provided the following:

- Rutting measurements on all pavement segments from the years 2000 to 2016, along with data identifying the segment (e.g., route, mileposts, GPS coordinates of segment, etc.).
- Construction history data that identifies specific locations and other required information for thin overlay segments on the pavement network.
- Traffic data in terms of equivalent daily traffic loading, which is a value similar to average daily ESALs.

In addition to the data provided by the agency, the following data were obtained from external sources:

- Climate data from the LTPP MERRA Climate tool for the years 2000 to 2014 in terms of the following variables:
  - Mean annual air temperature.
  - Mean annual number of freeze thaw cycles.
  - Mean annual count of the degree days above 90 degrees Fahrenheit.
  - Mean annual precipitation.
- Subgrade resilient modulus data from the databases developed as part of NCHRP Project 9-23A (Zapata, 2010).

The next step in the process was to identify control segments in the database. In this specific case, the agency has a history of decisions on each pavement segment, and so those segments that were recommended for thin overlay, but did not receive a thin overlay could be readily identified.

After gathering data and identifying control segments, the data were assessed to identify whether unrecorded maintenance had occurred during the analysis period. The analysis period was defined as the time starting when the pavement segments were first recommended for preservation and ending when another maintenance or rehabilitation occurred. A supervised machine learning algorithm detailed in Breiman (2001) was used to assess the data for the

existence of unrecorded maintenance. The machine learning algorithm was used in place of the logistic regression detailed in Chapter 3 for identifying probable unrecorded maintenance (e.g., see example 3.1), and all other recommended steps remained the same.

Additional constraints were placed on the data so that at least five years of performance data existed and that the segments were not more than 15 years old when the preservation was first recommended. Figure 16 shows an example of performance results for a thin overlay segment (Figure 16(a)) and control segment (Figure 16(b)) following the assessment of the data. The thin overlay segment has more data than the control segment, and shows approximately 0.12 inch increase in rutting between 2004 (immediately following overlay) and 2016 (last year of data). The control segment has fewer data between 2002 (beginning of analysis period) and 2008 (last year of data before maintenance occurred), and shows an increase in rutting of approximately 0.12 inches over that time period.

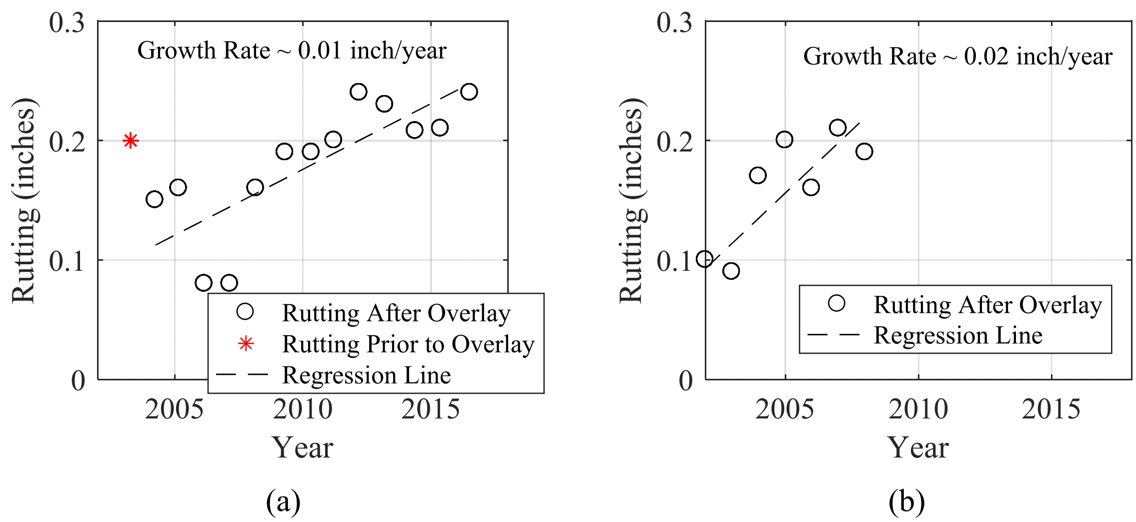


Figure 16. Sample rutting data for two Cases: (a) a thin overlay segment, and (b) a control segment.

The next step is to define the immediate change in rutting following the application of the overlay. As shown in Figure 16(a), the rutting following the application of the overlay is not necessarily zero. The change in rutting following the overlay was collected along with additional variables (e.g., climate, traffic, etc.), and a model was developed to relate the change in rutting to the rutting before the overlay, which was the only variable statistically related to the change in rutting. The results of the model are shown in Figure 17, along with the standard error, which can be used as a simple measure of uncertainty in the model predictions. Equation 4-1 shows the expected decrease in rutting as a function of the rutting before the overlay. For example, if an overlay is placed on a pavement with 0.2 inches of rutting, the rutting can be expected to decrease by 0.12 inches, and the rutting after the overlay is expected to be 0.08 inches. Two important notes about the results demonstrated in Figure 17:

- Many cases where the initial rutting is less than 0.2 inches show a worsening in rutting following application of the overlay, and therefore there is a range (i.e., when the initial rutting is less than 0.1 inches) that the model predicts an increase in rutting. This finding is consistent with results using other data sources, as demonstrated in the

model development details in Chapter 5 of the final report. However, when assessing only data with an initial rutting less than 0.1 inches, the change is zero on average.

- The rutting after application of the overlay is not measured immediately following treatment application, but can be many months after the overlay was placed. It is not expected that the thin overlay is constructed with ruts, but the results demonstrate that rutting often appears soon after placement of the overlay.

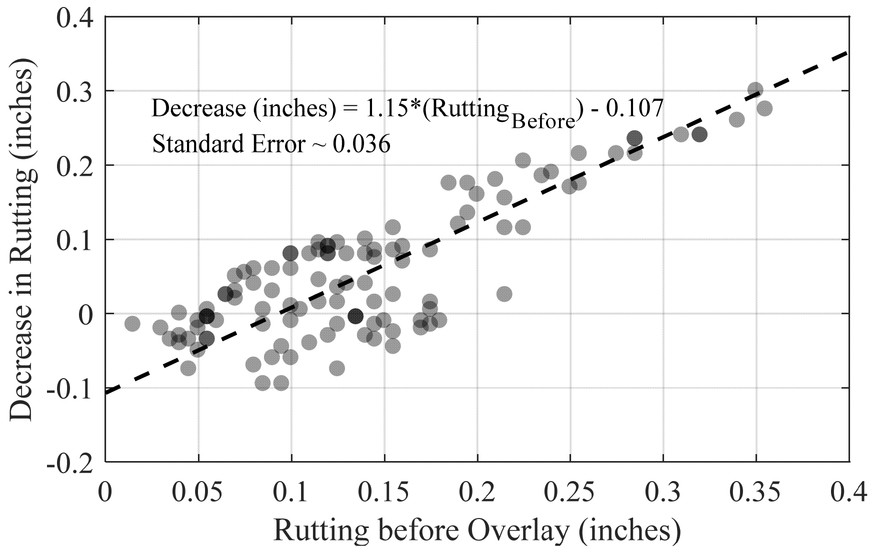


Figure 17. Immediate change in rutting following a thin overlay.

$$Rut_{Post} = 0.107 - 0.15 \times Rut_{Pre} \quad (4\text{-}1)$$

Where:

Rut_{Post} = rutting (inches) predicted after the overlay

Rut_{Pre} = rutting (inches) measured before the overlay

The next step is to estimate the growth rates for each of the treatment and control segments, and this was done using robust regression, which was introduced in Chapter 3 and is detailed in Carroll et al. (2006). Examples of the regression results were shown in Figure 16. The step following the generation of the growth rates, is to compare the overall distributions of the treatment and control segment growth rates, and this is shown in figure 18.

The results in figure 18 show that a significant percentage of treatment and control segments have negative rutting growth (though the mean growth rates are positive in both cases). These negative growth rates are likely a result of measurement variability – because the actual growth rate of rutting is very low, and measurement variability adds to the rutting values from early years greater than later years, then a negative rutting growth will be predicted. The same measurement error is also likely contributing to high growth rates, and thus it is not valid to simply discard the negative growth rates. The mean growth rates show that rutting growth is slightly reduced following the application of the overlay, but regression should be performed to control for the many potential causes of the differences in mean growth rates, which is the next step.

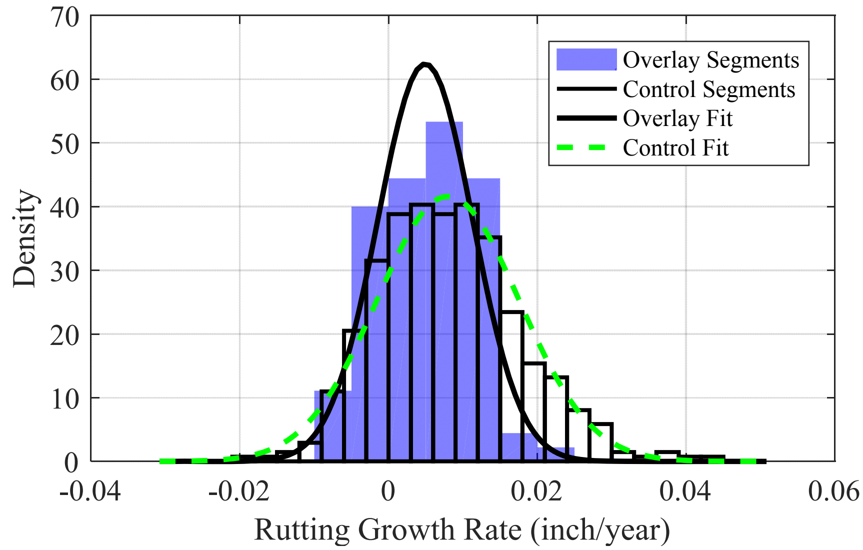


Figure 18. Comparison of thin overlay and control rutting growth rates.

