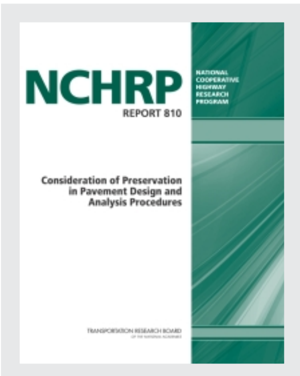

Consideration of Preservation in Pavement Design and Analysis Procedures

DETAILS

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP REPORT 810

Consideration of Preservation in Pavement Design and Analysis Procedures

Applied Pavement Technology, Inc.
Urbana, IL

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TRANSPORTATION RESEARCH BOARD

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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C O O P E R A T I V E   R E S E A R C H   P R O G R A M S

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APTech gratefully acknowledges the many individuals from state departments of transportation and industry organizations who participated in the interviews and provided information and feedback regarding the availability of data.

FOREWORD

By Amir N. Hanna
Staff Officer
Transportation Research Board

This report presents information on the effects of preservation on pavement performance and service life and describes three different approaches for considering these effects in pavement design and analysis procedures. These approaches could serve as a basis for developing procedures for incorporating preservation in the AASHTO *Mechanistic-Empirical Pavement Design Guide: A Manual of Practice* (MEPDG) and the AASHTOWare Pavement ME Design software. The material contained in the report will be of immediate interest to state pavement and maintenance engineers and others involved in the different aspects of pavement design and preservation.

Pavement preservation provides a means for maintaining and improving the functional condition of an existing highway system and slowing deterioration. Although pavement preservation is not expected to substantially increase structural capacity, it generally leads to improved pavement performance and longer service life and, therefore, should be considered in the pavement design process.

The AASHTO MEPDG and the AASHTOWare Pavement ME Design software provide methodologies for the analysis and performance prediction of different types of flexible and rigid pavements. However, these methodologies and related performance prediction models focus on new design and structural rehabilitation and do not explicitly consider the contributions of pavement preservation treatments to the overall pavement performance. Thus research was needed to identify approaches for considering the effects of preservation on pavement performance and to develop procedures that facilitate consideration of pavement preservation treatments in the MEPDG analysis process. Such procedures will ensure that the contributions of preservation to performance and service life are appropriately considered in the analysis and design process.

Under NCHRP Project 1-48, "Incorporating Pavement Preservation into the MEPDG," Applied Pavement Technology, Inc., initially worked with the objective of developing procedures for incorporating pavement preservation treatments into the MEPDG analysis process. However, as research progressed and available data associated with the performance of preservation-treated pavements were examined, it became evident that sufficient data were not available to support the development of performance-prediction models that account for these effects and would be appropriate for incorporation into the MEPDG analysis process. The research then focused on identifying and describing approaches that would serve as a basis for developing such models and illustrating how they would be incorporated in the MEPDG design and analysis procedures.

To accomplish this revised objective, the researchers reviewed available information on pavement preservation and pavement design (primarily as related to the MEPDG) and interviewed representatives of selected state highway agency (SHA) and pavement industry groups to assess pavement preservation and pavement design practices and the availability of data to support the development of approaches to account for the effects of pavement preservation in pavement design and analysis procedures. Based on this work, three approaches that would allow the consideration of preservation in the MEPDG design and analysis procedures were identified. One of these approaches accounts for all aspects of structural and functional performance associated with the application of preservation treatments. Another approach builds off of the calibration/validation process outlined in the AASHTO *Local Calibration Guide* by collecting extensive time-series performance data from a substantive set of preservation-treated test sections to support the development of calibrated models. A third approach considers the immediate and long-term changes in materials and structure properties resulting from treatment application, although it involves a high level of complexity to accurately define these changes. These approaches are described in detail, and examples that illustrate the step-by-step process for their incorporation into the MEPDG are presented.

Appendices A through I contained in the research agency's final report provide elaborations and detail on several aspects of the research; they are not published herein but are available by searching for *NCHRP Report 810* on the TRB website www.trb.org.

CONTENTS

Note: Photographs, figures, and tables in this report may have been converted from color to grayscale for printing. The electronic version of the report (posted on the web at www.trb.org) retains the color versions.

CHAPTER 1

Introduction

Background and Problem Statement

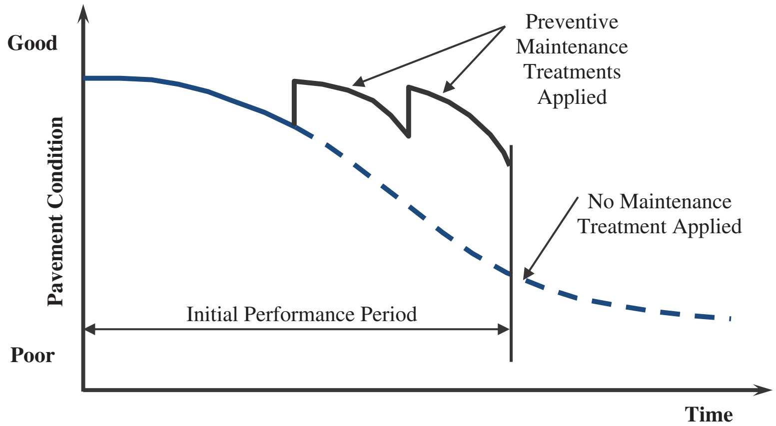
The methodology commonly used to design pavements in the United States was developed from pavement performance data collected during the American Association of State Highway Officials (AASHTO) road test conducted in Ottawa, Illinois, from 1958 to 1960. [The pavement design procedure is presented in reports that are alternately referred to as the *AASHTO Guide for Design of Pavement Structures,* the *AASHTO Design Guide,* and the *Guide.* Here the term "guide" is used generally to refer to the AASHTO pavement design procedure and associated versions of its documentation **prior** to the release of the new *Mechanistic-Empirical Pavement Design Guide* (MEPDG) developed under NCHRP Project 1-37A (ARA 2004; AASHTO 2008).] This methodology uses empirical performance models that were based on the limited range of site conditions at the road test, including the types of support materials, the types of applied loads, the environmental conditions, and the short duration of the data collection effort. The experiment at the road test was not set up to observe the long-term effects of maintenance actions, although some routine/corrective maintenance was performed on the test pavements (e.g., crack sealing and patching). Also, because the original design models were based on the observed performance of roads that were exposed to nearly continual loadings over a relatively short time, these models did not account for the effects of maintenance or environment on pavement performance.

The draft design procedure was first published in 1962, and several enhancements were introduced in subsequent revisions; all are incorporated in the *AASHTO Guide for Design of Pavement Structures* (AASHTO 1993). In particular, the guide added content on the rehabilitation of pavements with and without overlays and encouraged user agencies "to build a continuous and accurate performance database to increase the overall accuracy and confidence level of performance predictions" (AASHTO 1993).

The *Mechanistic-Empirical Pavement Design Guide: A Manual of Practice* (MEPDG; AASHTO 2008) was introduced in 2008. It notes that "preservation programs and strategies are policy decisions which are not considered directly in the distress predictions" and that "preservation treatments applied to the surface of hot-mix asphalt (HMA) layers early in their life may have an impact on the performance of flexible pavements and HMA overlays." It further notes that "the pavement designer needs to consider the impact of these programs in establishing the local calibration coefficients or to develop agency-specific values." These remarks suggest that the effects of pavement preservation are not fully considered in the MEPDG performance prediction models.

Preventive maintenance—the practice of keeping good roads in good condition—is a key component of pavement preservation. Preventive maintenance encompasses a variety of treatments whose application could have a positive effect on pavement performance, such as the following (from *Transportation Research Circular E-C078* 2005):

- *Preventing or Slowing Down Infiltration of Moisture and Incompressibles.* Crack and joint sealant materials, membrane seals applied over a pavement's entire surface, and certain patches will reduce the amount of water that infiltrates the pavement system. Sealing cracks and joints also keeps incompressibles from entering the pavement structure and impeding the expansion/contraction of the pavement.
- *Providing Protection Against Aging and Oxidation of Bituminous Surfaces.* The application of a new thin surfacing seals a bituminous surface and protects the underlying structural layer from some environmental effects. The process can be repeated several times after the surfacing ages and wears out, as long as the overall pavement remains structurally sound and the environmental effects are not too severe.
- *Restoring Surface Integrity.* Preventive maintenance treatments, such as slurry seals, chip seals, and partial-depth



Source: Peshkin et al. 2004.

Figure 1. Illustration of the effect of preventive maintenance treatments on pavement performance.

repairs, can correct non-severe, non-structural deterioration that is limited to the surface of a pavement (e.g., weathering and raveling, bleeding, loss of friction, roughness, and some HMA rutting).

- *Improving Surface Texture.* Preventive maintenance treatments, such as chip seals, thin overlays, and diamond grinding, improve the surface characteristics of the pavement by restoring the macrotexture of the pavement surface and influencing pavement surface friction and noise.

These effects contribute to improved overall performance (in comparison to the pavement without treatment) and a delayed need for rehabilitation (i.e., the pavement with preservation will reach a rehabilitation threshold much later); these effects should be reflected in the pavement performance prediction models. Figure 1 illustrates the effect of successive application of preventive maintenance treatments on pavement performance.

While the effects of preservation are easy to illustrate, their benefits are not easily quantified, for the following reasons:

- Preservation has not been widely practiced for a long time, and there remain many questions about its effect on commonly used measures of pavement performance.
- In general, preservation has not been practiced as part of a documented program (in contrast with capital projects, which more easily enter into an agency's formal records), making it difficult to distinguish between pavements that have and have not received preservation treatments.
- In some agencies, the practice of preservation varies among districts and is often influenced by fluctuations in funding and nontechnical factors. As a result, sustained effects are not adequately measurable.
- The effects of preservation are highly variable and depend on the existing pavement condition, treatment type, materials, treatment timing, construction quality, environment, traffic volume, and other factors. Therefore, a substantial amount of data is needed to adequately analyze the effect of preservation on pavement performance.
- The metrics used for monitoring pavement performance may not appropriately reflect the short- or long-term effects of preservation.

The MEPDG performance models were calibrated using data from in-service pavement sections included in the Long-Term Pavement Performance (LTPP) program. It is highly likely that these pavements were maintained over their lives, but the percentage of the sections that included the application of preservation treatments, as well as the type and time of application, are not known. Most likely, a preservation treatment was applied to some sections but not to others. Also, it is more likely that the MEPDG models incorporate the routine maintenance component of preservation but not necessarily the preventive maintenance component. Ideally, pavement design and performance models should consider the effects of preservation on performance. A procedure for calibrating the MEPDG models to account for the effects of preservation on pavement performance and design is needed.

Research Objective

The research was initially intended to develop procedures for incorporating pavement preservation treatments into the MEPDG design analysis process that would become part of the *MEPDG Manual of Practice.* However, it was determined in the early stages of the research that sufficient data were not available to support the development of such procedures. The research objective was then modified to focus on identifying and developing processes that would serve as a basis for developing these procedures.

Research Scope and Approach

To accomplish the research objective, the project documented the effects of preservation on performance by (1) conducting a literature review and telephone interviews with state highway agency (SHA) personnel and industry representatives and (2) identifying procedures that consider such effects in the design and analysis process.

The literature review covered recent or ongoing studies dealing with (1) pavement preservation practices for HMA and Portland cement concrete (PCC) pavements (or PCCPs), in terms of treatment usage and performance and the effect on pavement life and performance trends; (2) MEPDG evaluation and implementation activities (e.g., sensitivity testing, verification testing, local calibration, and other performance model refinements) and MEPDG use; and (3) pavement design applications that consider preservation.

Telephone interviews were held with representatives of 14 SHAs, selected on the basis of experience with pavement preservation and the MEPDG and on the possible availability of data on the effects of preservation on pavement performance. Also, telephone interviews were held with representatives of five industry organizations.

To better understand the extent to which the effects of preservation treatments were considered in the MEPDG performance prediction models, the test sections used in the development and calibration of these models (LTPP and non-LTPP sections) were identified and their maintenance and rehabilitation (M&R) history was examined.

The results of the literature review and interviews were used to further evaluate and define three possible approaches for considering the effects of preservation in the MEPDG procedures. These approaches consider developing pavement preservation response models, calibrating the models for preservation, or modifying material properties to account for the effects of preservation. The data required to fully develop these approaches were then identified, and their availability within SHAs was evaluated. It was concluded that sufficient data were not readily available to support the development of these approaches. The research then focused on describing and illustrating possible uses of the approaches.

Organization of Report

This report is presented in seven chapters, including this introductory chapter. Chapter 2 briefly describes the state of the practice with regard to pavement preservation. Chapter 3 describes the MEPDG process, its implementation and use, the extent of its consideration of preservation, and the availability of data to support developing models for incorporation into the MEPDG analysis procedures. Chapter 4 describes an approach for developing response models for considering the effects of preservation in the MEPDG procedures. Chapter 5 describes an approach for calibrating MEPDG performance models to account for the effects of pavement preservation. Chapter 6 describes an approach that considers the changes in material and pavement structural properties caused by preservation and addressing those changes in MEPDG models to reflect the effects of preservation. Chapter 7 summarizes the research findings and presents recommendations for further research.

Nine appendices for this report are available on the TRB website. Appendix A is a bibliography that describes the documents that were reviewed. Appendices B and C describe preservation strategies for HMA-surfaced and PCC-surfaced pavements, respectively, their use in the MEPDG, and their expected effect on distress. Appendices D and E contain brief syntheses on the topics of pavement preservation and the MEPDG, respectively. Appendices F and G summarize the responses of SHA and industry group representatives, respectively. Appendix H provides a listing of the LTPP test sections used in developing and calibrating the MEPDG models and identifies those sections whose performance data were influenced by applied preservation treatments. Appendix I examines the available SHA data and their suitability to support the development of approaches. These appendices can be found on the report summary web page by searching for *NCHRP Report 810* at www.TRB.org.

CHAPTER 2

State of the Practice

This chapter summarizes the state of the practice of pavement preservation and the MEPDG design analysis process as gleaned from a literature review and interviews with SHA and industry personnel. The summary covers items of relevance to the development of approaches for considering the effects of preservation in the MEPDG procedures, including (1) preservation programs and practices, (2) pavement and preservation treatment performance analysis techniques, and (3) preservation consideration in the MEPDG procedures.

Literature Review

The literature review focused on (1) highway pavement preservation activities and their effects on pavement performance and (2) MEPDG performance prediction models and their refinements and local calibrations. The review was limited to studies undertaken in the previous 5 to 7 years and targeted mostly domestic sources, including NCHRP and TRB, AASHTO, Federal Highway Administration (FHWA) and National Highway Institute, selected state departments of transportation (DOTs), national pavement research programs and centers (e.g., Innovative Pavement Research Foundation, Airfield Asphalt Pavement Technology Program, National Center for Asphalt Technology [NCAT], and National Concrete Pavement Technology Center), pavement preservation organizations (e.g., Foundation for Pavement Preservation and National Center for Pavement Preservation [NCPP]), and industry associations (e.g., National Asphalt Pavement Association [NAPA], American Concrete Pavement Association [ACPA], International Slurry Surfacing Association [ISSA], and Asphalt Emulsion Manufacturer's Association [AEMA]).

A bibliography of the identified documents is provided in Appendix A. Summaries of the effects of several HMA and PCC preservation treatments are provided in Appendices B and C, respectively. Two syntheses, one on pavement preservation and the other on the MEPDG, are provided in Appendices D and E, respectively; key aspects are presented in this chapter.

SHA and Industry Group Interviews

The literature review was supplemented with interviews of SHAs and industry groups. The SHA interviews provided information regarding pavement preservation policies and practices, agency perspectives on the effects of preservation on pavement performance, current pavement design procedures, MEPDG implementation status and activities (past, current, and future), and procedures used to consider preservation in the pavement design/analysis process. The industry group interviews provided information on the industry's involvement with pavement preservation and the MEPDG.

SHA Interviews

SHAs active in developing pavement preservation programs or evaluating or implementing the MEPDG were identified. These agencies were evaluated with consideration to (1) extent of preservation practice and level of agency experience with preservation; (2) extent of involvement in MEPDG evaluation, implementation, and use (particularly as it relates to local calibration and the incorporation of preservation into the MEPDG); and (3) likely availability of the data needed to evaluate the effects of preservation on pavement performance. Fourteen agencies (from Arizona, California, Indiana, Kansas, Maryland, Minnesota, Missouri, New Jersey, North Carolina, Ohio, Texas, Utah, Virginia, and Washington State) were then selected for interviews.

Interview participants were identified through discussions with SHA staff; they represented the areas of maintenance/

preservation, pavement design, pavement management, or research. The interviews addressed the following topics:

- Background, nature, and status of the agency's pavement preservation program.
- Scope of the agency's preservation program.
- Extent of the agency's tracking of the performance of preservation treatments.
- Agency's current pavement design procedure (if not MEPDG).
- Status of the agency's MEPDG implementation effort.
- Agency's desire for enabling the MEPDG analysis procedure to consider the effects of preservation treatments on pavement performance.
- Availability of performance data (with and without preservation) and other data (design, construction/materials, traffic, climate, etc.) that can be used in developing procedures for considering preservation in the MEPDG procedures.

Interview questions and responses are provided in Appendix F; key findings from the interviews are discussed in this chapter.

Industry Group Interviews

Representatives from five industry groups (ACPA, NAPA, AEMA, ISSA, and NCPP) were interviewed to determine their organization's (1) familiarity and involvement with pavement preservation practices, (2) level of involvement with SHAs in evaluating preservation treatment performance and developing preservation and practices, and (3) familiarity and involvement with the MEPDG. The questions and responses are provided in Appendix G; key findings from the interviews are discussed in this chapter.

Pavement Preservation Programs and Practices

This section describes SHA preservation programs and practices; specifically, the types of treatments and their relative levels of use as well as the conditions for their use.

Cuelho et al. (2006) conducted a survey of 34 SHAs and five Canadian provincial highway agencies (PHAs) to establish the frequency of using each of 16 preventive maintenance treatments for flexible pavements. Participants were asked to rate on a scale of 1 to 5 how often they use each treatment (1 being "never" and 5 being "always"); the mean ratings and corresponding rankings are listed in Table 1. As noted, the most frequently used treatments were crack sealing, thin HMA overlay, chip seal, maintenance of drainage features, and microsurfacing.

A survey of U.S. and Canadian highway agencies conducted in 2009 (Peshkin et al. 2011a; Peshkin et al. 2011b) provided updated information on pavement preservation programs and practices for all facility types and traffic levels (low, medium, and high) as defined by the agency.

Table 1. Frequency of use of preventive maintenance treatments for flexible pavements (Cuelho et al. 2006).

Treatment	Count	Percent[1]	Mean	St. Dev.	Don't Know	Never Heard of It	Overall Rank
Crack Seal	43	91.5	3.67	0.808	0	0	1
Fog Seal	43	91.5	1.77	0.718	0	0	11
Cape Seal	44	93.6	1.25	0.508	5	7	15
Chip Seal	44	93.6	3.20	1.286	0	0	3
Ultrathin Friction Coarse	43	91.5	1.92	0.784	2	3	9
Slurry Seal	44	93.6	1.74	0.621	1	0	12
Scrub Seal	43	91.5	1.24	0.435	1	9	16
Thin Overlay (with or without mill)	44	93.6	3.66	0.805	0	0	2
Microsurfacing	44	93.6	2.46	0.926	0	0	5
Hot In-Place Recycling	43	91.5	1.81	0.824	0	0	10
Cold In-Place Recycling	44	93.6	1.98	0.902	0	0	8
PCCP Diamond Grinding	44	93.6	2.38	1.011	2	0	6
PCCP Diamond Grooving	43	91.5	1.54	0.600	4	0	14
PCCP Undersealing	44	93.6	1.69	0.863	4	1	13
PCCP Dowel Retrofit	43	91.5	2.10	1.020	2	0	7
Maint. of Drainage Features	44	93.6	2.63	0.952	1	0	4

Note: [1] Out of 47 responses.

The survey (Peshkin et al. 2011a) provided information about treatment usage by pavement type (asphalt-surfaced or concrete-surfaced pavements) and highway setting (urban versus rural). The most extensively used treatments (≥67% of responding agencies) for asphalt-surfaced pavements, considering all traffic ranges and both urban and rural settings, were crack filling, crack sealing, and drainage preservation, and the moderately used treatments (33% to 66% of respondents) were thin HMA overlays, with and without milling. For concrete-surfaced pavements, the most extensively used treatments were crack sealing, diamond grinding, and full-depth patching, and the moderately used treatments were joint resealing, partial-depth patching, dowel-bar retrofit, and drainage preservation. This survey also indicated that some treatments, such as microsurfacing, chip seals, ultrathin whitetopping, and dowel-bar retrofit, were less commonly used on higher-trafficked roads due in part to expected durability issues. Another survey (Peshkin et al. 2011b) indicated less use of some treatments, such as slurry seals, microsurfacing, thin and ultrathin HMA overlays, joint resealing, diamond grinding, and diamond grooving, in more severe climates (e.g., deep freeze).

Considerations in selecting preservation treatments were safety concerns (76% of respondents), treatment cost (74%), and durability/expected life of treatment (64%) (Peshkin et al. 2011a). The primary asphalt-surfaced pavement deficiencies addressed by preservation were light and moderate surface distress (e.g., surface cracks, raveling/weathering, and bleeding) and friction loss. For concrete pavements, the primary performance issues addressed by preservation were smoothness/ride quality, light surface distress, friction loss, and noise.

The interviews revealed that most agencies equate preservation with preventive maintenance, but some agencies classify preservation as including a broader set of activities, ranging from preventive maintenance to major rehabilitation and even reconstruction. In some cases, the definition of preservation is most closely linked to allowable treatments from a funding perspective rather than a program approach. A few agencies have an official preservation program, and one or more staff are designated as preservation engineers.

The interviews also indicated that preservation treatments are applied to all types and classes of roads, usually guided by criteria that define the treatments that can be applied to a specific pavement type under specific conditions (e.g., traffic levels, existing pavement conditions). The use of preservation treatments varies among agencies; some only use a few treatments, and others use many different treatments (various combinations of HMA mix types, HMA overlay thicknesses, milling depths, and recycling options). The most commonly used treatments for asphalt-surfaced pavements are crack sealing, chip seals, microsurfacing, and thin HMA overlays. For concrete-surfaced pavements, the most commonly used treatments are diamond grinding, partial-depth repair, and full-depth repair.

Pavement and Preservation Treatment Performance

Treatment performance is a major consideration in accounting for the effects of future scheduled preservation in pavement design. This section presents findings from SHA studies to assess treatment performance and its effects on pavement condition over time and pavement life. Information is provided on the types of preservation that have been studied, the nature of the sources for the studies (i.e., experimental or test sections, in-service pavement management system [PMS] sections), the methods used to evaluate performance (i.e., performance of treatment versus treated pavement, performance measures used), and the experiences in developing performance trends or models that could be used in mechanistic-empirical pavement design procedures.

Cuelho et al. (2006) reported on several preservation performance studies conducted throughout North America between 1989 and 2005. They described the applied treatments and their advantages/disadvantages and reported the expected performance lives of each treatment. Although some of the studies included monitoring of pavement performance (e.g., roughness, cracking, rutting, and raveling), performance was generally reported in terms of treatment service life (i.e., how long a treatment lasts) or, in a few cases, the pavement life or the extension in pavement life as a result of the treatment).

In several pavement performance studies undertaken since 2005, condition data were collected and analyzed to assess performance and estimate pavement life extension (a summary is provided in Appendix D). Many of these studies evaluated in-service pavement sections on which preservation treatments were applied or included the design, construction, and performance monitoring of test sections.

More recent studies have focused on in-service sections and less on experimental sections. Evaluations of in-service sections are ongoing or recently completed in California, Illinois, Michigan, Louisiana, Indiana, and New England. Other recent in-service pavements are LTPP surface maintenance (Morian et al. 2011), Oklahoma pavement retexturing experiments (Gransberg et al. 2010), Minnesota DOT (MnDOT) flexible and rigid pavement preservation treatment test sections at the MnROAD test facility (MnDOT 2011), and the NCAT test site with 23 short sections of different flexible pavement preservation treatments (NCAT 2013).

The most common methods for assessing treatment performance are treatment service life, pavement life extension, and performance benefit area.

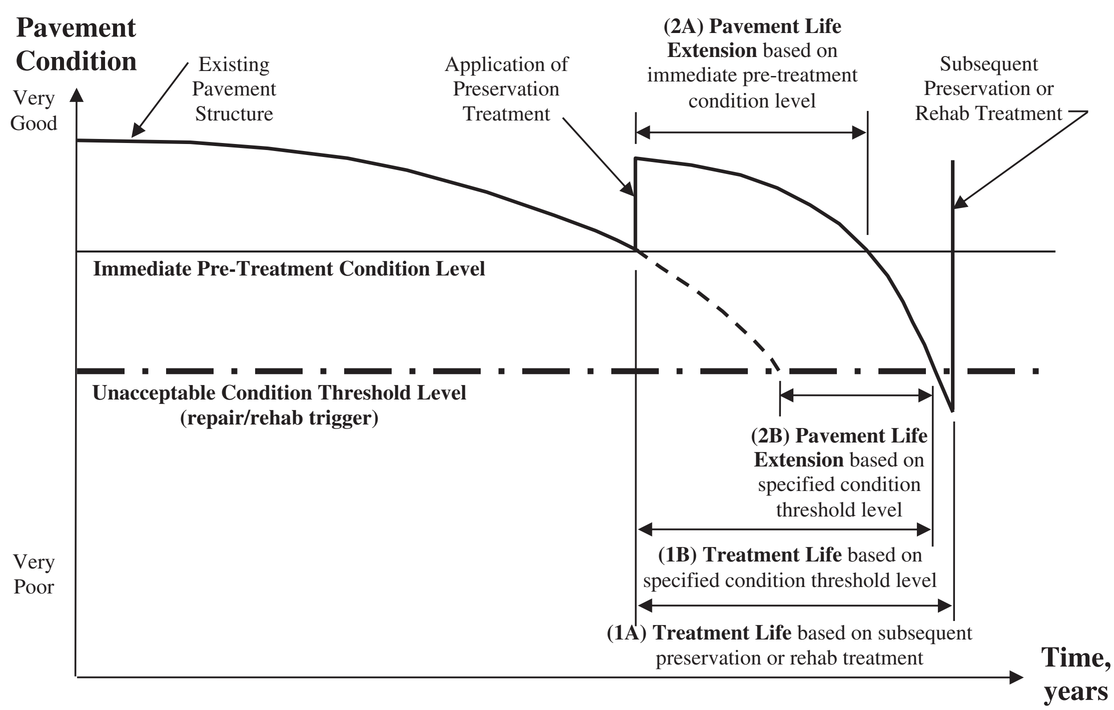
Treatment Service Life: Treatment service life refers to how long a treatment serves its function until a subsequent preservation and rehabilitation (P&R) treatment will be needed to address one or more issues (e.g., raveling, rutting, smoothness, and friction) that have reached a specified condition threshold.

Treatment service life can be estimated from analysis of historical P&R events or performance data. When considering historical P&R event data, the years in which preservation and other treatments were applied are identified, and the ages of the various applied treatments are computed, statistically analyzed, and presented in the form of (1) descriptive statistics (e.g., mean, standard deviation) of age at time of subsequent P&R, (2) frequency distribution plots that show the number of sections as a function of age (or traffic) that have failed (i.e., replaced with a P&R treatment), and (3) cumulative frequency distribution plots (i.e., failure curves or, alternatively, survival curves) that show the percentages of sections as a function of age (or cumulative traffic) that have failed.

When considering historical performance of a specific treatment, post-treatment time-series (or traffic-series) performance data (e.g., individual distresses, smoothness, overall condition ratings, composite condition indexes, friction, texture) are collected and statistically analyzed. Data may be presented in the form of plots of performance over time (or cumulative traffic) that show the time until a subsequent P&R treatment was applied (Scenario 1A in Figure 2) or the time until a specified condition threshold (considered unacceptable) is reached or is projected to be reached (Scenario 1B in Figure 2). Data may also be presented in the form of (1) descriptive statistics, (2) frequency distribution plots, or (3) cumulative frequency distribution plots.

Pavement Life Extension: Pavement life extension is expressed in terms of the number of years of additional pavement life attributed to treatment application. The added life may be estimated based on structural or functional performance, as characterized by key surface distresses (e.g., cracking, rutting, faulting, punchouts, raveling, and spalling), or as characterized by key pavement surface characteristics (e.g., smoothness, friction, texture, and pavement-tire noise). Because pavement life extension is related to the performance of the pavement without a preservation treatment, pre-treatment pavement condition is required for determining the life extension.

Pavement life extension can be estimated from analysis of historical performance data of a specific treatment. Both pre-treatment and post-treatment time-series (or traffic-series) performance data (e.g., individual distresses, smoothness, overall condition ratings, composite condition indexes, surface characteristics [e.g., friction, texture], and deflection properties) are collected in the form of (1) plots of performance over time (or cumulative traffic) that show the time until the immediate pre-treatment condition level was reached or is projected to be reached (Scenario 2A in Figure 2), (2) plots of performance over time (or cumulative traffic) that show the time until the specified condition threshold level was reached



Adapted from Peshkin et al. 2011a, Sousa and Way 2009a, and Rajagopal 2010.

Figure 2. Preservation treatment life and pavement life extension.