Fitting a model to data with a number of negative values can pose a challenge because a well fit model will predict a negative growth rate, which is not desirable and does not follow expected engineering models. For example, figure 19 shows the result of fitting a model to the data from this example and allowing negative values – though the model fits the data well, it will predict negative rutting growth approximately 30 percent of the time. In addition, the model shown in figure 19 is significantly overfit (it contains more than 10 model terms with many interactions), which means that it cannot be extrapolated over a larger range of inputs. Therefore, additional analyses were conducted to improve the model.

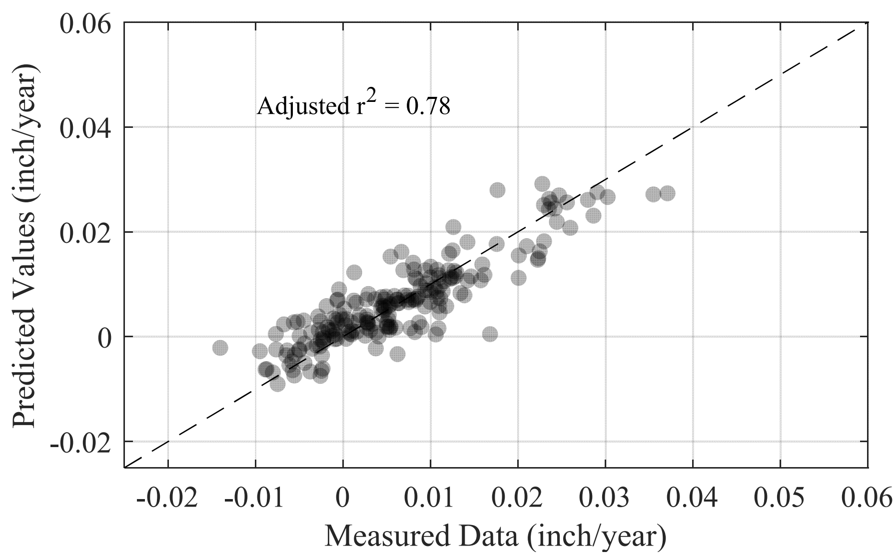


Figure 19. Model fit allowing negative results.

There are many ways to fit a model that does not predict a negative value, such as:

- Fitting a measurement error model that explicitly includes a random term that accounts for the negative values, and forcing the main predictor to be positive.

- Using censored regression techniques such as Tobit regression (e.g., see Serigos et al. (2017)).
- Forcing the data to be positive by using a model form that is only positive.

The last option was used in this example. The resulting model is given in Equations 4-2 and 4-3, and the model fit results are shown in Figure 20. The mean square error reported in Figure 20 provides a simple estimate of the error for the predictions.

$$Rut_{Growth} = e^{(M_{factor})} \quad (4\text{-}2)$$

$$M_{factor} = 695.4 - 2.94 * Rut_{pre} * \log_{10}(EAADT) - 22.27 * MAAT - 0.34 * FTC - 0.85 * Precip + 0.42 * Precip * Pres_{ind} + 9.17 * Rut_{pre} * Pres_{ind} + 0.29 * (\log_{10}(EAADT))^2 - 0.23 * MAAT * Pres_{ind} + 0.19 * MAAT^2 + 0.0047 * Precip^2 \quad (4\text{-}3)$$

Where:

Rut_{Growth} = estimated rut growth rate

Rut_{pre} = Rutting before overlay (inches)

EAADT = equivalent traffic loading values provided by the agency

MAAT = Mean annual air temperature (degrees Fahrenheit)

FTC = Mean annual number of freeze thaw cycles

Precip = Mean annual precipitation (inches)

$Pres_{ind}$ = preservation indicator (equals 1 if the overlay occurred and zero otherwise)

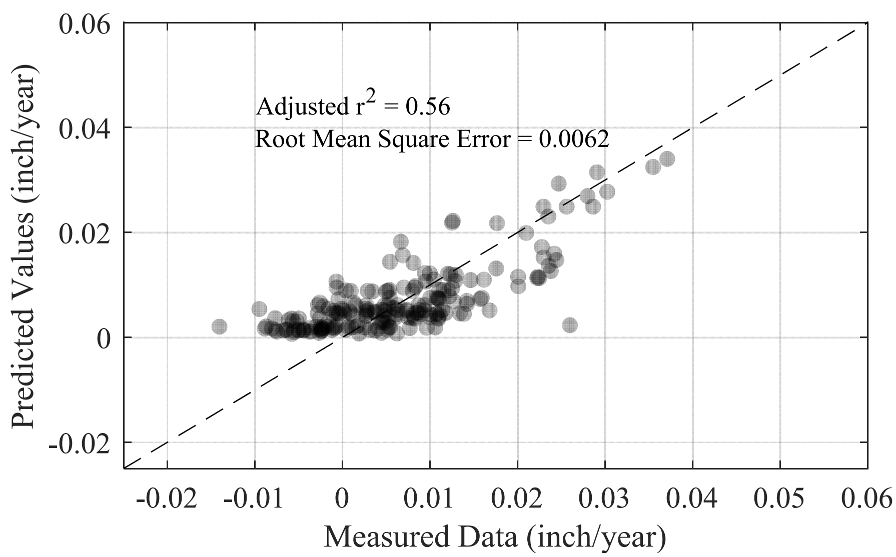


Figure 20. Model fit results for rut growth following thin overlay.

The final step is to assess the model fit results, which was done by performing Monte Carlo simulation. First, distributions of input variables (i.e., those values in Equation 4-3) were developed, and the correlation between those values was calculated. Then, a one-million iterations simulation was performed, and the output of the simulation is shown in Figure 21. As shown in this figure, the model produces reasonable results over the range of inputs for the agency that provided the data. Figure 22 shows the correlation between the inputs and model

outputs, and these too indicate that the model is reasonable. For example, the results in Figure 22 show that increases in traffic loading and mean annual temperature lead to an increase in rutting growth, but the application of the thin overlay (as reflected by the Preservation Indicator term) reduces the rutting growth.

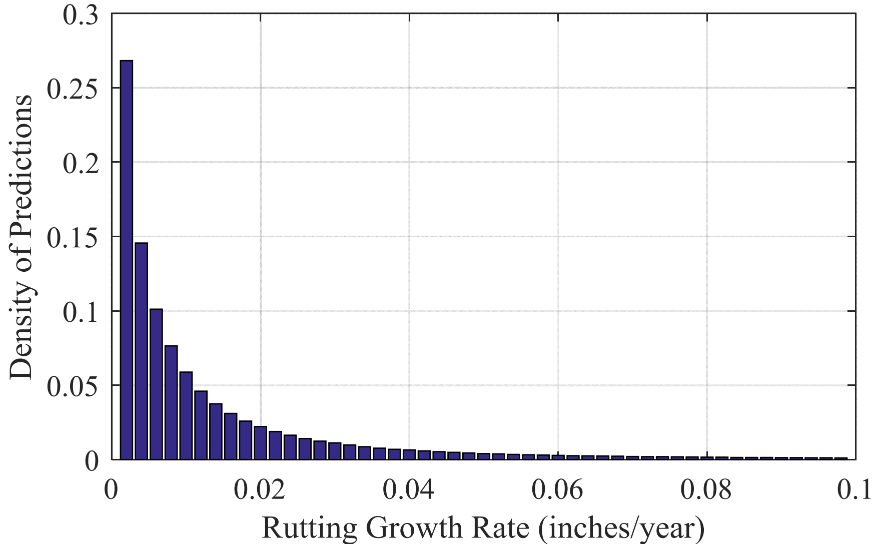


Figure 21. Results of Monte Carlo simulation.