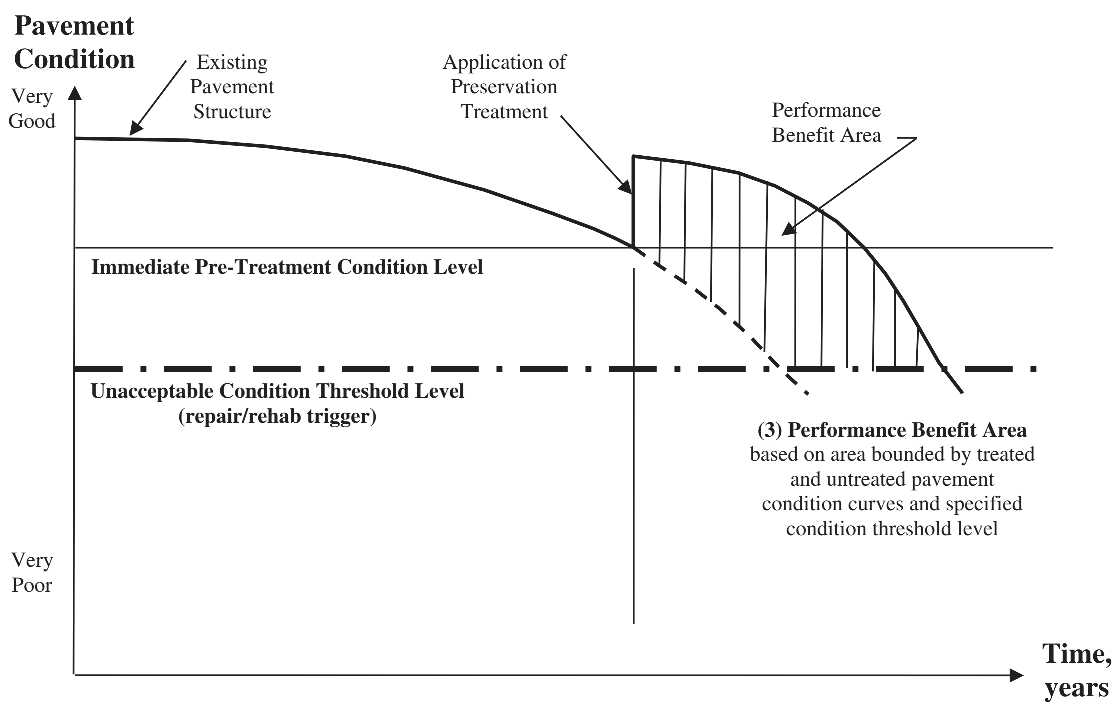
or is projected to be reached (Scenario 2B in Figure 2), and (3) descriptive statistics, frequency distribution plots, or cumulative distribution plots of pavement life extension.

Performance Benefit Area: The benefit provided by a treatment may be measured by the area under the pavement age versus performance curve (based on structural or functional performance) contributed by the treatment (i.e., above that provided by the untreated pavement). The performance benefit area can only be obtained through an analysis of historical performance data for both pre-treatment and post-treatment time-series (or traffic-series) pavement performance data (e.g., individual distresses, smoothness, overall condition ratings, composite condition indexes, surface characteristics [e.g., friction, texture], and deflection properties) that are collected for a particular preservation treatment type. The data are then statistically analyzed and presented in the form of (1) plots of performance over time (or cumulative traffic) that show the area bounded by the performance curves of the treated and untreated pavements and a specified condition threshold level (Scenario 3 in Figure 3), and/or (2) descriptive statistics of the performance benefit areas.

The responses indicated that pavement performance is monitored by most of the interviewed states, although some states have had problems either in tracking the locations of preservation treatment projects or reliability of the collected performance data. Experience in evaluating treatment performance data or developing treatment performance models varied among agencies. Treatment performance has generally been evaluated in terms of treatment life (based on experience, time between applications, or time until surface condition has returned to the pre-treatment level) and not in terms of effect on pavement life. Performance models have been developed for use in pavement programming; details are provided in Appendix F.

Preservation and the MEPDG

Consideration of preservation in the MEPDG has been noted in only three of the reviewed reports. Banerjee et al. (2010) used data from 13 LTPP Specific Pavement Studies 3 (SPS-3) test sections to develop local calibration factors for the MEPDG HMA rutting model that account for the combined effects of preservation treatment and climate. In the local calibration of the MEPDG HMA performance models, Von Quintus and Moulthrop (2007) used data from 102 pavement sections to demonstrate the value of separate fatigue cracking model calibration factors for sections with and without preservation treatments. California DOT (Caltrans) developed a tool to account for the effects of preservation in pavement design by (a) resetting distress and smoothness levels when a treatment is scheduled and (b) adjusting pavement structure moduli corresponding to scheduled preservation treatments (Ullidtz et al. 2010). Further details of these studies are provided in Appendix E.



Adapted from Peshkin et al. 2004.

Figure 3. Preservation treatment effectiveness as indicated by the performance benefit area.

Most of the interviewed SHAs did not consider pavement preservation in the design procedure. However, Minnesota noted that preservation treatments probably have been applied to all pavement sections used in the development of performance models for the *R*-value and Mn/Pave design procedures. Some agencies suggested that preservation can be considered in rehabilitation design by adjusting the structural coefficient values of the existing pavement layers in the AASHTO design procedure.

California's CalME program allows consideration of the effects of preservation on pavement performance by resetting certain distresses to zero at the year of treatment application (e.g., a thin overlay applied at year 10 reduces rutting to zero at that year). The program's incremental-recursive function also allows changes to asphalt material properties (e.g., dynamic modulus) to account for the effect of preservation treatments (e.g., a rejuvenator would soften the existing asphalt surface, and a seal coat would reduce the rate at which the existing asphalt surface hardens).

Most SHAs reported issues or limitations with the data needed for developing models that consider the effects of preservation in the design procedures. These limitations included compatibility between the agency PMS data and the MEPDG input data, pavement section location, availability of historical performance data, and availability of untreated sections for direct comparison with preservation-treated sections.

CHAPTER 3

Assessment of Consideration of Preservation in MEPDG Models

LTPP Test Sections

Because of the age of the LTPP and other test sections used in the development and calibration of the MEPDG performance prediction models, it has been suggested that preservation treatments may have been applied to these sections such that the developed models already reflect the effects of preservation. To determine whether preservation treatments were indeed applied to these sections and if their effects were accounted for in the performance data, the development of MEPDG prediction models for (a) transverse thermal cracking, fatigue cracking, rutting, and smoothness of both new/reconstructed flexible pavements and HMA overlays and (b) transverse slab cracking, joint faulting, punchouts (continuously reinforced concrete [CRC] pavement), and smoothness for new/reconstructed rigid pavements, restored jointed plain concrete (JPC) pavements, and JPC and CRC overlays was investigated.

The various sections used in the development and calibration of flexible and rigid pavement performance prediction models were identified along with the range of years in which performance data were used in the modeling. Maintenance history information for these sections was then extracted from the LTPP and other databases and summarized to provide an overview of the types of maintenance treatments applied, dates of application, and whether the treatments may have affected the pavement performance trends and consequently the MEPDG models. Table 2 lists the LTPP experiments that include sections of relevance to this evaluation.

MEPDG Consideration of Preservation

This section describes the LTPP and other pavement test sections that were used in developing and calibrating the various MEPDG performance prediction models. It also identifies those sections that received a preservation treatment and indicates whether the effects of preservation treatments are reflected in the performance data that were used. Appendix H provides information on LTPP sections used in the development and calibration of the MEPDG models, including the date of construction (or rehabilitation) and the date of inclusion in the LTPP program, the type of applied maintenance treatment (if any), and if there was consideration of preservation treatments effects. Table 3 lists the number of LTPP (general pavement studies [GPS] and specific pavement studies [SPS]) and other test sections used in the development and calibration of the various MEPDG performance prediction models (ARA, Inc. 2004).

Table 4 lists the total number of LTPP sections used in developing/calibrating the models, the number of sections to which some form of preservation was applied during the time period considered in developing/calibrating the models, and the percentage of sections in which the effects of preservation were considered in the data used in developing/calibrating each model. No information was available regarding the time range for the data used to develop or calibrate the models for thermal cracking and smoothness for new/reconstructed flexible pavements and HMA overlays, transverse cracking and joint faulting for restored JPC pavements and unbonded JPC overlays, and punchouts for bonded PCC overlays over CRC pavements.

Table 4 shows that preservation treatments have been applied to about 22% of the flexible pavement sections (new/reconstructed and HMA overlays combined) used in developing/calibrating the flexible pavement models. For new/reconstructed rigid pavement models, about 9% of the sections included preservation; no data were available for restored PCC and PCC overlays.

The most common types of preservation treatments that might have affected performance data of flexible pavements were crack sealing, fog seals, slurry seals, and seal coats. For rigid pavements, joint resealing (including longitudinal joints in both JPC and CRC), crack sealing, partial-depth repair, and full-depth repair may have affected performance data

Table 2. GPS and SPS experiments with possible data for MEPDG development.

Experiment ID	Experiment Title
GENERAL PAVEMENT STUDIES (GPS)	
GPS-1	Asphalt Concrete (AC) Pavement on Granular Base
GPS-2	AC Pavement on Bound Base
GPS-3	Jointed Plain Concrete (JPC) Pavement
GPS-4	Jointed Reinforced Concrete (JRC) Pavement
GPS-5	Continuously Reinforced Concrete (CRC) Pavement
GPS-6A	Existing AC Overlay of AC Pavement (existing at the start of the program)
GPS-6B	AC Overlay Using Conventional Asphalt of AC Pavement – No Milling
GPS-6C	AC Overlay Using Modified Asphalt of AC Pavement – No Milling
GPS-6D	AC Overlay on Previously Overlaid AC Pavement Using Conventional Asphalt
GPS-6S	AC Overlay of Milled AC Pavement Using Conventional or Modified Asphalt
GPS-7A	Existing AC Overlay on PCC Pavement
GPS-7B	AC Overlay Using Conventional Asphalt on PCC Pavement
GPS-7C	AC Overlay Using Modified Asphalt on PCC Pavement
GPS-7D	AC Overlay on Previously Overlaid PCC Pavement Using Conventional Asphalt
GPS-7F	AC Overlay Using Conventional or Modified Asphalt on Fractured PCC Pavement
GPS-7R	Concrete Pavement Restoration Treatments with No Overlay
GPS-7S	Second AC Overlay, Which Includes Milling or Geotextile Application, on PCC Pavement with Previous AC Overlay
GPS-9	Unbonded PCC Overlay on PCC Pavement
SPECIFIC PAVEMENT STUDIES (SPS)	
SPS-1	Strategic Study of Structural Factors for Flexible Pavements
SPS-2	Strategic Study of Structural Factors for Rigid Pavements
SPS-3	Preventive Maintenance Effectiveness of Flexible Pavements
SPS-4	Preventive Maintenance Effectiveness of Rigid Pavements
SPS-5	Rehabilitation of AC Pavements
SPS-6	Rehabilitation of JPC Pavements
SPS-7	Bonded PCC Overlays of Concrete Pavements
SPS-8	Study of Environmental Effects in the Absence of Heavy Loads
SPS-9P	Validation and Refinements of Superpave Asphalt Specifications and Mix Design Process
SPS-9A	Superpave Asphalt Binder Study

(a few instances of diamond grinding and grooving were also recorded in the LTPP database).

Review of the LTPP database revealed that the only recorded preservation treatments (and other maintenance and light rehabilitation) were those applied to a pavement section after it was included in the LTPP database. That is, preservation treatments that may have been applied to some GPS sections before the start of LTPP were not recorded. Hence, the number of preservation-treated sections used in developing/calibrating the different MEPDG models is likely larger than what is listed in Table 4.

MEPDG Design Approach

The design approach used in the MEPDG as illustrated in Figure 4 (AASHTO 2008) includes three stages. The evaluation stage (Stage 1) includes the collection, evaluation, or estimation of input data (e.g., foundation support, material characterization, traffic, and climate). The analysis stage (Stage 2) includes the evaluation of selected pavement design strategies using pavement response models (based on calculated stresses, strains, and deflections) and distress transfer functions for estimating pavement distresses. The strategy selection stage (Stage 3) occurs outside of the MEPDG and deals with considerations unrelated to thickness design, such as construction, policy issues, and life-cycle cost analysis (LCCA).

Preservation can be addressed in the design/analysis process either as part of the analysis stage (Stage 2) or the strategy selection stage (Stage 3). In this latter case, LCCA will identify the cost and performance effects of pavement preservation treatments. This chapter describes three approaches for considering preservation in the analysis stage. One approach requires the development of pavement preservation response models and distress transfer functions. Another approach requires the calibration of MEPDG models using pavement preservation performance data. The third approach accounts for the effects of preservation by adjusting pavement distress and modifying material properties used as inputs in MEPDG

Table 3. LTPP test sections used in MEPDG model development and calibration (ARA, Inc. 2004).

Pavement Model	Experiment Type	Number of LTPP Sections		
		GPS	SPS	Total
FLEXIBLE PAVEMENTS				
Fatigue Cracking[1] Model—New/Reconstructed Flexible Pavements	GPS-6B, SPS-1	79	16	95
Fatigue Cracking[1] Model—HMA Overlay over Flexible Pavements	GPS-6B, SPS-5	13	33	46
Fatigue Cracking[1] Model—HMA Overlay over Fractured Slab Pavements	SPS-6	0	3	3
Fatigue Cracking[1] Model—HMA Overlay over JPC Pavements	GPS-7B, SPS-6	4	3	7
Thermal Cracking Model—New/Reconstructed Flexible Pavements[2]	GPS-1	22	0	22
Rutting Model—New/Reconstructed Flexible Pavements	GPS-1, GPS-2, SPS-1	79	16	95
Rutting Model—HMA Overlay over Flexible Pavements	GPS-6B, SPS-5	14	32	46
Rutting Model—HMA Overlay over Fractured Slab Pavements	SPS-6	0	3	3
Rutting Model—HMA Overlay over JPC Pavements	GPS-7B, SPS-6	4	3	7
Smoothness Model—New/Reconstructed Flexible Pavements and HMA Overlays	GPS-1, GPS-2, GPS-6, GPS-7	N/A	N/A	N/A
RIGID PAVEMENTS				
Punchout Model—New/Reconstructed CRC[3]	GPS-5	43	0	43
Transverse Joint Faulting Model—New/Reconstructed JPC[4]	GPS-3, SPS-2	64	83	147
Transverse Cracking Model—New/Reconstructed JPC[5]	GPS-3, SPS-2	63	84	147
Transverse Joint Faulting and Cracking Models—Restored JPC[6]	SPS-6	0	8	8
Transverse Joint Faulting and Cracking Models—Unbonded JPC Overlays	GPS-9	16	0	16
Punchout Model—Unbonded CRC Overlays[7]	GPS-9	2	0	2
Punchout Model—Bonded PCC Overlay over CRC	SPS-7	0	4	4
Smoothness Model—New/Reconstructed JPC	GPS-3	78	0	78
Smoothness Model—New/Reconstructed CRC	GPS-5	45	0	45

Notes: [1] Bottom-up alligator and top-down longitudinal cracking. [2] Also includes non-LTPP sections from the MnROAD study. [3] Also includes 17 non-LTPP sections from Illinois (I-80 and I-94 in Cook County and U.S. 40 in Fayette County). [4] Also includes 110 non-LTPP sections in nine states from the FHWA Rigid Pavement Performance and Rehabilitation study (RIPPER). [5] Also includes 13 non-LTPP sections in seven states from the FHWA Rigid Pavement Performance and Rehabilitation study. [6] Also includes 15 non-LTPP sections from the ACPA Diamond Grinding Study and NCHRP Project 10-41 study. [7] Also includes six non-LTPP sections in four states from the NCHRP Project 10-41 study. N/A = not available.

models. Availability of data to support the development of these approaches is described in the following sections.

Evaluation of Data Availability

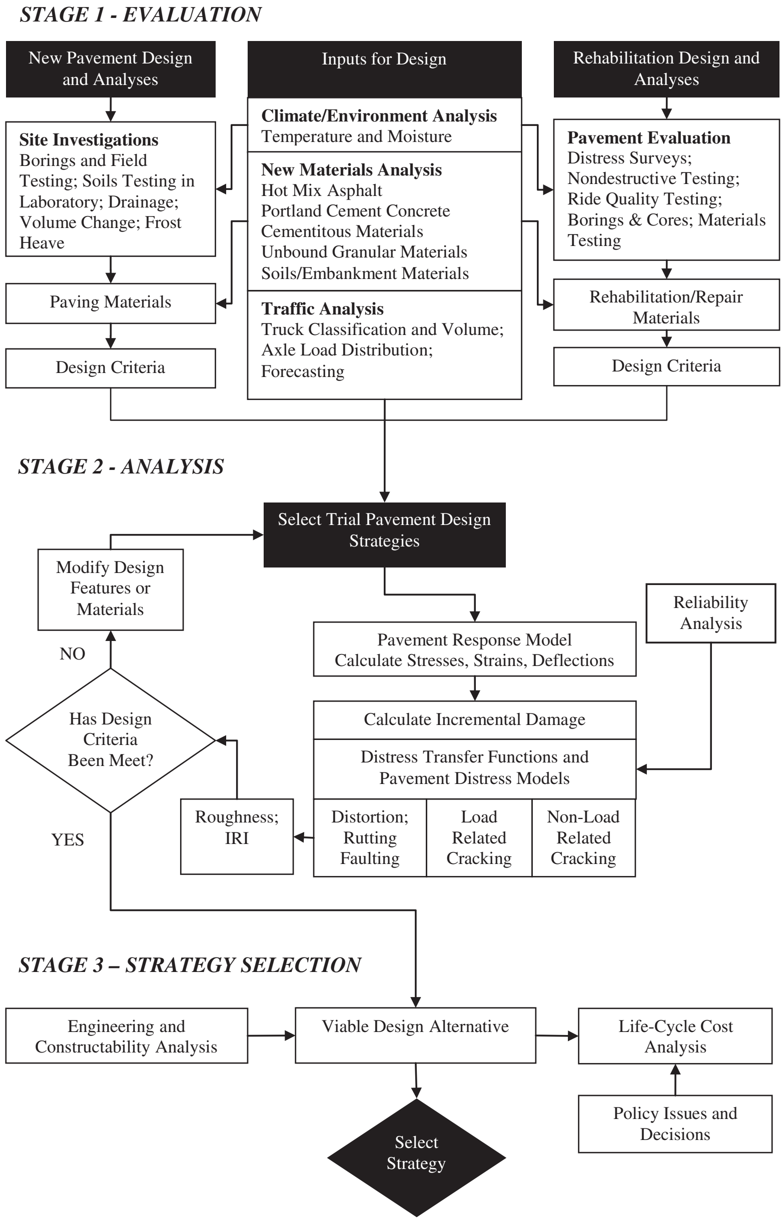
An assessment of the availability of the data required for considering preservation in the MEPDG was made by (1) identifying the required data elements, (2) determining availability of the required data elements, and (3) assessing the appropriateness of available data. Because pavement preservation is more commonly used for flexible pavements, this assessment focused on flexible pavement preservation. Design, preservation, and pavement management practices and experiences of the 14 interviewed SHAs indicated that eight states (Arizona, Indiana, Kansas, Minnesota, Missouri, North Carolina, Texas, and Washington) may have the types of data required for implementing this approach; the data available from these states were evaluated. (Appendix I provides details.)

The consideration of preservation effects requires design analysis of a baseline/untreated pavement structure and a corresponding preservation-treated pavement structure using the AASHTOWare Pavement ME Design software. Therefore,

Table 4. Consideration of preservation in LTPP test sections.

MEPDG Performance Model	Number of Test Sections				Percent Test Sections with Preservation Effects Considered in Performance Data
	Preservation Effects Considered in Performance Data	Preservation Effects Not Considered in Performance Data	Effects Unknown	Total	
FLEXIBLE PAVEMENTS					
Fatigue Cracking[1] Model—New/ Reconstructed Flexible Pavements	20	63	12	95	21
Fatigue Cracking[1] Model—HMA Overlays over Flexible Pavements	1	45	0	46	2
Fatigue Cracking[1] Model—HMA Overlays over Fractured Slab Pavements	2	1	0	3	67
Fatigue Cracking[1] Model—HMA Overlays over JPC Pavements	5	7	0	12	42
Thermal Cracking Model—New/ Reconstructed Flexible Pavements	N/A	N/A	N/A	N/A	N/A
Rutting Model—New/Reconstructed Flexible Pavements	14	74	7	95	15
Rutting Model—HMA Overlays over Flexible Pavements	21	25	0	46	46
Rutting Model—HMA Overlays over Fractured Slab Pavements	2	1	0	3	67
Rutting Model—HMA Overlays over JPC Pavements	4	3	0	7	57
Smoothness Model—New/ Reconstructed Flexible Pavements and HMA Overlays	N/A	N/A	N/A	N/A	N/A
RIGID PAVEMENTS					
Punchout Model—New/Reconstructed CRC	10	31	2	43	23
Transverse Joint Faulting Model—New/Reconstructed JPC	10	122	15	147	7
Transverse Cracking Model—New/Reconstructed JPC	12	123	12	147	8
Transverse Joint Faulting and Cracking Models—Restored JPC	N/A	N/A	N/A	N/A	N/A
Transverse Joint Faulting and Cracking Models—Unbonded JPC Overlays	N/A	N/A	N/A	N/A	N/A
Punchout Model—Unbonded CRC Overlays	N/A	N/A	N/A	N/A	N/A
Punchout Model—Bonded PCC Overlay over CRC	N/A	N/A	N/A	N/A	N/A
Smoothness Model—New/ Reconstructed JPC	7	68	3	78	9
Smoothness Model—New/ Reconstructed CRC	3	41	1	45	7

Notes: [1] Bottom-up alligator and top-down longitudinal cracking. N/A = not available.



Note: IRI = International Roughness Index.

Figure 4. MEPDG conceptual analysis process (AASHTO 2008).

input data required for this analysis, such as design properties and analysis parameters, traffic and climate characteristics, structure properties, material layer properties, and foundation and bedrock properties, must be established. A complete listing of required inputs is available in several sources (AASHTO 2008, the AASHTOWare Pavement ME Design software and Software Help System, and FHWA 2010). Table 5 lists the data elements required for the design analysis of untreated and preservation-treated pavement structures.

Sources of Required Data Elements: Required data are likely to be available from different sources. Data on pavement condition when a preservation treatment is applied may be obtained from pavement management data or from the guidelines for preservation treatment application, and preservation treatment material properties data may be obtained from actual historical materials test data. As-built records will provide pavement structure data, and actual historical materials test data or sampling and testing will provide data on existing HMA surface material properties. Existing pavement moisture and thermal profile data may be derived from instrumented test sections, and data on immediate post-treatment distress/smoothness will likely be available from pavement management data.

Availability of the Required Data: Because efforts to evaluate preservation treatment performance and to evaluate, calibrate, implement, or use the MEPDG would require the types of data elements considered in this assessment, relevant states' efforts were identified. The availability of a pavement management program and system database, a construction/materials

Table 5. Data elements required for AASHTOWare Pavement ME Design analysis.

Data Category	Data Element
Analysis Parameters	• Typical designs of untreated pavement structure. • Preservation-treated pavement structure. • Design life. • Design reliability (for individual distresses and smoothness). • Performance indicators (e.g., rutting, transverse cracking, bottom-up alligator cracking, top-down longitudinal cracking, reflective cracking, and IRI). • Pavement/treatment failure thresholds (corresponding to the application of a rehabilitation treatment or a follow-up preservation treatment).
Structure Properties	• Untreated design strategy (layer types, materials, and thicknesses). • Preservation-treated design strategy (layer types, materials, and thicknesses). • Surface shortwave absorptivity.
Preservation Treatment Application Parameters	• Treatment timing corresponding to either the optimal timing identified using OPTime or to an agency-specified timing value. – Distress, smoothness, and/or overall condition levels of original pavement at time of treatment application. • Treatment material properties. – Engineering and thermal properties (e.g., Poisson's ratio, dynamic modulus, tensile strength, creep compliance, thermal conductivity, heat capacity, surface shortwave absorptivity, coefficient of thermal contraction). – Volumetric properties (e.g., air voids, effective asphalt content, voids filled with asphalt, mix density, asphalt binder grade/viscosity. • Effect of treatment on existing pavement structure (e.g., removal depth of existing HMA surface [milling], treatment application thickness, layer interface condition [degree of bond between treatment and existing HMA surface]). • Effect of treatment (short- and long-term) on existing HMA surface layer material properties. – Engineering and thermal properties (same as above). – Volumetric properties (same as above). • Effect of treatment (short- and long-term) on moisture and thermal profile of existing pavement. – Drainage/infiltration potential, cross-slope and drainage path length, surface shortwave absorptivity.
Performance Modeling Parameters	• Immediate adjustment of post-treatment performance levels. – Post-treatment distress/smoothness measurements. • Long-term adjustment of post-treatment distress level via rate of redevelopment of distresses/smoothness. – Reflection cracking (of fatigue and thermal cracks in existing flexible pavement)—data for defining *a* and *b* model parameters (essentially treatment thickness) and data for defining *d* model parameter, which governs the acceleration ($d > 1$) or delay ($d < 1$) in the formation of reflective cracks.

Note: IRI = International Roughness Index.

database, and any type of MEPDG design/materials database was then determined. A suitability rating was assigned to each state for each approach; the results were used to select five states (Indiana, Minnesota, Missouri, North Carolina, and Texas) for a detailed investigation of data availability. An electronic survey of these states was then conducted to identify the data that could be used to develop the proposed approaches; the responses were compiled and summarized. (Details are provided in Appendix G.)

Appropriateness of Available Data: The information obtained regarding the availability and reliability of data was evaluated for each of the key data elements. A score of 1 through 5 was assigned for each element, with a score of 1 denoting a lack of data to support the development of the proposed approach and a score of 5 denoting good overall availability of useful data. (Details are provided in Appendix G.) The overall scores indicated that the development and validation of approaches for incorporating preservation in the MEPDG process are not currently feasible. As a result, the research was focused on preparing detailed processes for three approaches and illustrating processes for their implementation. These processes are described in the following chapters.

CHAPTER 4

Developing Response Models for Considering the Effects of Preservation in the MEPDG Procedures

In this approach, test sections of preservation treatments or strategies are constructed and monitored, and the obtained data are analyzed in order to develop pavement response models and distress transfer functions associated with those treatments or strategies. The test sections consider a range of pavement and surface material types, a range of traffic loadings and climatic conditions, and different treatment types and strategies, and include pavements that receive no treatments after initial construction (until rehabilitation) to serve as controls.

Process Description

Several steps are required to develop response models that consider the effects of preservation on pavement performance.

1. *Treatment and Strategy Selection:* The various preservation treatments or strategies and the related performance objectives are identified. Since the MEPDG evaluates pavement condition in terms of ride, rutting, cracking, and faulting, preservation treatments that influence these parameters are considered. Table 6 lists examples of suggested preservation treatments for addressing specific objectives and the affected performance measures (Peshkin et al. 2004).
2. *Experimental Design Development:* An experimental design is developed that includes the range of relevant variables (e.g., pavement type, treatment and strategy types, traffic, environment, treatment timings). The experimental design should take into consideration recently constructed pavements that have received no preservation treatments but on which preservation treatments will be applied at a later time and also should consider the following key elements (Peshkin et al. 2004):
   - Site selection: Pavement type, pavement design, existing pavement condition, pavement age, traffic level, and climate condition.
   - Treatment types: Selected treatments to address different pavement preservation objectives.
   - Treatment timing: Varied treatment application timing to consider the effects of existing pavement condition on treatment performance (i.e., when to apply the first treatment and how often subsequent treatments are applied).
   - Site layout: Project length, section length, and replicate sections.
   - Experiment duration: Depending on the type of treatment (e.g., a few years for crack sealing or fog sealing or several years for thin overlay or diamond grinding).

   The experimental design could range from one test site representing a specific pavement design, climatic zone, and traffic level to multiple test sites encompassing different pavement designs subjected to different traffic levels and climates. One or more similar or different preservation treatments applied at similar or different times after construction (except for control sections that remain untreated) may be considered.
3. *Test Section Construction:* A combination of existing pavements and new test sections that meet the requirements of the experimental design are constructed according to specific requirements.
4. *Performance Monitoring:* Test sections (including control sections) are monitored on at least an annual basis using either manual or automated condition surveys (more frequent performance monitoring might be necessary for some treatments). The performance evaluation of HMA pavements should include block cracking, fatigue cracking, linear cracking, rutting, bleeding, raveling, weathering (oxidation), polished aggregate, potholes, and patching, and the evaluation of PCC pavements should include corner breaks, linear cracking, joint seal damage, joint spalling, joint faulting, pumping, blowups, and patching (Peshkin et al. 2004). Measurement of surface friction, surface texture, and tire-pavement noise performance may be considered because preservation treatments are frequently applied to address these pavement surface characteristics.

Table 6. Preservation treatment and performance objectives.

Preventive Maintenance Objective	Preservation Treatments		Performance Measure/ Condition
	HMA Pavements	PCC Pavements	
Improve Ride	SlS, MS, thin HMAOL, UTBWC	DG	IRI
Extend Pavement Life	CrS, FS, ScS, ChS, SlS, MS, thin HMAOL, UTBWC	CrS, JRS, DG	Cracking, patching, rutting, raveling, faulting, pumping, spalling, potholes
Reduce Moisture Infiltration	CrS, FS, ScS, ChS, SlS, MS, thin HMAOL, UTBWC	CrS, JRS	Cracking, patching, rutting, raveling, faulting, pumping, spalling, potholes

Notes: CrS = crack seal, FS = fog seal, SlS = slurry seal, ScS = scrub seal, ChS = chip seal, MS = microsurfacing, HMAOL = HMA overlay, UTBWC = ultrathin bonded wearing course, JRS = joint resealing, DG = diamond grinding, IRI = International Roughness Index.

5. *Performance Models Development:* Performance prediction models are developed for the various pavement preservation treatments or strategies using the data obtained from the preservation test sections to supplement the MEPDG models. The models should consider the effects of climate, traffic loading, material properties, and existing pavement condition. The NCHRP Project 1-37A Final Report (ARA, Inc. 2004) describes and illustrates the model forms and variables used to develop acceptable performance models.
6. *Model Calibration and Validation:* In this final step, the developed performance models are calibrated and validated using the procedures identified in the AASHTO *Guide for the Local Calibration of the Mechanistic-Empirical Pavement Design Guide* (herein referred to as the *Local Calibration Guide*) (AASHTO 2010). The calibration process should recognize that preservation treatments can affect the structural properties and thermal/moisture conditions of the existing pavement and the material properties of the top pavement layer; these will affect the computed stresses and strains. Preservation treatment thickness (or removal depth, in the case of milling/grinding) from design or as-built records, thermal/moisture profile data from instrumented pavements, and pavement structure material property data from non-destructive testing (NDT) may be used to adjust layer thicknesses, temperatures, water contents, or material properties to reflect treatment application. The calibration process will result in revised coefficients for either or both the load-response model and distress transfer function associated with a particular performance indicator.