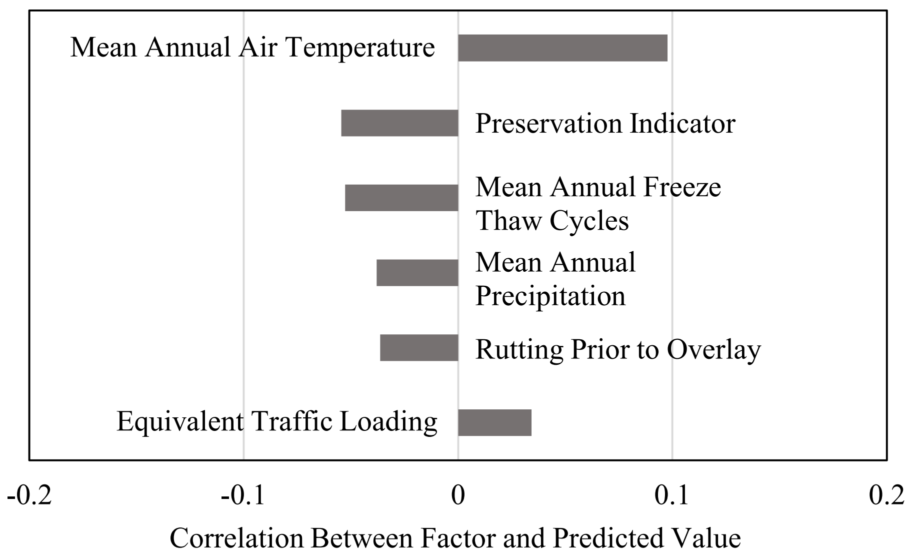


Figure 22. Sensitivity of model to input variables.

4.2. Example 2 – Developing Cost Models

The first step is to gather the expected cost data to estimate preservation costs. To demonstrate one example of developing cost models, microsurfacing cost information was gathered from one agency that provided support in the development of this guide – this is the initial step. Table 4 shows the items required for estimating the cost of microsurfacing for the DOT that submitted the information.

Table 4. Example cost items associated with microsurfacing.

Item	Unit	Value
Microsurfacing	Dollars per Square Yard	$ 3.30
Temporary Pavement Markings	Fixed Cost per Mile (2-lanes)	$ 2,800
Reflectorized Raised Pavement	Fixed Cost per Mile (2-lanes)	$ 290
Pavement Striping	Fixed Cost per Mile (2-lanes)	$ 3,730
Mobilization	8 Percent of Microsurfacing Cost	8%
Temporary Signs and Barricades	8 Percent of Microsurfacing Cost	8%
Construction Layout	8 Percent of Microsurfacing Cost	8%

The next step following the collection of preservation cost items is to estimate the level of uncertainty in the costs, which were not provided by the DOT. In this example, qualitative values for uncertainty were developed as follows:

- The microsurfacing cost was treated as a normally distributed variable with a mean value of $3.30 per square yard, and a standard deviation of $0.10. This represents the case that variability in the costs are evenly distributed around the average, and that 95 percent of the time, the cost will fall between $3.10 and $3.50 per square yard.
- Similar to microsurfacing cost, the fixed cost items were treated as normally distributed variables with a standard deviation equal to 5 percent of the cost.
- The mobilization, temporary signs and barricades, and construction layout percentages were treated as triangular distributions between 7 and 9 percent, with a peak (mean) value at 8 percent, and this is demonstrated in Figure 23.

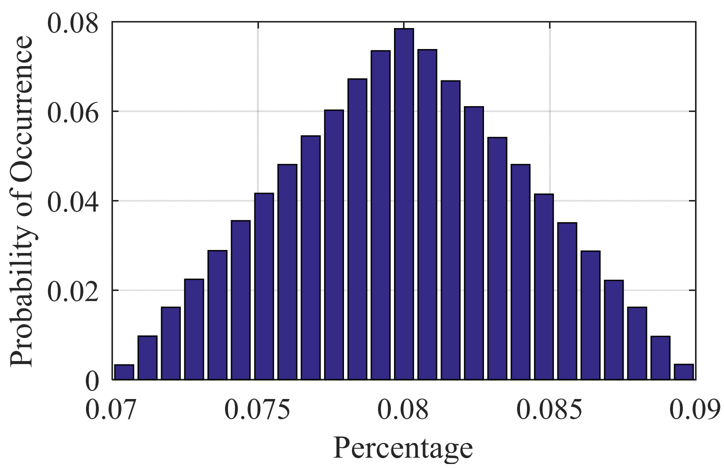


Figure 23. Distribution of percentage values associated with mobilization, temporary signs and barricades.

Monte Carlo simulation was used to estimate the resulting distribution of costs for applying microsurfacing to a one-mile long segment with two 12-foot wide lanes, and the results are shown in Figure 24. The mean of the distribution is the same as would be calculated using the values in Table 4 without uncertainties, but the distribution provides valuable information. For example, although the expected cost is approximately $64,430, there is approximately a 20 percent chance that the cost will exceed $66,000, which was estimated in this case as the mean plus 0.85 times the standard deviation.

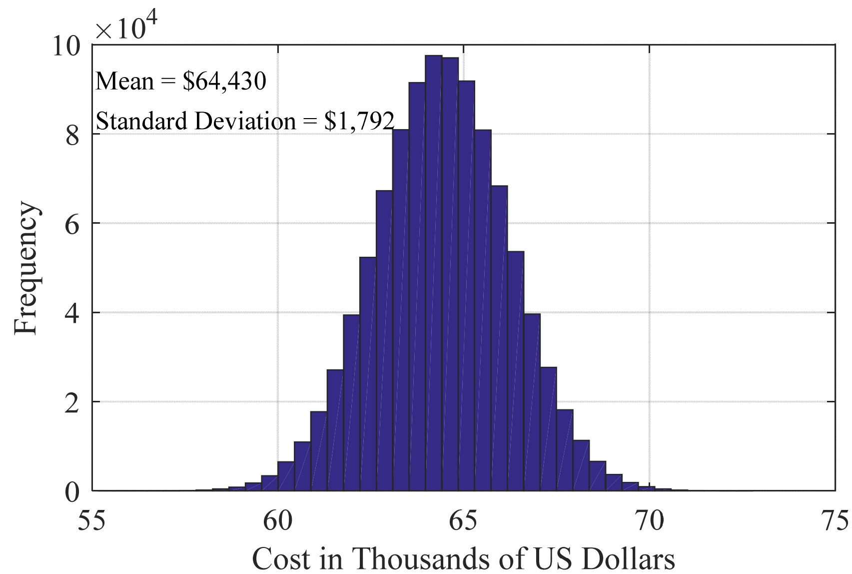


Figure 24. Distribution of cost estimates.

The next step is to account for inflation or discounting over time by estimating the net present value as given in Equation 3-3. Similar to the uncertainties described above, the discount or inflation rate can also be treated as a distribution of values. For example, Figure 25 demonstrates the present worth cost calculation when the discount value is assumed to be a triangular distribution with a minimum value of 2 percent, a maximum value of 4 percent and an expected value of 3 percent. The microsurfacing costs used in year zero are a continuation from the previous steps – i.e., a mean of $64,430 and standard deviation of $1,792.

To demonstrate a calculation using Equation 3-3 and the values presented previously in this example, a discount rate of three percent was used to calculate the present worth cost of the preservation treatment if applied in year 5:

$$Present\ Worth\ Cost = \frac{\$64{,}430}{(1+0.03)^5} = \$55{,}578$$

Similarly, the mean present worth cost in year five using a discount rate of two percent equates to:

$$Present\ Worth\ Cost = \frac{\$64{,}430}{(1+0.02)^5} = \$58{,}356$$

An uncertainty in the discount rate of one percentage point extrapolated over five years results in an uncertainty in present worth costs of approximately five percent.

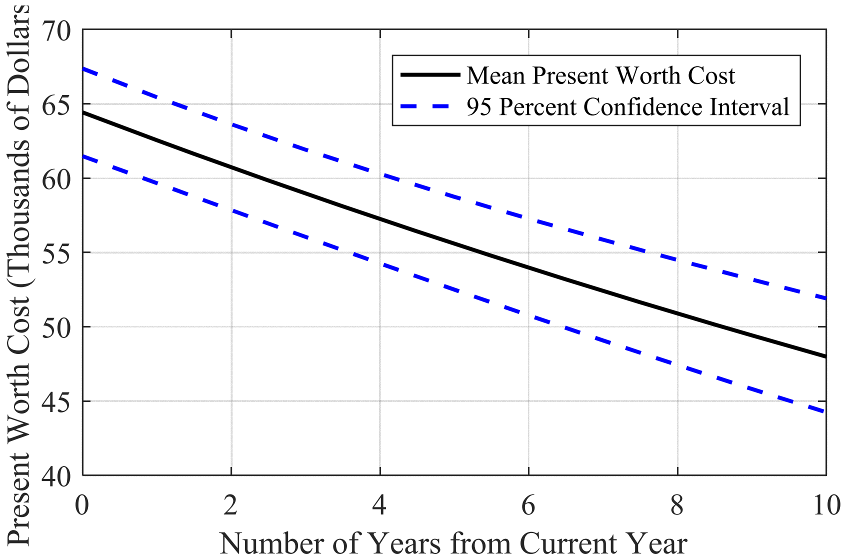


Figure 25. Present worth cost estimation of microsurfacing.

4.3. Example 3 – Estimating Performance

The objective of this example is to demonstrate the calculation of performance following the application of a thin overlay using three performance measures, IRI, transverse cracking and rutting. The performance models used in this example are detailed in Chapter 5 of the final report, and the following inputs were assumed:

- IRI before the overlay is 110 inches/mile.
- Rutting before the overlay is 0.15 inches.
- Transverse cracking before the overlay is 150 feet/mile.
- Average annual daily traffic is 2,500.
- Mean annual air temperature is 48 degrees Fahrenheit.
- Mean annual precipitation is 35 inches.
- Count of the degree days above 90 degrees Fahrenheit is 28.
- Subgrade resilient modulus is 12,000 pounds per square inch.