Feasibility Assessment

Developing pavement preservation response models provides a comprehensive framework for accounting for the effects of preservation treatments or strategies on pavement performance (both structural and functional) but requires an extensive experimental investigation and long-term data collection effort. The design analysis requires a modified Pavement ME Design software program that includes new models to supplement the current MEPDG models and new programming code and input screens for defining the possible treatments or strategies and details (e.g., thicknesses and properties of treatments and the criteria for their application). Implementing this approach requires the development of a detailed experimental design, the identification of locations for test sections (including untreated control sections), the application of preservation treatments, and the collection of performance monitoring data over several years. Also, it requires the development of a database of relevant information (e.g., preservation treatments or strategies, traffic conditions, climate conditions, pavement performance measures) and a significant data analysis and modeling effort to develop performance prediction models. The approach can also be used to develop models for surface defects (e.g., raveling and deformation distresses) and pavement surface characteristics (e.g., friction and noise) that are not considered in the MEPDG.

Because of the requirement for long-term performance monitoring and data collection, this approach is likely to be implemented as part of a national research effort or a multiagency cooperative research program. However, it can also be implemented under an agency-wide effort. An example illustrating the process of developing pavement preservation response models is presented in the following.

Example of Implementation Process

The Indiana Department of Transportation (INDOT) is one of a few agencies that have constructed MEPDG-designed pavements or pavements specifically intended for additional performance model calibration. INDOT has completed over 100 paving projects since 2009 using the MEPDG design analysis procedure (Nantung 2010). The projects included both flexible and rigid designs located on roads throughout the state ranging from Interstates to moderately trafficked U.S.

and state routes to low-volume state routes. Data from these projects are used in a hypothetical example to illustrate the development of pavement preservation response models for conventional and full-depth HMA pavements treated with a single application of chip seals, microsurfacing, or thin HMA overlay. This follows the process described in this chapter and incorporates certain assumptions.

Step 1: Preservation Treatment and Performance Model Selection

The flexible pavements considered in this example were designed according to the MEPDG procedures. Preservation treatments, such as a single application of chip seals, microsurfacing, or thin HMA overlay, are considered. Table 7 shows the key performance objectives for each treatment and the associated application criteria. Models for predicting rutting, transverse thermal cracking, alligator cracking, longitudinal cracking, International Roughness Index (IRI), raveling/weathering, and friction will be considered.

Step 2: Experimental Design Development

Considering the two distinct climates available in Indiana: wet, hard freeze, and spring thaw (northern half of state) and wet, freeze-thaw cycling (southern half of state), the matrix shown in Table 8 has been proposed to serve as the experimental design. It includes six test sites, designated Test Sites 1 through 6, each of which will include 20 test sections (two replicates of each of the nine preservation sections and the untreated control section). The experimental design also identifies the preservation treatments proposed for each site and their time of application.

Step 3: Test Site Identification and Construction

From the many flexible pavement projects that were designed and constructed in recent years using the MEPDG, several projects with sufficient length to accommodate the planned 20 test sections have been identified as candidates for Test Sites 1 through 5; no projects were identified for Test Site 6. However, a review of the design and construction/materials data for these projects revealed that candidate projects for Test Site 1 lacked the materials/construction data needed for analysis and model building. Therefore, Test Site 1 was eliminated from the experiment design, and the matrix was modified to include only four test sites (Test Sites 2 through 5).

The four most appropriate projects were selected to serve as Test Sites 2 through 5. These projects were constructed in 2010 and 2011. The design and construction/materials data for these pavements were compiled. According to the schedule for preservation treatment application given in the experimental matrix, these treatments will be applied between 2014 and 2019 (first treatment will be applied in 2014 as a 4-year treatment for pavements built in 2010, and last treatment will be applied in 2019 as an 8-year treatment for pavements built in 2011). Table 9 shows the revised experimental design matrix.

Test section limits were established within each site with consideration given to construction/materials data and other relevant items.

The preservation treatments listed in Table 9 for the different test sections will be constructed between 2014 and 2019. Treatment design and construction/materials data (including weather conditions) will be collected, reviewed, and compiled for use in the performance model development.

Table 7. INDOT HMA pavement preventive maintenance treatments (INDOT 2011).

Treatment	AADT[1]	Existing Pavement Distress	Rutting, in.	IRI, in./mi	Friction Treatment?	Surface Aging
Crack Seal	Any	Low to moderately severe surface cracks	N/A	N/A	No	N/A
Fog Seal	<5,000[2]	Low-severity environmental surface cracks	N/A	N/A	No[3]	Reduces aging and oxidation, arrests minor raveling
Seal Coat (i.e., Chip Seal)	<5,000[2]	Low-severity environmental surface cracks	<0.25[4]	N/A[4]	Yes	Arrests aging, oxidation, and minor raveling
Microsurfacing	Any	Low-severity surface cracks	Any	<130	Yes	Arrests aging, oxidation, and minor raveling
UBWC	Any	Low to moderately severe surface cracks	<0.25	<140	Yes	Arrests aging, oxidation, and moderate raveling
HMA Inlay	Any	Low to moderately severe surface cracks	Any	<150	Yes	Replaces aged, oxidized, or raveled surface
HMA Overlay	Any	Low to moderately severe surface cracks	Any	<150	Yes	Arrests aging, oxidation, and moderate raveling

Notes: [1] For mainline pavement. [2] Unless traffic can be adequately controlled. [3] Treatment may reduce skid numbers. [4] Treatment does not address this. N/A = not applicable. AADT = average annual daily traffic.

Table 8. Proposed experimental design matrix.

Climate Zone	Preservation Treatment	Flexible Pavements		
		Conventional HMA	Full-Depth HMA	
		Low-Volume State Routes	Moderate Volume U.S. and State Routes	Interstate and Freeway Routes
1 (Wet, Hard Freeze, and Spring Thaw)	(0) Untreated control	Site 1	Site 2	Site 3 (chip seals excluded)
	(1a) Chip seal @ Year 4			
	(1b) Chip seal @ Year 5			
	(1c) Chip seal @ Year 6			
	(2a) Microsurface @ Year 4			
	(2b) Microsurface @ Year 5			
	(2c) Microsurface @ Year 6			
	(3a) Thin HMA OL @ Year 4			
	(3b) Thin HMA OL @ Year 5			
	(3c) Thin HMA OL @ Year 6			
2 (Wet, Freeze-Thaw Cycling)	(0) Untreated control	Site 4	Site 5	Site 6 (chip seals excluded)
	(1a) Chip seal @ Year 4			
	(1b) Chip seal @ Year 6			
	(1c) Chip seal @ Year 8			
	(2a) Microsurface @ Year 4			
	(2b) Microsurface @ Year 6			
	(2c) Microsurface @ Year 8			
	(3a) Thin HMA OL @ Year 4			
	(3b) Thin HMA OL @ Year 6			
	(3c) Thin HMA OL @ Year 8			

Note: HMA OL = HMA overlay.

Table 9. Revised experimental design matrix.

Climate Zone	Preservation Treatment	Flexible Pavements		
		Conventional HMA	Full-Depth HMA	
		Low-Volume State Routes	Moderate Volume U.S. and State Routes	Interstate and Freeway Routes
1 (Wet, Hard Freeze, and Spring Thaw)	**Site Description:**	**Site 1—No project available**	**Site 2—U.S. 24 Phase 2, Fort Wayne 2011**	**Site 3—Airport Expressway @ I-465, Indianapolis 2010**
	(0) Untreated control		✓	✓
	(1a) Chip seal @ Year 4		✓	
	(1b) Chip seal @ Year 5		✓	
	(1c) Chip seal @ Year 6		✓	
	(2a) Microsurface @ Year 4		✓	✓
	(2b) Microsurface @ Year 5		✓	✓
	(2c) Microsurface @ Year 6		✓	✓
	(3a) Thin HMA OL @ Year 4		✓	✓
	(3b) Thin HMA OL @ Year 5		✓	✓
	(3c) Thin HMA OL @ Year 6		✓	✓
2 (Wet, Freeze-Thaw Cycling)	**Site Description:**	**Site 4—SR 66, Evansville 2010**	**Site 5—SR 641, Terre Haute 2010**	**Site 6—No project available**
	(0) Untreated control	✓	✓	
	(1a) Chip seal @ Year 4	✓	✓	
	(1b) Chip seal @ Year 6	✓	✓	
	(1c) Chip seal @ Year 8	✓	✓	
	(2a) Microsurface @ Year 4	✓	✓	
	(2b) Microsurface @ Year 6	✓	✓	
	(2c) Microsurface @ Year 8	✓	✓	
	(3a) Thin HMA OL @ Year 4	✓	✓	
	(3b) Thin HMA OL @ Year 6	✓	✓	
	(3c) Thin HMA OL @ Year 8	✓	✓	

Notes: HMA OL = HMA overlay. Shaded cells indicate no test sections (suitable projects not available).

Step 4: Performance Monitoring and Database Development

A condition data collection protocol was developed to record annual measurements of rutting, transverse thermal cracking, alligator cracking, longitudinal cracking, IRI, raveling/weathering, friction, and macrotexture (as a supplement to friction). Also, a falling weight deflectometer (FWD) testing plan to evaluate pavement structural response before and after the application of preservation treatments was also developed.

The DOT will monitor test site conditions and collect the required data, according to the data collection protocol, for several years following the placement of the preservation treatments. These data, together with the data collected during construction, will be reviewed for completeness and accuracy and will be compiled into a database.

Step 5: Develop Performance Models

As sufficient time-series performance data become available from the test sections, performance prediction models and distress transfer functions will be developed for both the untreated control pavements and the preservation-treated pavements. Also, raveling and friction models will be developed. The raveling models will consider asphalt binder grade/viscosity and content, aggregate type, air voids in the HMA mixture, pavement age, axle load repetitions, thermal conductivity, surface shortwave absorptivity, and average annual freezing index. The friction models will consider variables such as aggregate type and polish susceptibility, aggregate gradation, asphalt binder grade/viscosity, effective asphalt binder content, pavement age, and axle load repetitions.

Step 6: Model Calibration and Validation

The procedures identified in the *Local Calibration Guide* (AASHTO 2010) will be used to calibrate and validate the models developed for each performance parameter. The original pavement structure data, treatment application thickness data, and before-and-after deflection data from FWD testing will be used to modify appropriate parts of the models (e.g., layer thicknesses, material properties, moisture contents, temperatures) to reflect the effects of preservation treatment application. For example, the HMA layer rut depth model is adjusted to reflect the post-treatment effect on HMA layer thickness, depth confinement factor, and mix layer temperature. Similarly, the alligator and longitudinal cracking model is adjusted to reflect the post-treatment effect on HMA layer thickness and dynamic modulus. This process results in a unique set of calibration coefficients for each preservation treatment (in addition to the calibration coefficients for the control pavement).

CHAPTER 5

Calibrating MEPDG Models to Account for Preservation

This approach considers pavement preservation by calibrating the MEPDG local models. Calibration is a systematic process for eliminating any bias and minimizing the residual errors between observed or measured results from the real world and predicted results from the model (AASHTO 2010). The approach assumes that the MEPDG distress prediction models do not account for the effects of pavement preservation and that these effects can be considered by modifying the calibration coefficients. The modified calibration process lends itself to models that directly calculate the magnitude of distress from pavement response (e.g., rutting) and those that calculate the incremental damage index from pavement response and then use a transfer function to convert damage to a distress type (e.g., fatigue cracking).

Preservation-based calibration requires a sufficient amount of performance data for pavements subjected to a specific preservation treatment or strategy (preferably on a variety of sites subjected to different levels of climate, traffic, etc.). These data are used to recalibrate the performance prediction models (e.g., roughness, rutting, cracking, and faulting) to account for the effect of the treatment or strategy using the procedures described in the AASHTO *Local Calibration Guide* (AASHTO 2010). The performance data derived from either in-service pavement sections or test sections specifically constructed and monitored are used in this calibration.

The calibration procedure considers the coefficients and exponents of the MEPDG flexible and rigid pavement transfer functions or distress/smoothness models and adjusts one or more of these coefficients to result in better agreement between predicted and observed distress/smoothness (Kim et al. 2011). Although preservation treatments may affect other surface condition parameters (e.g., raveling, bleeding, segregation, distortions) and performance indicators (e.g., friction, noise), this approach only addresses the effects of treatments on the performance prediction models included in the MEPDG.

The preservation-based local calibration effort requires developing input values for the selected pavement/test sections and performing multiple runs of the AASHTOWare Pavement ME Design software. The process will then establish a unique set of calibration parameters (k, β, and C) for use in the MEPDG models to better reflect the performance of specific preservation-treated pavements. Figure 5 illustrates the calibration effect using smoothness as an example. The IRI values predicted by the MEPDG (default) model are mostly greater than the measured IRI values (overprediction), and the amount of overprediction increases as IRI increases. Also, there is a wide amount of scatter (high variability/error) in the linear trend line fitted through the predicted versus measured data points. Calibrating the model using the data for the preservation-treated sections will account for the effect of preservation more appropriately.

Tables 10 and 11 list the calibration parameters of the MEPDG flexible and rigid pavement transfer functions or distress/smoothness models and their default values as given in the AASHTOWare Pavement ME Design software program. These parameters, typically considered in the local calibration process, will be used in the preservation-based model calibration procedure.

The preservation-based model calibration can be performed using one of four approaches detailed in the *Local Calibration Guide* (AASHTO 2010):

- *Full Sample:* All sections (i.e., n data sets) are used in the calibration process; no sections remain for validation.
- *Traditional Split Sample:* A portion of the total number of sections (usually more than half) is used to calibrate the models; the remainder is used to validate model accuracy.
- *Jackknife testing:* A rolling set of calibrations and validations are performed using n-1 data sets.
- *Split-Sample Jackknife Testing:* A combination of split-sample testing and jackknife testing is performed that uses an n/2 jackknifing scheme.

Process Description

The process for calibrating the MEPDG models to account for preservation effects, as summarized in the following, is similar to the process for calibrating MEPDG models to local

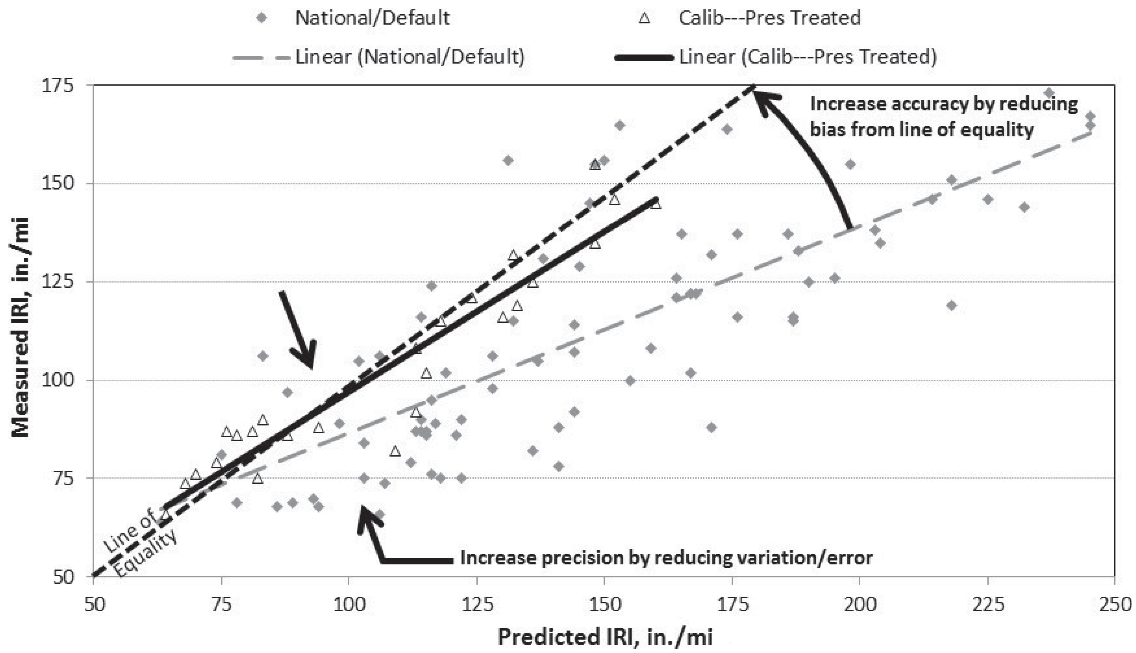


Figure 5. Illustration of effect of model calibration on accuracy of performance prediction.

conditions described in the AASHTO *Local Calibration Guide* (AASHTO 2010).

1. *Select Hierarchical Input Level for Each Input Parameter:* The level for each input parameter is selected considering field and laboratory testing capabilities, material/construction specifications, and traffic data collection procedures/equipment. Different input levels are likely to be selected for different input parameters.
2. *Develop Experimental Plan or Sampling Template:* A detailed, statistically sound experimental matrix is developed to represent the different conditions, materials, and

Table 10. Calibration parameters for flexible pavement transfer function (AASHTO 2010).

Distress		Eliminate Bias	Reduce Standard Error
Total Rutting	Unbound Materials[1] and HMA Layers	$k_{r1} = -3.35412$ $\beta_{r1} = 1$ $\beta_{s1} = 1$	$k_{r2} = 1.5606$ $k_{r3} = 0.4791$ $\beta_{r2} = 1$ $\beta_{r3} = 1$
Load-Related Cracking	Bottom-Up Alligator Cracking	$k_{f1} = 0.007566$ $C_2 = 1$	$k_{f2} = 3.9492$ $k_{f3} = 1.281$ $C_1 = 1$
	Top-Down Longitudinal Cracking	$k_{f1} = 0.007566$ $C_2 = 3.5$	$k_{f2} = 3.9492$ $k_{f3} = 1.281$ $C_1 = 7$
	Semi-Rigid Pavements (CTB layer)	$\beta_{c1} = 1$ $C_2 = 1$	$C_1 = 1$ $C_2 = 1$ $C_4 = 1{,}000$
Non-Load-Related Cracking	Transverse Thermal Cracking	$\beta_{t3} = 1$ $k_{t3} = 1.5$	$\beta_{t3} = 1$ $k_{t3} = 1.5$
Smoothness/IRI		$C_4 = 0.015$ (new/reconstructed HMA) $C_4 = 0.00825$ (HMA overlay)	$C_1 = 40$ (new/reconstructed HMA) $C_1 = 40.8$ (HMA overlay) $C_2 = 0.4$ (new/reconstructed HMA) $C_2 = 0.575$ (HMA overlay) $C_3 = 0.008$ (new/reconstructed HMA) $C_3 = 0.0014$ (HMA overlay)

Notes: Unless otherwise noted, the calibration coefficients pertain to both new/reconstructed HMA pavements and HMA overlays. CTB = cement-treated base. [1] Includes unbound materials for base, subbase, and subgrade layers.

Table 11. Calibration parameters for rigid pavement transfer function (AASHTO 2010).

Distress		Eliminate Bias	Reduce Standard Error
JPC Transverse Joint Faulting		$C_1 = 1.0184$	$C_1 = 1.0184$
JPC Slab Cracking		$C_1 = 2$ $C_4 = 1$	$C_2 = 1.22$ $C_5 = -1.98$
CRC Punchouts	Fatigue	$C_1 = 2$	$C_2 = 1.22$
	Punchouts	$C_3 = 216.842$	$C_4 = 33.1579$ $C_5 = -0.58947$
	Crack Widths	$C_6 = 1$	$C_6 = 1$
Smoothness/IRI	JPC	$J_4 = 25.24$	$J_1 = 0.8203$
	CRC	—	$C_1 = 3.15$ $C_2 = 28.35$

Note: Unless otherwise noted, the calibration coefficients pertain to both new/reconstructed JPC/CRC pavements and JPC/CRC overlays.

practices. The experimental matrix would ideally include key factors, such as design type (i.e., new/reconstructed, rehabilitation), pavement type/design (e.g., conventional HMA pavement, HMA overlay on existing PCC pavement), preservation strategy (e.g., preservation with one-time application of a specific treatment type, preservation with multiple treatment applications, no preservation), traffic level or facility type, and climate. The availability of sufficient in-service or experimental test sections (both treated with preservation and not treated) is required. An example of such an experimental matrix is shown in Table 12.

3. *Estimate Sample Size for Specific Distress Prediction Models:* The sample size or number of pavement sections needed to verify/calibrate the coefficients needs to be determined. Both the bias and precision of the prediction models are considered, and a level of significance (typically 90%) must be selected to determine the required sample size. Generally, some sections are used to calibrate all models, and replicate sections are used to provide an estimate of the pure

Table 12. Example experimental/sampling matrix for preservation-based local calibration.

Pavement Type/Design	Preservation Treatment/Strategy	Interstate and Major Arterial Routes		Minor Arterial Routes	
		Climate 1	Climate 2	Climate 1	Climate 2
New/Reconstructed Conventional HMA	(0) Untreated control				
	(1a) Treatment A @ Year 3				
	(1b) Treatment A @ Year 4				
	(2) Treatment B @ Years 3 and 6				
	(3) Treatment B @ Year 3 and Treatment C @ Year 6				
New/Reconstructed Deep-Strength HMA	(0) Untreated control				
	(1a) Treatment A @ Year 4				
	(1b) Treatment A @ Year 5				
	(2) Treatment B @ Years 4 and 8				
	(3) Treatment B @ Year 4 and Treatment C @ Year 8				
HMA Overlay on Existing Flexible Pavement	(0) Untreated control				
	(1) Treatment A @ Year 4				
	(2) Treatment B @ Year 4				
	(3) Treatment C @ Year 4				
HMA Overlay on Existing Rigid Pavement	(0) Untreated control				
	(1) Treatment A @ Year 3				
	(2) Treatment C @ Year 3				
	(3) Treatment D @ Year 3				

error. The suggested minimum numbers of sections for analysis of each distress type over the entire experimental/sampling matrix are as follows (AASHTO 2010):

- Distortion (rutting, joint faulting): 20 sections.
- Load-related cracking (bottom-up alligator and top-down longitudinal cracking, transverse slab cracking): 20 sections.
- Non-load–related cracking (transverse thermal cracking): 26 sections.
- Reflection cracking: 26 sections.

A more refined estimate of the sample size requirements can be obtained using the following equations (AASHTO 2010):

$$n = \left(\frac{Z_{\alpha/2} \times \sigma}{e_t} \right)^2 \qquad \text{Eq. 1}$$

$$e_t = Z_{\alpha/2} \times S_e \qquad \text{Eq. 2}$$

where:

n = Minimum number of sections required for a given distress/IRI prediction model calibration/validation.

$Z_{\alpha/2}$ = 1.601 for a 90% confidence interval.

σ = Performance indicator threshold/design criteria (to be selected by the agency; typical values include 0.4 in. for rutting, 20% for fatigue cracking, 1,500 ft/mi for transverse thermal cracking, 10% for slab cracking, 0.1 in. for joint faulting, and 130 in./mi for roughness).

e_t = Tolerable bias at 90% reliability.

S_e = Standard error of estimate (reasonable values include 0.1 in. for rutting, 7% for alligator cracking, 600 ft/mi for longitudinal cracking, 250 ft/mi for transverse thermal cracking, 7% for slab cracking, 0.05 in. for joint faulting, and 18 in./mi for roughness).

The same test sections could be used for calibrating multiple models to keep the number of sections to a minimum. Also, because IRI is a function of the other distresses, calibrating the IRI model using the same sections used for calibrating the model requiring the largest sample size would be desirable.

The experimental matrix can be developed if an adequate number of sections with the required types and ranges of performance data are available. Otherwise, other options must be considered, such as combining LTPP or other test sections with the available sections, limiting the analysis only to those factors represented by the available sections, or expanding the acceptable range for some input parameters. In the situations where recently constructed sections are included and no or limited performance data are available, calibrations can be performed at a future time when the required data have become available.

4. *Select Roadway Segments:* In-service pavement or test sections (e.g., LTPP sections) appropriate to fill the cells in the experimental matrix are identified. Although some consideration should have been given to performance data, sections that have at least three time-series distress/smoothness data points (from condition surveys) covering a 10-year period are generally required (AASHTO 2010). However, for preservation-treated sections, at least four time-series points (two points prior to the preservation treatment and two points after) and at least a 5-year period following the preservation treatment are desired.
5. *Extract and Evaluate Distress and Project Data:* The data needed to conduct MEPDG design runs for the cells of the experimental/sampling matrix (herein referred to as analysis cells) are collected and examined. It is necessary to ensure that the collected distress/smoothness data (likely obtained from the agency PMS database) are consistent with the formats used by the MEPDG. Discrepancies in the data formats may be addressed by developing and applying conversion equations or algorithms. Another important consideration is ensuring that the pavement sections cover a range of data for a particular distress and smoothness. It is generally recommended that the average maximum distress/roughness level for the sections exceed 50% of the design criteria (AASHTO 2010). For example, for a rutting design threshold of 0.75 in., the average maximum rut depth for the sections should be at least 0.375 in. Gaps in data should be identified and addressed.
6. *Conduct Field and Forensic Investigations:* The data needed to fill the identified gaps are obtained. This may be done by conducting field or laboratory investigations (pavement surveys and/or forensic testing of materials and pavement structure), reviewing construction practices and specifications, or by other means.
7. *Assess Bias:* Distress/smoothness for each analysis cell in the experimental matrix is predicted from MEPDG design runs using the MEPDG default calibration factors. (Details are provided in Appendix C.) The predicted values (at a 50% reliability level) for a set of cells representing a particular treatment type/strategy are then plotted and compared to the measured values, and the bias and standard error of the estimate for each particular distress/smoothness model are determined.

Figure 6 illustrates examples of predicted versus measured rut depth for asphalt pavements with different mixes. The need for calibrating a specific model is determined from null hypothesis statistical testing of a paired t-test

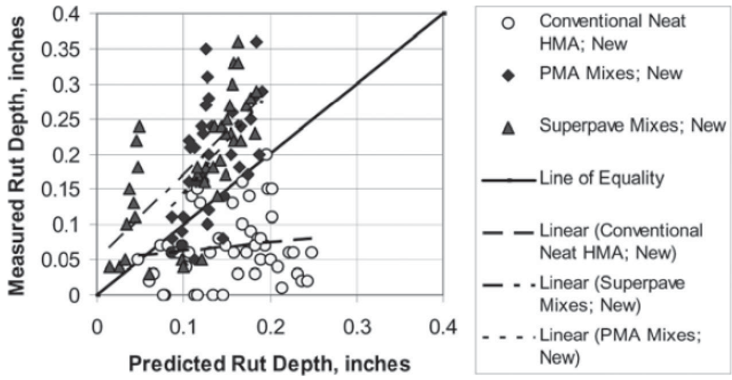


Figure 6. Example plot of predicted versus actual distress (AASHTO 2010).

that determines if there is a significant difference between sets of measured and predicted distress/smoothness and from an analysis of the intercept and slope estimates in the measured versus predicted linear regression model. In the example shown in Figure 6, the trend lines of the three data sets are statistically analyzed to determine if they are significantly biased in relation to the line of equality, which represents perfect prediction accuracy; calibration of the prediction model is required only if the trend line is found to be statistically different.

Model prediction capability is assessed by performing a linear regression of the measured (y) and predicted (x) values (model form $y_i = b_o + m(x_i)$, where b_o is the y-intercept and m is the slope) and computing the coefficient of determination (R^2). In general, models with R^2 values above 65% are considered to have good prediction capabilities, and those with values below 50% are considered to have poor prediction capabilities. A poor correlation indicates the need for calibration.

Model accuracy is estimated by means of the standard error of the estimate (S_e), which is computed as the square root of the average squared error of prediction. The reasonableness of S_e can be compared with the S_e values obtained from the national/global model calibration (Titus Glover and Mallela 2009); these values are shown in Table 13.

Model bias (e_r) is determined through the following series of hypothesis testing (AASHTO 2010):

- Hypothesis 1: There is no bias or systematic difference between the measured and predicted values of distress/smoothness. A paired t-test is performed to test the following null (H_0) and alternative (H_A) hypotheses:
  - H_0: $\Sigma(y_{measured} - x_{predicted}) = 0$, where $y_{measured}$ equals the measured value, and $x_{predicted}$ equals the predicted value from the model.
  - H_A: $\Sigma(y_{measured} - x_{predicted}) \neq 0$.
- Hypothesis 2: The linear regression model developed using measured and predicted distress/smoothness has

Table 13. Statistics for new asphalt concrete (AC) and JPC pavements performance prediction models (Titus Glover and Mallela 2009).

Pavement Type	Performance Model	Model Statistics		
		Coefficient of Determination, R^2	Standard Error of Estimate, S_e	Number of Data Points, N
New HMA	Alligator cracking	0.275	5.01%	405
	Transverse thermal cracking	Level 1*: 0.344 Level 2*: 0.218 Level 3*: 0.057	—	—
	Rutting	0.58	0.107 in.	334
	IRI	0.56	18.9 in./mi	1,926
New JPC Pavement	Transverse slab cracking	0.85	4.52%	1,505
	Transverse joint faulting	0.58	0.033 in.	1,239
	IRI	0.60	17.1 in./mi	163

Note: * Level of inputs used for calibration.

an intercept of zero. Statistics from the linear regression analysis are examined to test the following null and alternative hypotheses:

- H_0: $b_o = 0$.
- H_A: $b_o \neq 0$.

- Hypothesis 3: The linear regression model developed using measured and predicted distress/smoothness has a slope (m) of 1.0. Statistics from the linear regression analysis are examined to test the following null and alternative hypotheses:
  - H_0: $m = 1.0$.
  - H_0: $m \neq 1.0$.

If any of these null hypotheses are rejected, then the specific distress/smoothness prediction model should be recalibrated. If the null hypotheses are accepted (indicating no bias), the standard error of the estimate for the data set should be compared to the global calibration data set.

Figure 7 and Table 14 provide an example for a rutting model using hypothetical data for several full-depth HMA pavement/test sections, with and without preservation. Figure 7 compares the predicted (using the national calibration coefficients in the Pavement ME Design software) and measured values of total rutting for three sets of sections (untreated sections, sections treated with preservation type A, and sections treated with preservation type B). The figure shows that the overall (all sections combined) rutting model prediction capability is poor ($R^2 = 0.29$) but that the overall standard error of the estimate (S_e) for the model is lower than the national calibration coefficients (0.057 in. versus 0.107 in.). The results of hypothesis testing for overall model bias presented in the table show that each null hypothesis was rejected at the 10% significance level such that model recalibration is required to account for the effects of preservation or other factors.