Figure 26 shows the IRI growth using the models for the case that no overlay is applied (i.e., the control case), as well as the IRI growth assuming an overlay is applied in the current year (labelled year 0). Figure 27 shows the rutting growth and Figure 28 shows the transverse cracking growth for control and overlay segments. The difference in the starting points for each of the performance measures is equal to the immediate changes detailed in Chapter 5 of the final report. The models demonstrate that the application of a thin overlay has an immediate effect on all three performance measures, and a long-term effect by reducing the rate of growth of IRI and transverse cracking.

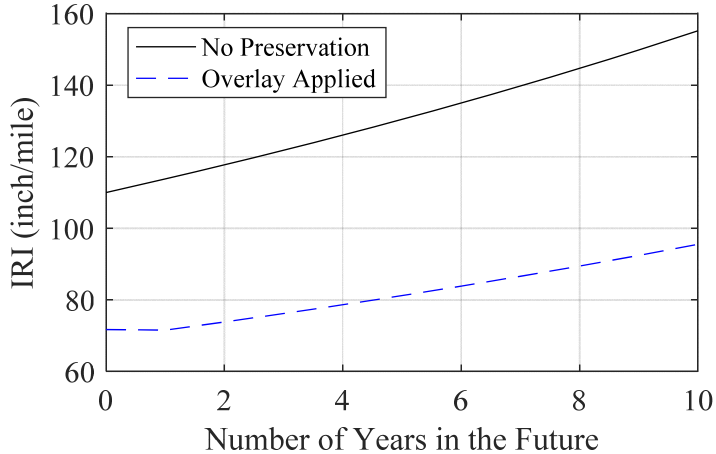


Figure 26. IRI growth for control and preservation segment.

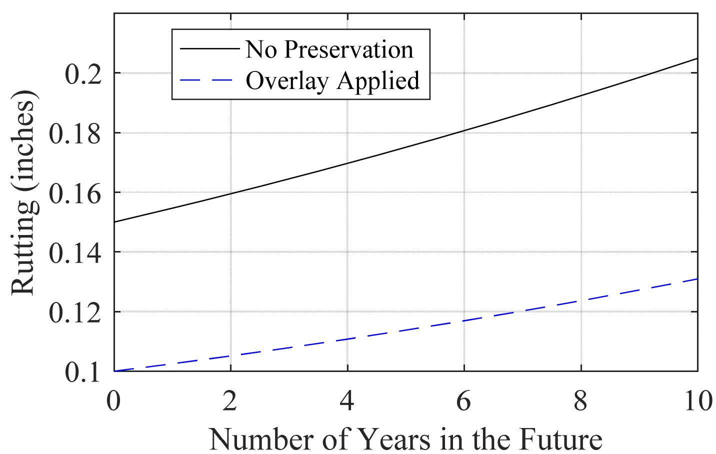


Figure 27. Rutting growth for control and preservation segment.

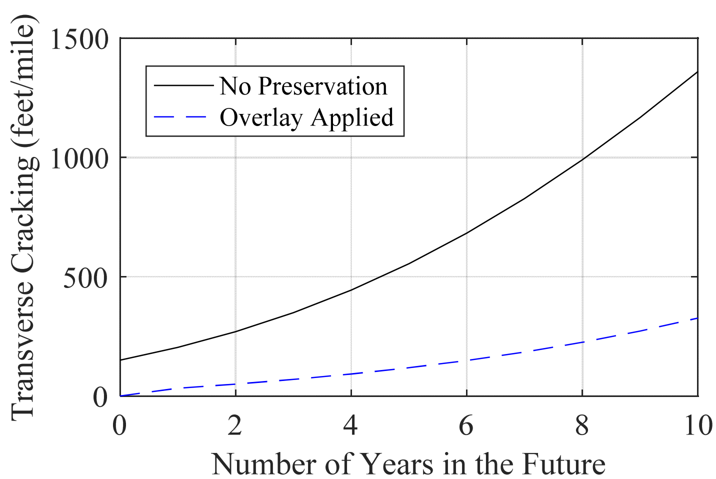


Figure 28. Transverse cracking growth for control and preservation segment.

As shown in Chapter 5 of the final report, uncertainty in the performance prediction models is relatively high, with the root mean square error of the IRI growth model being approximately 3, the root mean square error of the rutting growth model being 0.01 and the root

mean square error of the transverse cracking growth model being 80. In addition, the immediate change in condition has significant uncertainties. The mean square error of the change in IRI is 17 inches per mile and the mean square error of the change in rutting is 0.04 inches. The transverse cracking is predicted to be completely eliminated, and no uncertainty is associated with that prediction.

After defining the models and uncertainties, thresholds need to be defined. Thresholds define the limit of each performance measure beyond which preservation is no longer a consideration, and they are required in order to estimate performance. In this example, the thresholds were set as:

- 150 inches per mile for IRI.
- 0.3 inches for rutting.
- 800 feet per mile for transverse cracking.

Following the definition of the models, uncertainties and thresholds, the benefits can be calculated using the approach recommended in Chapter 3. For this example, a Monte Carlo simulation with 10,000 iterations was used to calculate the benefits. Figure 29 shows the plot of the IRI benefits, with the mean benefit and the lower 5th percentile and upper 95th percentile of values. Similarly, Figure 30 shows the mean and 90 percent confidence intervals for the rutting benefit, and Figure 31 shows the same for the transverse cracking benefit. The uncertainties provide a considerable amount of information, such as:

- In all cases, there is less than a five percent chance that applying preservation prior to year four provides the most benefit. Furthermore, the drop in benefit between year four and five for the 5th percentile line indicates that, for the cases where year four provides the maximum benefits, it is because the thresholds are exceeded in year five.
- For all values within the 5th and 95th percent confidence range, the maximum benefit is realized when preservation is applied between year four and year nine.
- The mean value indicates that the benefits are maximized between year four and five.

The final step in estimating benefits is to calculate a weighted benefit per the approach detailed in Chapter 3. For this example, equal weights (0.33) were assigned to each performance measure, and the results are shown in Figure 32. This figure shows that:

- Uncertainties are relatively low in the first four years, but are very high beyond that.
- Mean value shows the maximum benefits are seen in years four and five, but the 95th percentile of the values show the maximum benefits may be realized as far as eight years out.

The results of the benefits are one component of the cost benefit analysis, and Example 4 will demonstrate how the benefits developed in this example can be combined with costs to estimate preservation timing.

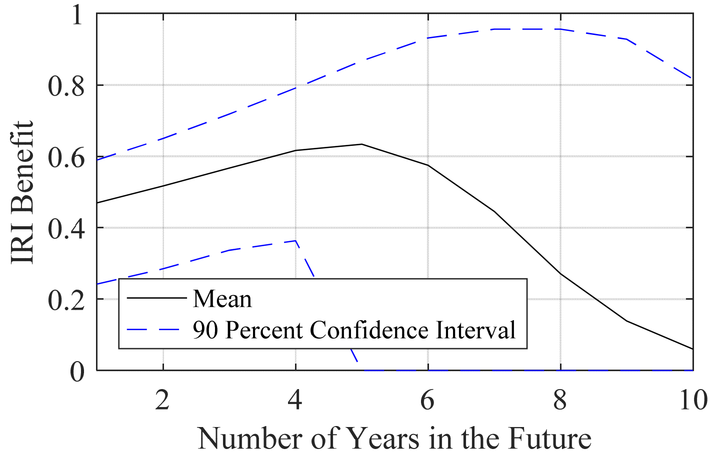


Figure 29. Mean IRI benefit with 5th and 95th percentile values.

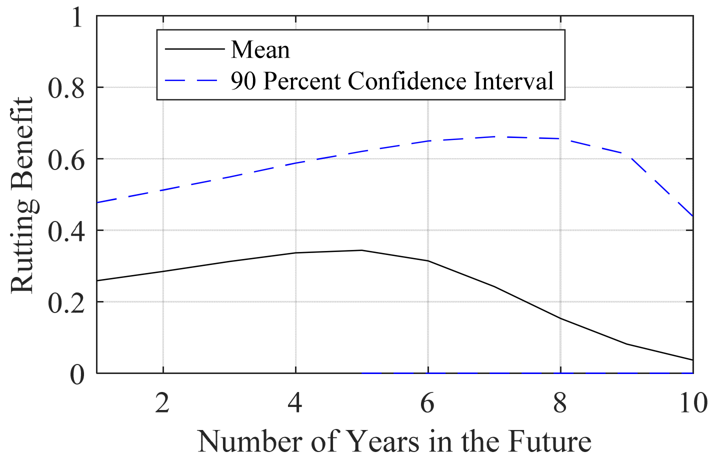


Figure 30. Mean rutting benefit with 5th and 95th percentile values.