Table 14 summarizes the results of similar testing performed for each individual set of sections (untreated, preservation A-treated, and preservation B-treated). Although some improvement was observed in the model prediction capability and S_e, each of these models was also shown to be locally biased (at least one of the three null hypotheses rejected) and requires recalibration.

8. *Eliminate Bias of Distress and IRI Prediction Models:* The cause of the bias, if it exists, is first determined through careful evaluation of the bias statistics. The bias that may exist for a given distress/smoothness model (e_r, S_e, residual errors [$y_{measured} - x_{predicted}$]) is then reduced or eliminated by running the Pavement ME Design software using adjusted calibration factors. The AASHTO *Local Calibration Guide* (AASHTO 2010) identifies the coefficients of the MEPDG models that should be targeted for bias adjustment.

The bias in the prediction mode is described in one of three scenarios (AASHTO 2010): (1) high precision and high bias, (2) low precision and low bias, or (3) low precision and high bias. Scenario 1 requires less effort to reduce the bias than Scenarios 2 and 3. Bias testing that

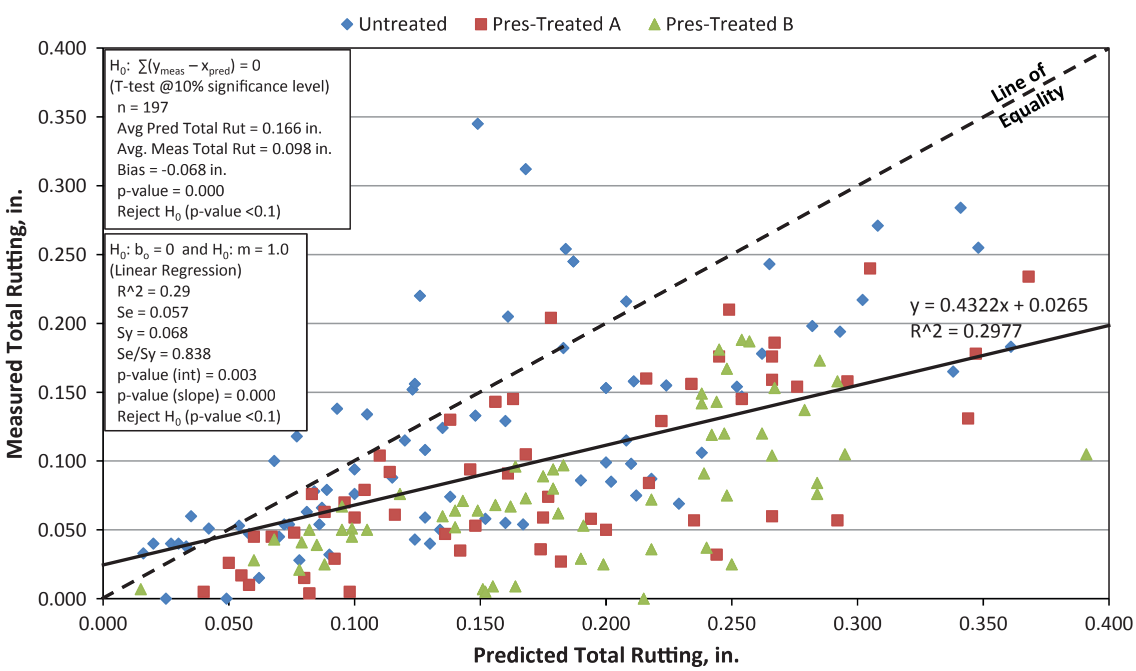


Figure 7. Hypothetical illustration of predicted versus measured total rut depth for full-depth HMA pavements.

Table 14. Bias statistics for a hypothetical rutting model.

Null Hypothesis	Parameter	Untreated Sections	Preservation A-Treated Sections	Preservation B-Treated Sections
	Number	81	55	61
	Avg. predicted rutting, in.	0.145	0.175	0.186
	Avg. measured rutting, in.	0.118	0.092	0.077
	Bias (e_r), in.	-0.027	-0.082	-0.109
	R^2	0.37	0.50	0.40
	S_e	0.061	0.045	0.039
H_0: $\Sigma(y_{measured} - x_{predicted}) = 0$	T-test p-value	0.001	0.000	0.000
	Accept/reject H_0	Reject	Reject	Reject
H_0: $b_o = 0$	Regression p-value (intercept)	0.002	0.974	0.934
	Accept/reject H_0	Reject	Accept	Accept
H_0: $m = 1.0$	Regression p-value (slope)	0.000	0.000	0.000
	Accept/reject H_0	Reject	Reject	Reject

Note: Hypothesis testing performed at 10% significance level.

focuses on traffic, climate, pre-treatment pavement condition, and treatment material/mix characteristics should provide a basis for adjusting the calibration coefficients. Tables 15 and 16 list the model coefficients that can be adjusted to reduce bias. Figures 8 and 9 show the Pavement ME Design program menu screens where the model calibration adjustments can be made for new flexible and new rigid pavements, respectively; similar menu screens are available in the program for HMA overlays and PCC rehabilitation treatments.

Different approaches have been used to adjust the model coefficients and improve prediction accuracy and reduce prediction bias. One frequently used approach involves performing numerous Pavement ME Design runs using a large factorial of values for key coefficients (e.g., β_{r2} and β_{r3} for rutting, β_{f2} and β_{f3} for fatigue cracking) and

Table 15. Summary of rutting model bias statistics for untreated and preservation-treated sections following bias elimination/reduction.

Null Hypothesis	Parameter	Untreated Sections	Preservation A-Treated Sections	Preservation B-Treated Sections
	Number	81	55	61
	Avg. predicted rutting, in.	0.131	0.112	0.080
	Avg. measured rutting, in.	0.118	0.092	0.077
	Bias (e_r), in.	-0.013	-0.019	-0.003
	R^2	0.79	0.93	0.89
	S_e	0.034	0.017	0.017
H_0: $\Sigma(y_{measured} - x_{predicted}) = 0$	T-test p-value	0.002	0.000	0.177
	Accept/reject H_0	Reject	Reject	Accept
H_0: $b_o = 0$	Regression p-value (intercept)	0.501	0.210	0.531
	Accept/reject H_0	Accept	Accept	Accept
H_0: $m = 1.0$	Regression p-value (slope)	0.000	0.000	0.000
	Accept/reject H_0	Reject	Reject	Reject

Note: Hypothesis testing performed at 10% significance level.

Table 16. Experimental/sampling matrix for Michigan preservation-based local calibration.

Pavement Type/Design	Preservation Treatment/Strategy	Interstate and Other Freeway Routes (NFC-1 and NFC-2)		Other Principal Arterial and Minor Arterial Routes (NFC-3 and NFC-4)	
		Climate Zone 1 (Severe)	Climate Zone 2 (Moderate)	Climate Zone 1 (Severe)	Climate Zone 2 (Moderate)
New/Reconstructed Flexible Pavement or HMA-Overlaid Flexible Pavement	(0) Untreated control	2	2	2	2
	(1) Double microsurfacing	2	2	2	2
	(2) Thin HMA overlay (1.5–2.0 in.)	2	2	2	2

then using Microsoft Excel Solver to determine the optimal values for all coefficients that give the smallest sum of squared error (SSE) between the predicted and measured distress/smoothness. Another approach involves optimizing all model coefficients simultaneously using the genetic algorithm (GA) optimization technique within MATLAB (Kim et al. 2011).

In the hypothetical example presented earlier, the untreated pavement group exhibits low precision and low bias, and the two preservation-treated groups exhibit high precision and high bias. After a detailed evaluation of the effects of different factors on bias, the rutting calibration coefficients (β_{s1}, β_{r1}, β_{r2}, β_{r3}) were modified to reduce the difference between measured and predicted rutting values; the resulting predicted versus measured plots are shown in Figure 10, and the corresponding bias statistics are listed in Table 15. Hypothesis testing still indicates an unacceptable level of bias for each group, but the prediction capability and accuracy of each has been greatly increased, and the bias has been greatly decreased.

9. *Assess the Standard Error of the Estimate:* The standard error of the estimate for each recalibrated model and each analysis cell is compared with reasonable values of the standard error of the estimate provided in the *MEPDG*

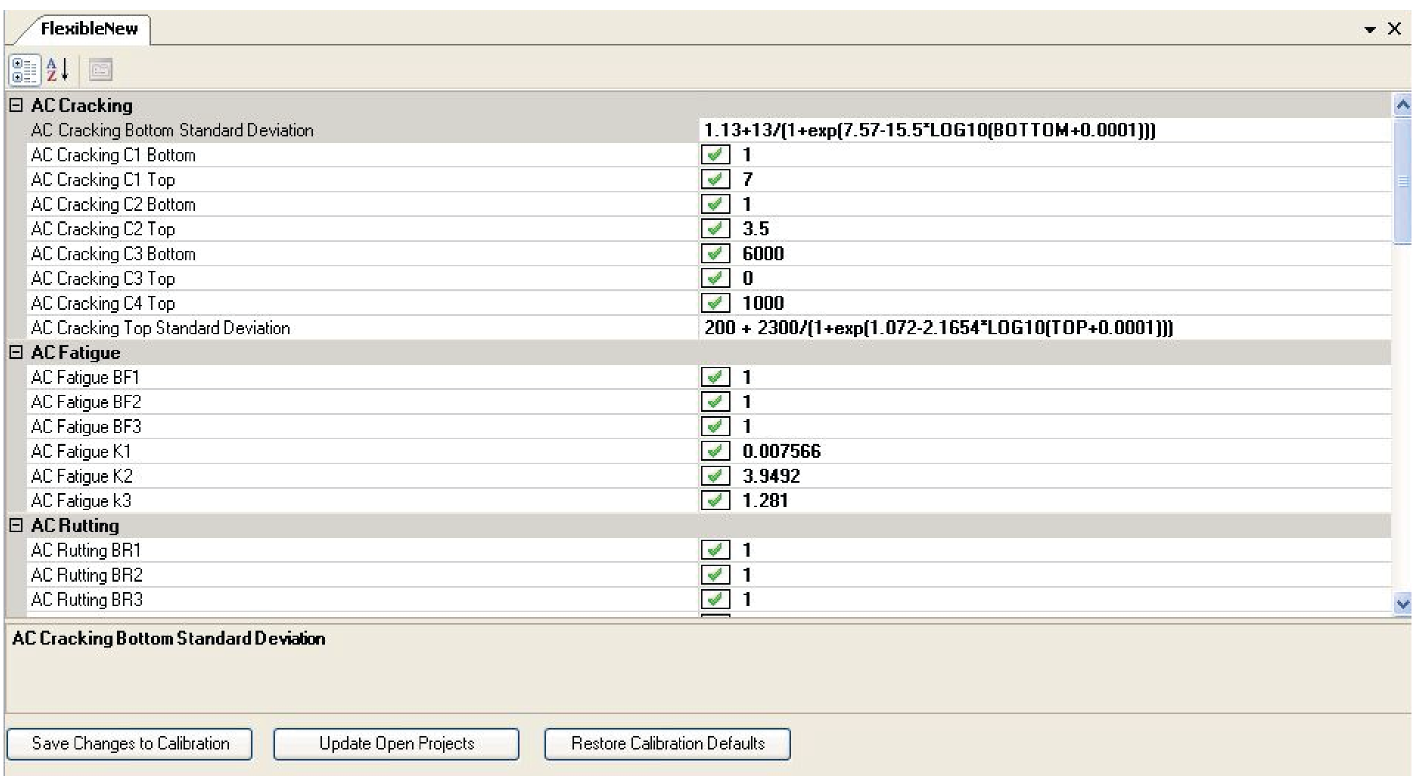


Figure 8. Distress model calibration settings—new flexible pavements.

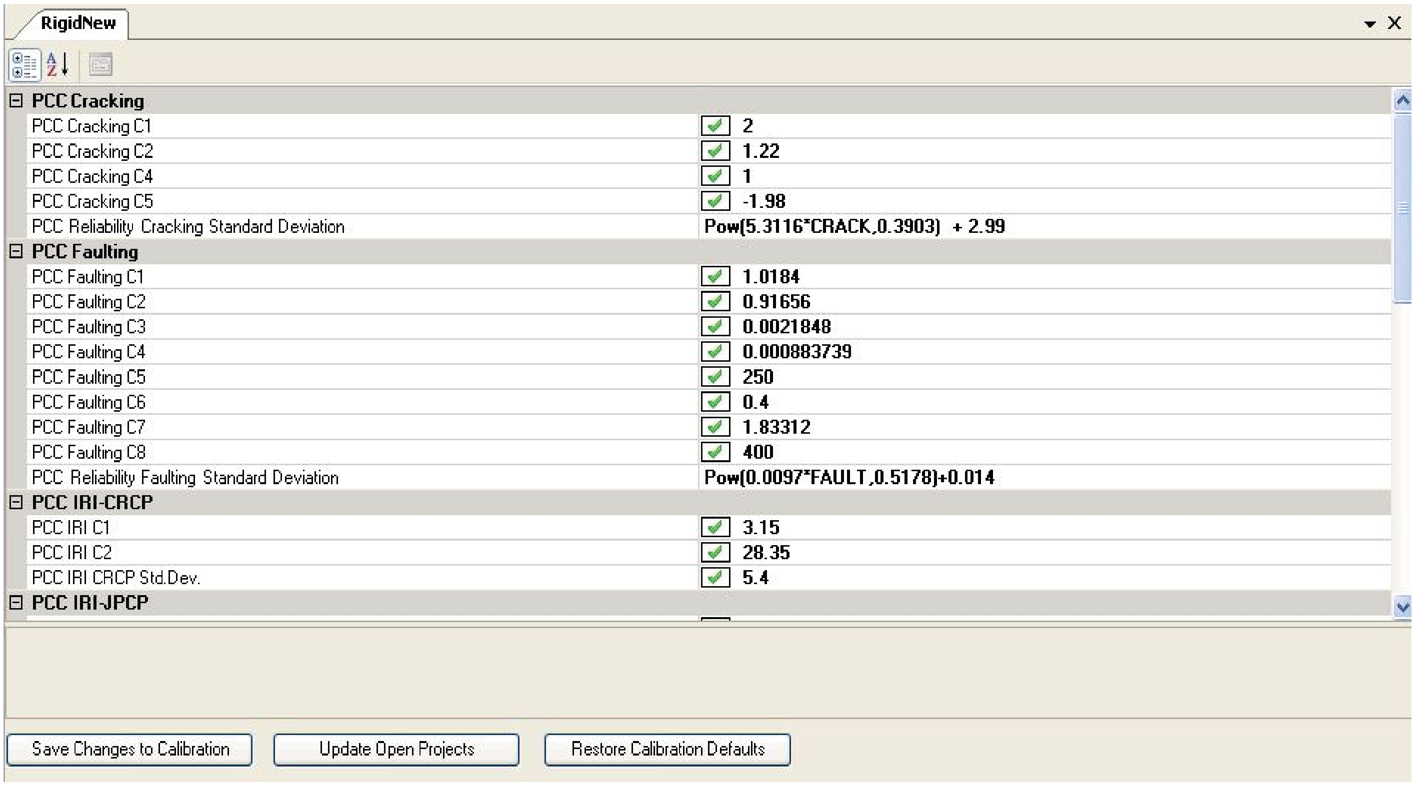
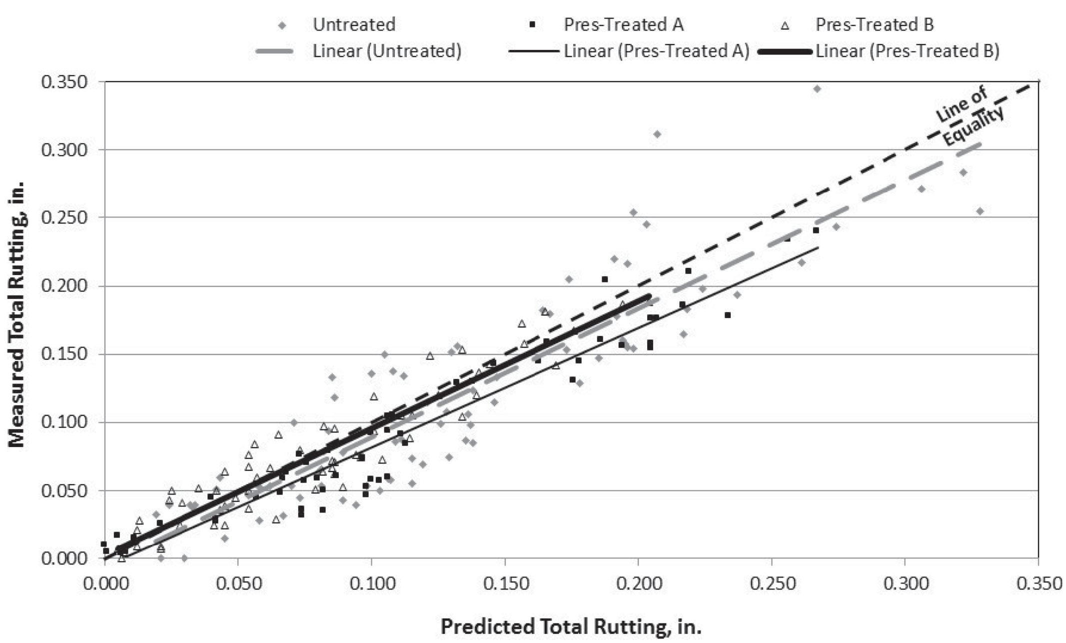