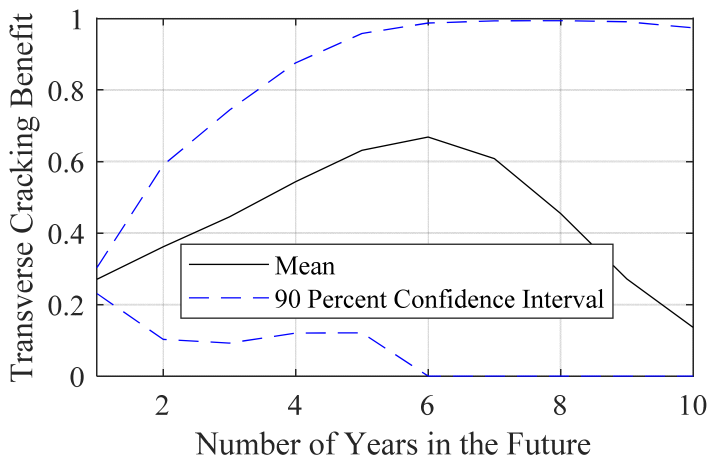


Figure 31. Mean transverse cracking benefit with 5th and 95th percentile values.

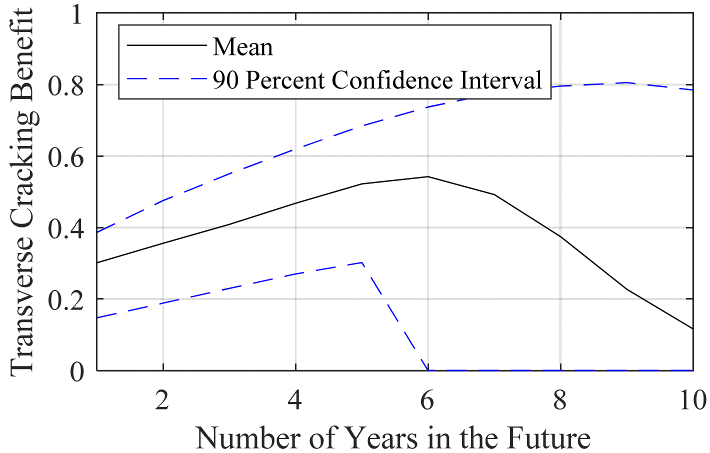


Figure 32. Combined benefits with 5th and 95th percentile values.

4.3.1. Assessing Climate Effects on Benefits

The benefits calculation in Figure 32 represents a cool to moderate climate with average precipitation (e.g., the upper Midwest of the US). As demonstrated in the models in Chapter 5 of the final report, multiple non-condition based factors are expected to affect performance measure growth rates, and the performance measure growth rates affect the benefits calculation. This example builds from the previous example and demonstrates the effect of changes in climatic variables on the expected benefits of applying a thin overlay.

To demonstrate the effect of climate on the benefit calculation, the example from the previous section of this chapter was revised to represent a warm and dry climate (i.e., parts of the US States of Texas, Oklahoma and Kansas). The condition based inputs remained the same as the previous example, and are repeated here:

- IRI before the overlay is 110 inches/mile.
- Rutting before the overlay is 0.15 inches.
- Transverse cracking before the overlay is 150 feet/mile.
- Average annual daily traffic is 2,500.
- Mean annual air temperature is 60 degrees Fahrenheit.
- Mean annual precipitation is 20 inches.
- Count of the degree days above 90 degrees Fahrenheit is 50.
- Subgrade resilient modulus is 12,000 pounds per square inch.

Figure 33 shows the IRI growth using the models for the case that no overlay is applied (i.e., the control case), as well as the IRI growth assuming an overlay is applied in the current year (labelled year 0). Figure 34 shows the rutting growth and Figure 35 shows the transverse cracking growth for control and overlay segments. The difference in the starting points for each of the performance measures is equal to the immediate changes detailed in Chapter 5 of the final report. The rate of growth of the IRI and rutting are higher in the warm and dry climate when compared to the moderate climate represented in the previous example. The transverse cracking growth is minimal after the application of the growth rate for the first seven years, after which it begins to increase.

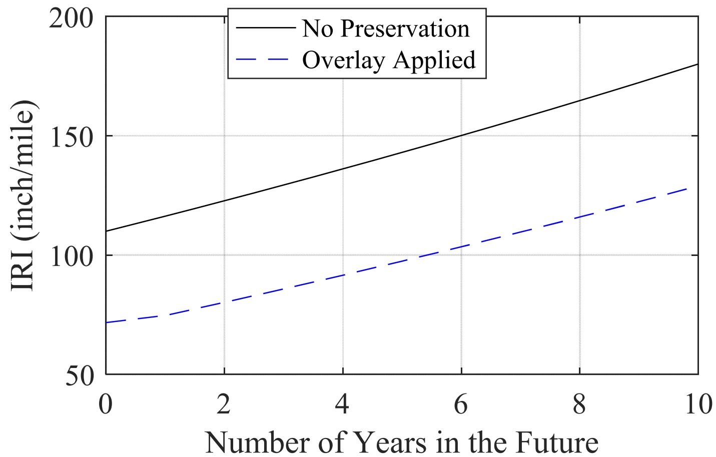


Figure 33. IRI growth for control and preservation segment.

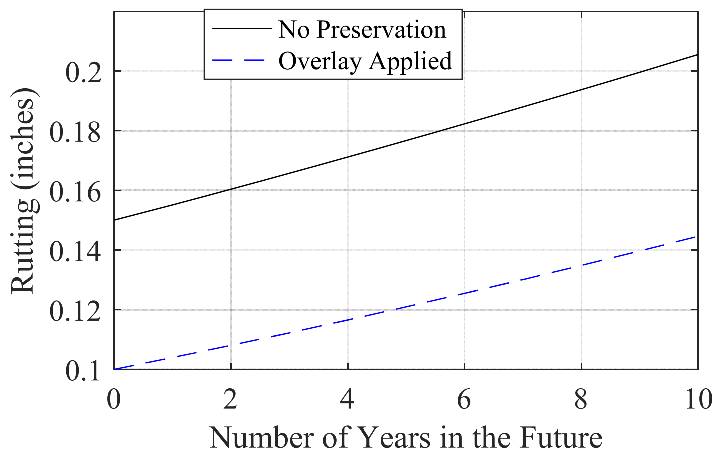


Figure 34. Rutting growth for control and preservation segment.

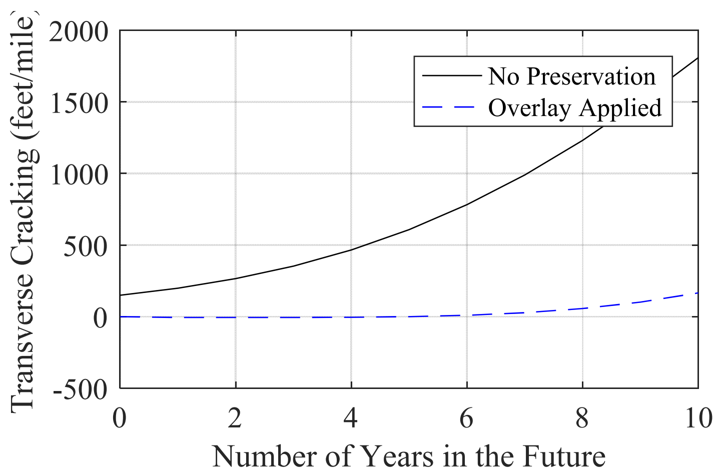


Figure 35. Transverse Cracking Growth for Control and Preservation Segment

The same uncertainties that were used in the previous example were used in this case. Finally, the same thresholds for performance measures as the previous example was used, and those are: 150 inches per mile for IRI, 0.3 inches for rutting and 800 feet per mile for transverse cracking.

The weighted benefits were calculated assuming equal weights (0.33) between the three performance measures, and the results are shown in Figure 36. The results in the figure illustrate many important concepts, such as:

- The benefits are maximized in year 5, which is the same as the previous example, but there is a much higher probability that the pavement will exceed the predefined thresholds by year 6 in the warmer and drier climate.
- The benefit in this case is influenced much more by the immediate change in condition than the long-term change in performance, and this explains why the benefits are maximized just prior to the time when the thresholds are exceeded.
- The overall weighted benefit is much higher in the warmer and dryer climate than the climate represented in the previous example. Much of this is derived from the very low predicted growth of transverse cracking following the application of the overlay.

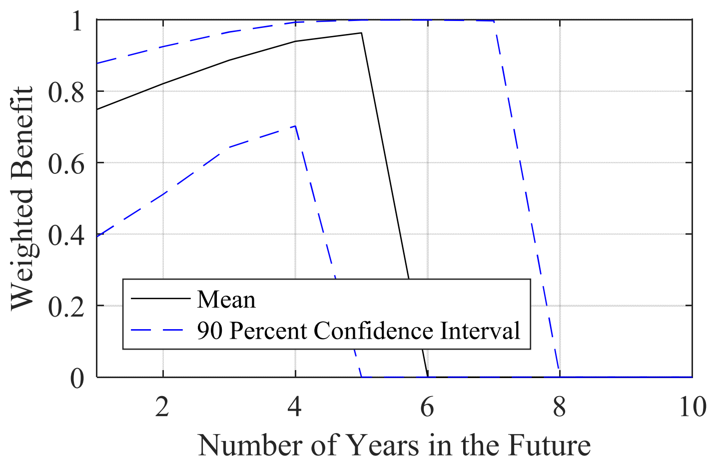


Figure 36. Weighted benefits for thin overlay in warm and dry climate.

4.4. Example 4 – Selecting Preservation Timing and Assessing Results

This section will demonstrate how the costs and benefits detailed previously in Examples 2 and 3 are combined to estimate preservation timing. First, the approach for a single treatment will be detailed, and then the approach for comparing timing across multiple treatments will be presented.

4.4.1. Assessing the Timing for a Single Treatment

This example will build from the thin overlay analysis, and use the benefits detailed in the previous section (Example 3) to assess preservation timing. The approach for estimating costs is the same that was presented earlier in this chapter (Example 2) using thin overlay data supplied by an agency shown in Table 5.

Table 5. Example cost items associated with a thin overlay.

Item	Unit	Value
Thin Overlay (Hot Mix)	Cost per Mile (2-lanes)	$137,300
Asphalt Patching	Cost per Mile (2-lanes)	$29,140
Cold Planing	Cost per Mile (2-lanes)	$28,420
Temporary Pavement Markings	Cost per Mile (2-lanes)	$ 2,800
Reflectorized Raised Pavement	Cost per Mile (2-lanes)	$ 290
Pavement Striping	Cost per Mile (2-lanes)	$ 3,730
Mobilization	8 Percent of Overlay Cost	8%
Temporary Signs and Barricades	8 Percent of Overlay Cost	8%
Construction Layout	8 Percent of Overlay Cost	8%

The following values for uncertainty were assumed:

- The costs associated the overlay, pavement markings and striping will be treated as normally distributed variables with a mean equal to the values shown in Table 5, and a standard deviation of 5 percent of the mean.
- The costs for patching and cold planing will be treated as normally distributed variables with a mean of equal to the value in Table 5, and a standard deviation of 10 percent of the mean.
- The mobilization, temporary signs and barricades, and construction layout percentages will be treated as triangular distributions between 7 and 9 percent, with a peak (mean) value at 8 percent.

The costs were discounted over time (as detailed in Chapter 3), and the discount rate was assumed to be a triangular distributions between 1 and 4 percent, with a peak (mean) value at 3 percent. The discount rate is not assumed to be evenly distributed; the most likely value is assumed as 3 percent, the maximum possible value is 4 percent and the minimum possible value is 1 percent. The estimated costs as a function of time are shown in Figure 37.

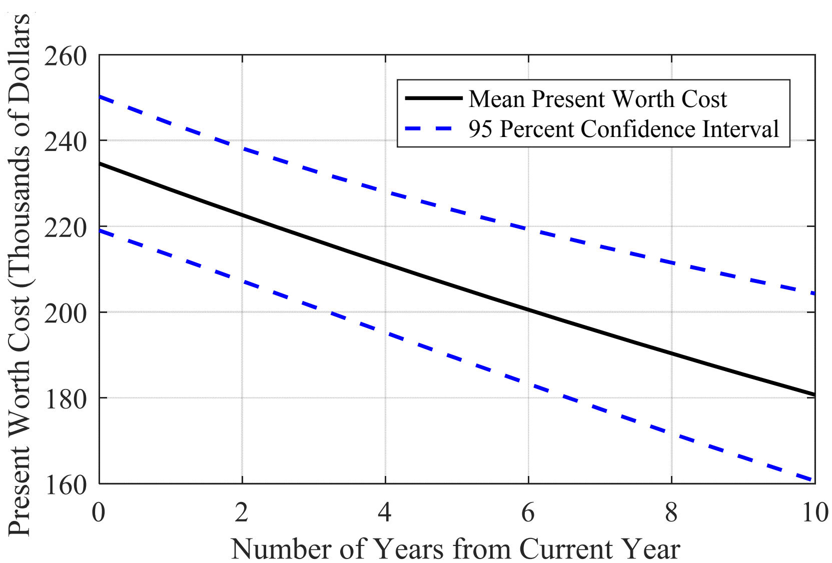


Figure 37. Present worth cost of a thin overlay for one-mile (two-lanes) of pavement.

Using the costs shown in Figure 37 and the benefits shown in Figure 32, along with an assumption of equal weights for costs and benefits, the values of the function given in Equation 3-4 of Chapter 3 were calculated, and the results are shown in Figure 38. The results of this assessment indicate that the overlay should be planned five years into the future. However, the results also show that there is a risk that the performance measures will exceed at least one of the previously defined thresholds less than five years in the future (see the significant jump in the confidence interval between years 4 and 5). Additionally, the uncertainties increase significantly after year 4, and the mean value changes little between years 4 and 6, indicating that the agency may wish to select year 4 for the timing to reduce risks.

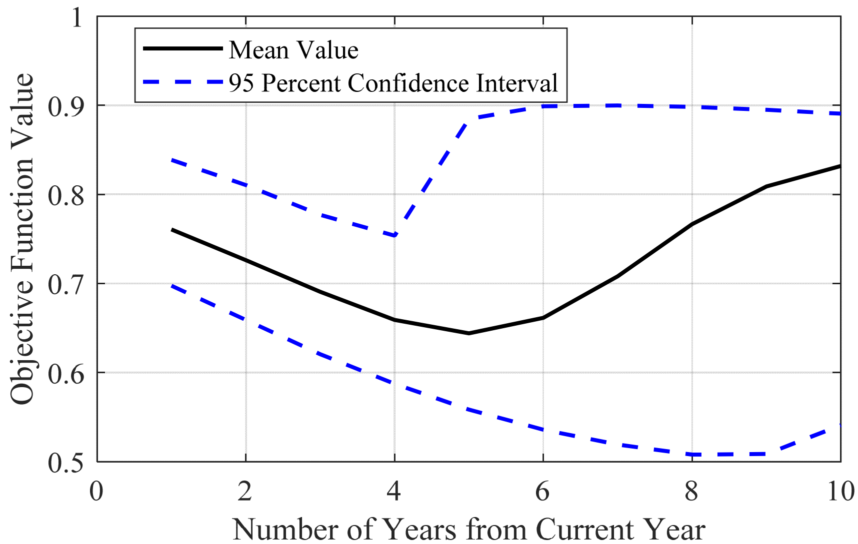


Figure 38. Outputs from the Equation 3-4 for selecting timing.

When assessing the output of the timing, it is important to assess the influence of many assumed values. For example, the costs and benefits were assumed to be equally weighted in the results shown in Figure 38. However, Figure 39 shows two cases, one where the benefits are weighted ten times the costs, and one where the costs are weighted ten times the benefits. The results show that, if benefits are prioritized much more than costs, the overlay should be applied in year 5. However, if the costs are weighted much higher than the benefits, then the overlay should be deferred as far into the future as feasible.

The influence of the weights applied to each performance measure was also assessed. Three scenarios were evaluated: (1) the IRI is weighted ten times more than the other performance measures, (2) the rutting is weighted 10 times more than the other measures, and (3) the transverse cracking is weighted 10 times more than other measures. The results are shown in Figure 40, and they show that the varying weights do not affect the timing in this case, but do effect the relative benefit of preservation. Less benefit is seen when rutting is weighted the highest because the overlay does not affect rutting growth, and changes the rut depth to a constant value despite the initial condition.

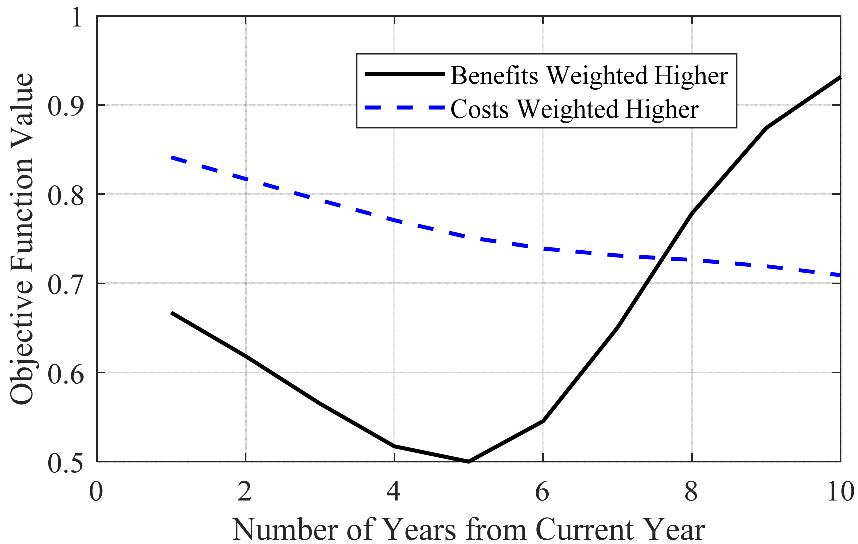


Figure 39. Timing when cost and benefit weights are varied.

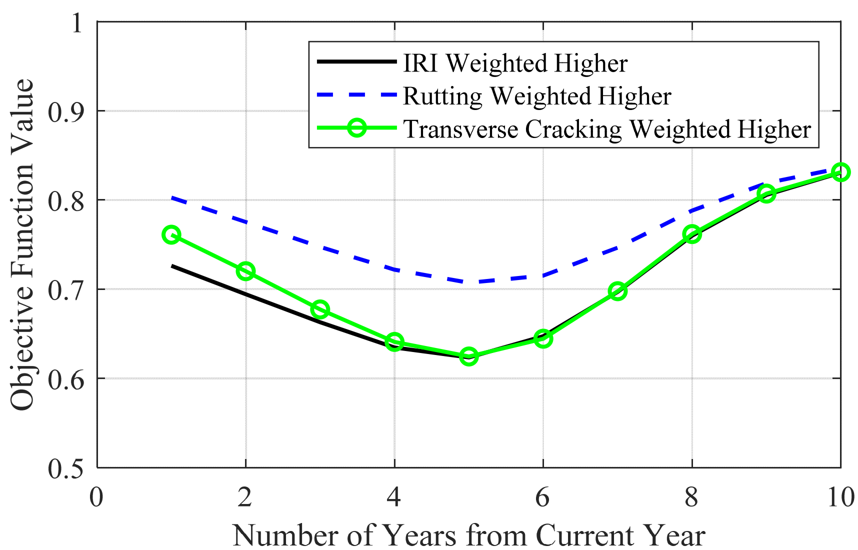


Figure 40. Timing when performance measure weights are varied.

The last assessment was performed assuming equal weights between all values, but using an inflation rate instead of a discount rate. The inflation rate was assumed to be a triangular distributed value between 1 and 4 percent, with a peak (mean) value at 3 percent. The results are shown in Figure 41, and they indicate that preservation timing ranges from year 4 to year 5 in the future with little change in the function value between those years. These results are similar to using the discount rate because the benefits show a clear maximum in those years. If more weight is given to costs when using an inflation rate, the recommended timing would be earlier.

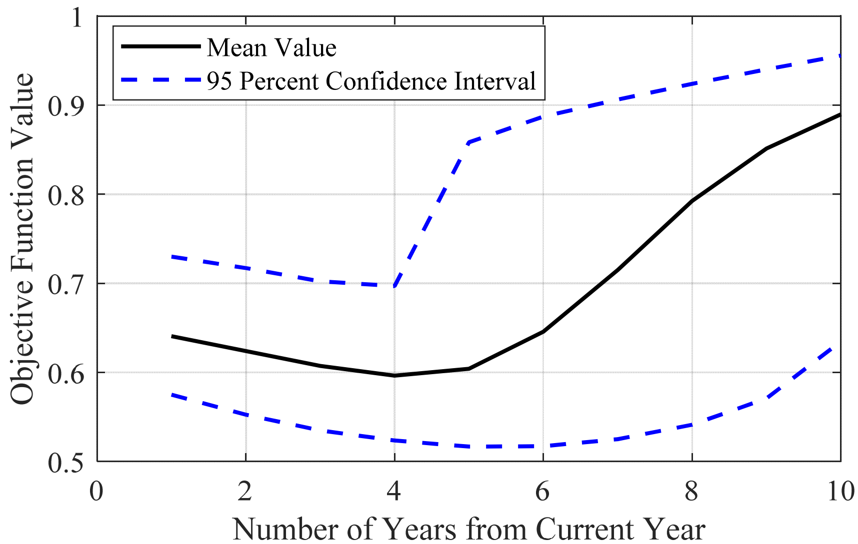


Figure 41. Timing when using an inflation rate.

4.4.2. Comparing Timing from Multiple Treatments

The final example in this chapter demonstrates the comparison of multiple treatments; a chip seal and thin overlay. This comparison requires the assumption that both treatments are applicable on the same pavement, which is not always a valid assumption. For example, multiple DOTs that supplied data for the development of this guide indicated that chip seals were typically applied only on low volume routes. However, the same condition and non-condition based factors that were used in the previous thin overlay timing example will be used in this analysis. Furthermore, the results for the thin overlay timing presented in Figure 38 will be used for this example.

The approach for estimating costs for the chip seal is the same that was presented earlier in this chapter for microsurfacing. In this example, data supplied by multiple DOTs was used to estimate the chip seal cost and related items. Information from a Virginia Transportation Research Council report was used to estimate the cost of the chip seal in dollars per square yard (Izeppi et al., 2016), and the additional items (e.g., mobilization) were estimated using the same amounts as presented in Table 4. The details of the cost items are shown in Table 6.

Table 6. Example cost items associated with chip seal.

Item	Unit	Value
Chip Seal	Dollars per Square Yard	$ 1.80
Temporary Pavement Markings	Fixed Cost per Mile (2-lanes)	$ 2,800
Reflectorized Raised Pavement	Fixed Cost per Mile (2-lanes)	$ 290
Pavement Striping	Fixed Cost per Mile (2-lanes)	$ 3,730
Mobilization	8 Percent of Chip Seal Cost	8%
Temporary Signs and Barricades	8 Percent of Chip Seal Cost	8%
Construction Layout	8 Percent of Chip Seal Cost	8%

The values for uncertainty were assumed the same as for the thin overlay example.

The costs were discounted over time, and the discount rate was assumed to be a triangular distributions between 1 and 4 percent, with a peak (mean) value at 3 percent. The mean cost of the chip seal per mile (2-lanes) in the first year was found to be $38,270, and the standard deviation is $1,760.

In order to make a fair comparison, the same control curve must be used in both cases (i.e., the do-nothing scenario should produce the same results for thin overlay's and chip seals). The example performance models developed as part of the development of this guide do not produce the same results for both cases for two reasons:

1. The pavements selected as a control for chip seals during that model development were necessarily different than those chosen to represent controls for thin overlay's (e.g., different agencies supplied thin overlay and chip seal data, etc.).
2. The example models were developed for the primary purpose of describing the effects of condition and non-condition based factors on preservation timing for single treatments, not across multiple treatments.

Therefore, the approach used for this specific example was to calculate the changes in growth rates of the performance measures between control and chip seal segments using the chip seal models, and then apply those results to the control segment growth rates for thin overlays. For example, if the IRI growth rate of a control segment using the chip seal model between two years was 4 inch/mile/year, and the chip seal segment growth rate was 3 inch/mile/year between the same years, the growth rate of the control segment was calculated using thin overlay control models and multiplied by a factor of ¾ to estimate the change in the chip seal IRI growth. Figure 42 shows the IRI and transverse cracking growth over a ten year time period for control and chip seal pavements, assuming the chip seal is applied in the current year. No change in rutting was found in the chip seal models.

The weighted benefits for the chip seal were calculated assuming equal weights for the three performance measures, and the results are shown in Figure 43. Because of the specific definition of benefits recommended in this guide, a direct comparison can be made between the results in Figure 43 and those in Figure 32. The weighted benefits for the chip seal are considerably lower than those for applying the thin overlay (see Figure 32) because the initial change in condition for the chip seal is zero for IRI and rutting, and the change in growth rates of the performance measures are lower than for the thin overlay. Furthermore, the most significant component added to the benefit is the immediate change in transverse cracking, which results in the benefits being maximized in year 6 (i.e., where the largest change in transverse cracking is expected before the pavement exceeds preservation thresholds), whereas the maximum benefits for the thin overlay were in year 5.

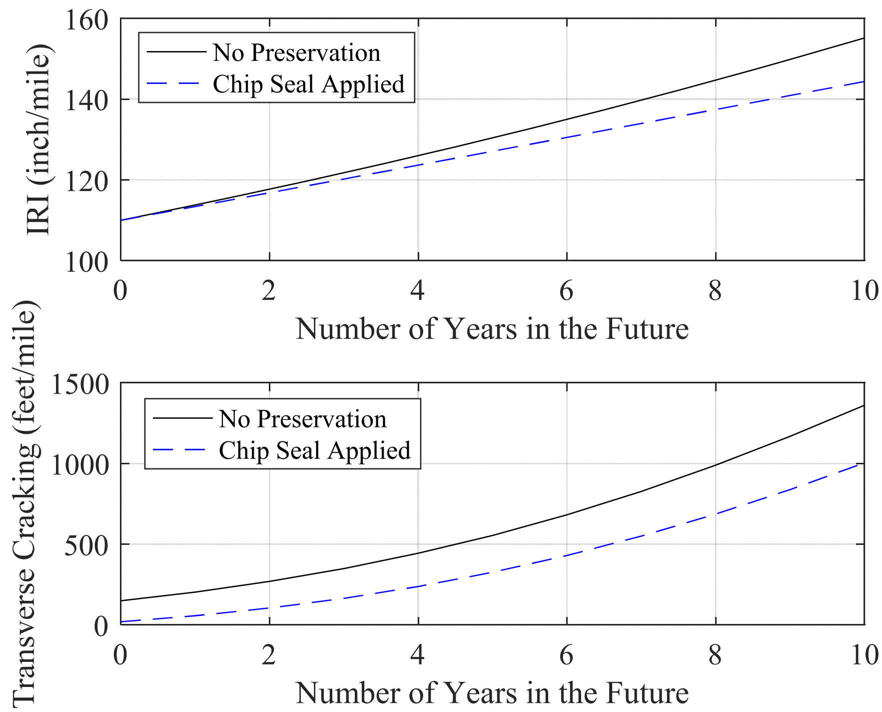


Figure 42. IRI and transverse cracking growth for control and preservation segment.

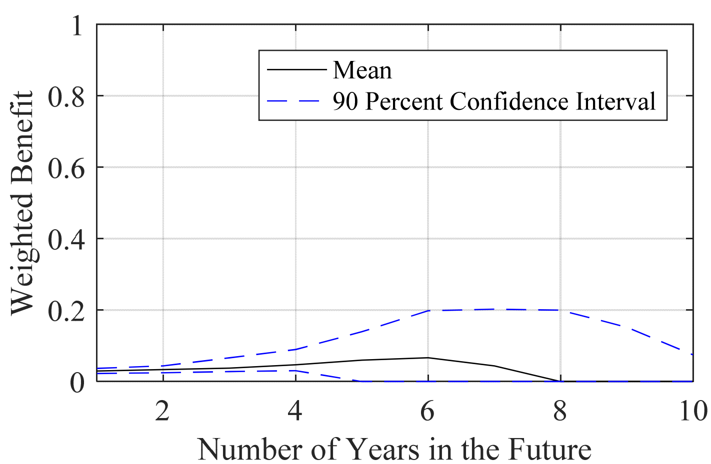


Figure 43. Weighted benefits from applying a chip seal.

The timing was calculated for chip seals using Equation 3-4 and equal weights for costs and benefits, and the comparison of the timing for thin overlay and chip seal is shown in Figure 44. The results show that the best timing for preservation is to apply a thin overlay 5 years from the last condition measurements (which define year zero). Although the benefits from applying the chip seal were much lower than the benefits for the thin overlay, the costs were also considerably lower, which led to comparable outputs resulting from Equation 3-4. The analysis approach is structured so that the lowest value (y-axis) provides the best combined value for performance benefit and cost. In this example, the curve for the thin overlay is lower than the curve for the chip seal and therefore will provide the best value.

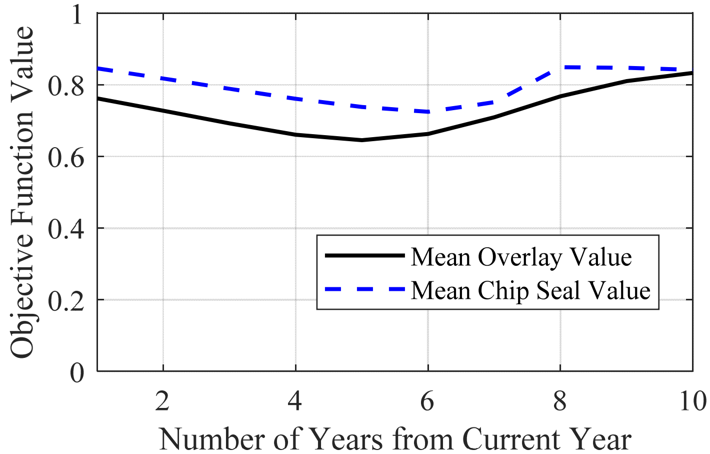


Figure 44. Comparison of outputs from Equation 3-4 using thin overlay and chip seal.

CHAPTER 5. SUMMARY AND RECOMMENDATIONS

5.1. Summary

This guide provides an analytical approach for determining the timing when a specific preservation treatment should be applied for asphalt pavements. The approach presented in this guide is based on a comparison of the costs associated with placing a preservation treatment and the expected benefits resulting from improved pavement performance. A recommended preservation timing framework was developed and presented to formalize the approach for preservation timing. The framework presented in Chapter 2 defined necessary inputs (e.g., existing pavement condition, etc.); Chapter 3 provided specific recommendations on assembly of inputs, development of models and timing determination; Chapter 4 provided examples for each step. The expectation is that a pavement preservation treatment should be placed on a pavement at such a time that the expected benefits are maximized and the expected costs are minimized.

The approach recommended in this guide is summarized using the following five recommended activities:

1. Define the performance measures and preservation treatments considered in the analysis.
2. Quantify the immediate and long-term effects of preservation treatments on the performance measures.
3. Calculate the preservation benefits as a function of time.
4. Establish cost models as a function of time.
5. Combine the costs and benefits and select the appropriate timing.

A critical review of the literature and agency practice revealed that cost benefit analysis was not the only approach for preservation timing; some approaches used expert judgement or tried to assess changes in material properties of the original pavement resulting from a preservation treatment. This guide did not consider approaches to define preservation treatment timing based on changes in material properties, but the effects of changes in material properties are expected to be captured in the evaluation of post-treatment pavement performance. Benefits resulting from a change in the material properties of the original pavement structure should be evident as a change in the expected pavement performance; otherwise those benefits do not reflect the intended use of preservation (i.e., improving the functional performance of a pavement).

Similar to changes in material properties, expert judgment was not recommended as the primary approach for determining preservation timing, but is an important element in the approach in this guide. For example, Chapter 3 requires that performance models be developed for preservation timing be evaluated for reasonableness, which requires expert judgment to assess the predictions. The evaluation of uncertainties in costs, as well as the final assessment of timing with uncertainties (see the section 4 examples in Chapter 4) all require expert judgement. Instead, this guide promotes the use of quantitative analysis that is supplemented with expert judgement where necessary.

Defining the benefit of a treatment as preservation treatment life, or the life extension associated with the application of preservation, are concepts that are discussed extensively in the literature, but were not recommended for use in this guide. However, the approach recommended in this guide can be expanded to also calculate a life or life extension associated with a preservation treatment. Additionally, the models presented in Chapter 5 of the final report can be used to calculate a value for life (or life extension) by estimating the time until defined thresholds are reached.

5.2. Recommendations

The implementation of the approaches detailed in this guide will lead to a preservation treatment timing program that leverages an agency's existing data. However, the approaches in this guide should not be viewed as static. Instead, routine updates and improvements should be pursued to ensure that the supporting models reflect the current business practices within an agency.

5.2.1. Routine Updates

Pavement condition data is one of the cornerstone elements of the recommendations made in this guide, as they are required for developing the performance models that define preservation treatment benefits. Additionally, data collection technologies are generally updated over time to improve the accuracy and precision of the measured condition data. Similarly, image recognition techniques are also being updated over time, which allows for historical pavement condition data to be reinterpreted to match updated technologies. Therefore, it is recommended that updates to the performance models (Chapter 3) be made when changes in pavement condition data collection technologies or changes to image recognition algorithms are made. The updates to performance models should also reflect updates to the uncertainty estimates for pavement performance.

Similar to pavement condition, cost data elements should be revisited over time. For example, many of the DOTs that submitted data for the development of this guide have costs expressed as a single value (e.g., expected treatment cost per lane-mile, etc.), and those costs do not vary with pavement condition. However, one agency that provided costs did show the expected costs increasing with worsening pavement condition. If the costs are expected to increase with worsening pavement condition, this increase will offset some of the discounting (or add to the inflation) of the future costs, which may lead to preservation treatment timing being recommended earlier in the analysis period.

Finally, many additional updates can be made to the framework and recommended methods over time, including:

- Updates to the relative weights that reflect the importance of specific performance measures. For example, if strategic initiatives within an agency change to reflect more importance to a specific performance measure, the weights in the preservation timing framework should also be updated.
- Updates to the approach for including uncertainties to better reflect risk approaches implemented within an agency. Currently, the uncertainties for the benefits are derived from the uncertainties in pavement performance prediction, and the uncertainties in the cost are expressed qualitatively. However, additional components

of uncertainty may be included to better account for specific risks an agency may be concerned with.

5.2.2. Inclusion of Additional Treatments and Measures

This guide recommended a framework and set of methodologies for determining the timing of preservation based on a common set of performance measures and treatments. The performance measures recommended in this guide have many benefits (as noted in Chapter 3), but additional performance measures may be considered as long as the criteria in Chapter 3 are met. For example, if an agency measures pavement surface friction and applies preservation to address inadequate friction, then friction should be considered as a performance measure. The framework and methods presented in this guide are flexible to account for additional measures such as composite measures like the PCI.

Similarly, the specific preservation treatments modeled in this guide were selected based on the data submitted by agencies and collected from the LTPP. As shown by Rada et al. (2018), the treatments modeled in this guide are representative of the most common preservation treatments for asphalt pavements. However, the framework and methods presented in this guide are flexible so that additional preservation treatments can be added. When considering the inclusion of new performance measures or preservation treatments, the same methods detailed in Chapter 3 will need to be followed, with the first step being to ensure adequate data exist to develop performance and cost models.

Finally, this guide only considered preservation treatments for asphalt surfaced pavements. However, the framework and methods presented in this guide are flexible enough to accommodate preservation treatments for Portland cement concrete (PCC) pavements. The performance measures for PCC pavements will likely have some difference from those recommended in Chapter 3 (e.g., rutting may not be a concern on PCC), but the required models are the same. Therefore, it is recommended that PCC pavement preservation treatments be studied in the future to facilitate the development of supporting models for preservation timing.

5.2.3. Other Considerations

The analysis of pavement performance data can sometimes require more advanced techniques than is traditionally described in pavement literature. For example, Deming regression, robust regression and censored regression were all used in this guide, and these techniques are not consistently demonstrated in pavement literature. Therefore, it is expected that some additional training in pavement performance prediction would benefit agencies as they implement the recommendations in this guide, and that training is recommended. Additionally, the use of statistical analysis software can greatly enhance the model development, and it is recommended that such software be used when implementing the recommendations in this guide.

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