Figure 9. Distress model calibration settings—new rigid pavements.



Note: Pres-treated = preservation-treated.

Figure 10. Comparison of predicted and measured total rut depth for full-depth HMA pavements following bias elimination/reduction.

Manual of Practice (AASHTO 2008); these values are listed in the following.

- HMA-Surfaced Pavements
  - Bottom-Up Alligator Cracking: 7% of total lane area.
  - Top-Down Longitudinal Cracking (confined to wheel paths): 600 ft/mi.
  - Reflective Cracking (confined to wheel paths, and combined with alligator and longitudinal cracking in wheel paths): 600 ft/mi.
  - Rut Depth: 0.10 in.
  - Transverse Thermal Cracking: 250 ft/mi.
- PCC-Surfaced Pavements
  - Transverse Joint Faulting in JPC (mean): 0.05 in.
  - Transverse Slab Cracking in JPC (bottom-up and top-down): 7% cracked slabs.
  - Punchouts in CRC: 4 punchouts/mi.

Null hypothesis statistical testing for the experimental/sampling matrix will result in one of three possible outcomes. These outcomes and recommended courses of action are:

- Errors are not significantly different: The calibrated factors can be used (no attempts to reduce standard error are required).
- Errors are significantly different, but the errors of the calibrated factors are smaller than those of the MEPDG-calibrated factors: the locally calibrated factors can be used (no attempts to reduce standard error are required).
- Errors are significantly different, but the errors of the calibrated factors are greater than those of the MEPDG-calibrated factors: the model should be recalibrated to lower the standard error (unless a higher standard error is considered acceptable).

10. *Reduce Standard Error of the Estimate:* A high standard error can be reduced by (a) computing the standard error within each cell of the experimental/sampling matrix and determining if the local standard error term is dependent on any of the matrix factors (such as preservation strategy), and (b) adjusting the calibration values of the distress transfer functions to reduce the standard error of the recalibration data set considering the coefficients of the MEPDG models identified in the AASHTO *Local Calibration Guide.* The values for the coefficients of the model are then improved by evaluating the goodness of fit using either an analytical approach (for models that suggest a linear relationship) or a numerical optimization approach (for models that suggest a nonlinear relationship). If the standard error cannot be significantly reduced due to large measurement error, then proceed with Item 11.
11. *Interpretation of Results, Deciding on Adequacy of Calibration Parameters:* The standard error of the estimate for each distress/smoothness prediction model is evaluated to determine the effect on the resulting designs at different reliability levels. This is done by determining the expected design lives (for different reliability levels) for typical site features and pavement structures or rehabilitation strategies; results are checked for reasonableness. Attempts to reduce the standard error of the estimate for specific models should take into consideration adjusting the calibration factors or possibly modifying the failure criteria or trigger values for these models.

Feasibility Assessment

Model calibration to account for preservation resembles the concept of calibrating the MEPDG performance models to account for local conditions. The design analysis would use the Pavement ME Design software program and calibration factors for the various performance prediction models (MEPDG models only) to reflect the effects of preservation. Implementing this approach requires a significant level of effort to identify pavement test sections that cover a range of pavement types, preservation treatments/strategies, and traffic and climatic conditions and to gather relevant performance and other data. The calibration process requires statistical analyses of prediction model bias and error and identifying new calibration factors through iterative runs of the Pavement ME Design software or other means.

The SHA interviews suggested that several agencies have the components needed for implementing this approach. The vast majority deal with new/reconstructed HMA and JPC, as well as HMA overlays of existing flexible and rigid pavements, and use three or more preservation treatment types for flexible pavements and at least two treatment types for rigid pavements. Some of the LTPP or PMS sections in these agencies could serve as calibration sections for local conditions but not for a variety of climate and traffic conditions. This approach requires no modifications to the Pavement ME Design software and entails no added complexity in the use of the program. It simply uses the preservation-based calibration coefficients in the design analysis computations.

Because of the requirement for extensive data covering the long-term performance of a variety of preservation treatments subjected to different levels of traffic and climate, this approach is also likely to be implemented as part of a national research effort or a multi-agency cooperative research program. An example illustrating the process for calibrating MEPDG models for preservation is presented in the following.

Example of Implementation Process

The Michigan Department of Transportation (MDOT) maintains a database covering many years of preservation data for hundreds of pavement sections located throughout the state on roads with different functional classes. For the most part, the underlying pavements were constructed between 1985 and 2002 as part of major rehabilitation, resurfacing, or reconstruction projects. The preservation treatments were applied between 1992 and 2008. (In some cases, two or three treatments have been applied during that period.) Some data from this database, together with other data derived from agency specifications, manuals, and reports or otherwise estimated/assumed, are used in a hypothetical example to illustrate the calibration of MEPDG models to account for the effect of preservation. Untreated sections used in this example were constructed between 1985 and 2005. The example follows the process described in this chapter and incorporates certain assumptions.

Step 1: Select Hierarchical Input Level for Each Input Parameter

Because the majority of the analyzed sections were more than 10 years old, and no detailed mix design or materials testing data were available for these projects, Level 3 materials inputs were used for the Pavement ME Design runs. Also, because detailed information regarding the traffic used in designing these pavements was not available, the available basic traffic data (e.g., average daily traffic [ADT], percent trucks) were used in combination with the national/default values (i.e., a combination of Levels 1 and 3) for the other traffic parameters. Climate data were classified as Level 1 as they were available from the nearest of 19 weather stations.

Step 2: Develop Local Experimental Plan or Sampling Template

Performance analysis was only feasible for preservation treatments placed on HMA-surfaced pavements (i.e., new/reconstructed flexible pavements, HMA-overlaid flexible pavements, and HMA-overlaid rigid pavements) as only a few preservation treatments were placed on PCC-surfaced pavements to provide sufficient performance data. This example considers two treatment types for HMA-surfaced pavements: double microsurfacing and thin HMA overlay. The preservation treatments were applied to pavements that were neither severely distressed nor severely distorted in terms of cross-section; over 200 sections/projects of each were available for consideration.

In developing the experimental/sampling matrix, the following types of traffic, climate, and pavement were considered:

- Climatic Zone
  - Moderate: Hot summers and cold winters (southern and central parts of the Lower Peninsula).
  - Severe: Warm, but shorter summers and longer, cold to very cold winters (northern part of Lower Peninsula and entire Upper Peninsula).
- Traffic
  - Moderate to High: Interstates and other freeways (National Functional Classification [NFC] Categories 1 and 2).
  - Low: Other principal arterials and minor arterials (NFC Categories 3 and 4).
- Pavement Type
  - New/Reconstructed Flexible Pavements: HMA on aggregate base and subbase.
  - HMA-Overlaid Flexible Pavements: Structural HMA overlays of existing flexible pavements.

Detailed pavement cross-section data were not readily available for many of the sections; only information on the basic pavement type (i.e., flexible, composite, or rigid) was available. New/reconstructed flexible pavements and HMA-overlaid flexible pavements were combined into one category.

Considering the recommended minimum numbers of sections of 20 for rutting and the availability of sections with adequate performance data, a goal of at least two pavement sections for each cell (i.e., combination of traffic, climate, and preservation treatment/strategy) was established for a total of 24 sections, as shown in Table 16.

Step 3: Estimate Sample Size for Specific Distress Prediction Models

According to Equation 1, the number of sections required for analysis for a 90% level of significance ($Z_{\alpha/2} = 1.601$), a 0.5-in. rut depth threshold (σ, the assumed threshold value for this example), and a 0.1-in. rut depth standard error of the estimate (S_e) is 25. This number is very close to the goal of 24 presented in Table 16; therefore, attempts were made to locate these sections.

Step 4: Select Roadway Segments

Table 17 shows the pavement sections identified for calibrating the rutting model. All of these sections had a major structural improvement performed between 1986 and 1999, consisting of either a conventional overlay (structural HMA overlay on existing flexible pavement) or a crush/shape-and-overlay (pulverization, mixing, and replacing of existing HMA layers followed by structural HMA overlay). Other improvement types included mill-and-HMA overlay, rubblize-and-

Table 17. Experimental/sampling matrix.

Pavement Type/Design	Preservation Treatment/ Strategy	Interstate and Other Freeway Routes (NFC-1 and NFC-2)		Other Principal Arterial and Minor Arterial Routes (NFC-3 and NFC-4)	
		Climate Zone 1 (Severe)	Climate Zone 2 (Moderate)	Climate Zone 1 (Severe)	Climate Zone 2 (Moderate)
New/Reconstructed Flexible Pavement or HMA-Overlaid Flexible Pavement	(0) Untreated control	• U-2: U.S. 41 Baraga Co. • U-5: U.S. 10 Mason Co.	• U-9: U.S. 131 Mecosta Co. • U-10: M-46 Montcalm Co.	• U-4: M-69 Dickenson Co. • U-8: M-66 Missaukee Co.	• U-11: M-90 Lapeer Co. • U-12: M-50 Lenawee Co.
	(1) Double microsurfacing	• DM-1: I-75 Crawford Co. • DM-2: I-75 Crawford Co.	• DM-5: I-196 Van Buren Co. • DM-6: U.S. 12 St. Joseph Co.	• DM-3: M-183 Delta Co. • DM-4: M-55 Ogemaw Co.	• DM-7: M-50 Monroe Co. • DM-8: M-40 Van Buren Co.
	(2) Thin HMA overlay (1.5–2.0 in.)	• TO-1: M-72 Oscoda Co. • TO-2: U.S. 41 Houghton Co.	• TO-5: M-46 Montcalm Co. • TO-6: U.S. 131 Mecosta Co.	• TO-3: U.S. 41 Keweenaw Co. • TO-4: M-113 Grand Traverse Co.	• TO-7: M-57 Kent Co. • TO-8: M-52 Ingham Co.

Notes: Climate Zone 1 is represented by the Upper Peninsula and the northern half of the Lower Peninsula and consists of MDOT Regions 1 and 2. Climate Zone 2 is represented by the southern half of the Lower Peninsula and consists of MDOT Regions 3 through 7. DM# = double microsurfacing section ID; TO# = thin HMA overlay section ID; U# = untreated section ID.

HMA overlay, and reconstruction with conventional HMA pavement.

A preservation treatment was later placed on the improved pavement sometime between 1999 and 2007. Rutting data were available for several years before and after preservation treatment application and were considered sufficient for the calibration.

Step 5: Extract and Evaluate Distress and Project Data

Rutting and other pavement performance data for the selected sections were obtained and reviewed. The data for total rutting in the pavement structure were obtained from automated surveys performed biennially on the state's trunkline roads in accordance with the *Distress Identification Manual for the Long-Term Pavement Performance Program* (Miller and Bellinger 2003). Transverse profiles were measured continuously over the length of testing, and average rut depths for the left-wheel path, right-wheel path, and both-wheel paths were computed for 0.1-mi-long segments.

The total rutting for most of the untreated sections exceeded 0.25 in. (50% of the 0.5-in. threshold criterion). For about half of the preservation-treated sections (i.e., double microsurfacing and thin HMA overlay sections), total rutting was about 0.25-in.; the remaining sections had total rutting of at least 0.15 in.

Available traffic (average annual daily traffic [AADT], percent commercial trucks), pavement cross-section, and subgrade (soil type) information for the various sections was compiled and reviewed. Some materials data (e.g., asphalt binder grade) were available, but other materials inputs (e.g., HMA mix volumetrics and dynamic modulus, aggregate base, subbase, and subgrade soil resilient moduli) were estimated from data in related reports (Buch et al. 2008, Baladi et al. 2009, Von Quintus and Perera 2011) or the LTPP database (DataPave). The national/default values contained in the AASHTOWare Pavement ME Design software were used for the remaining materials and traffic input data.

Step 6: Conduct Field and Forensic Investigations

No supplemental testing was required or performed.

Step 7: Assess Local Bias (Verification of Global Calibration Values to Preservation)

The performance of the treated pavement structure was computed for each section using the Pavement ME Design software. The computed values of total rutting (at 50% reliability) and the measured values for similar sections (i.e., untreated, double microsurfacing, and thin HMA overlay sections) were then plotted for comparison. Figure 11 shows the plots for the untreated, double microsurfacing, and thin HMA overlay sections. The figure also shows a linear trend line fitted through all of the predicted versus measured data points (data for all three sets of sections) and lists the relevant statistics for a combined/overall rutting model. These statistics indicate very poor model prediction ($R^2 = 0.03$) and that each null hypothesis regarding model bias was rejected at the 10% significance level. Thus, model recalibration was necessary.

Table 18 summarizes the results of similar testing for individual sets of sections in which the predicted rutting was considerably greater than actual rutting (>0.5 in. versus <0.25 in.), and model prediction capabilities were very poor ($R^2 \leq 0.11$) such that recalibration was required.

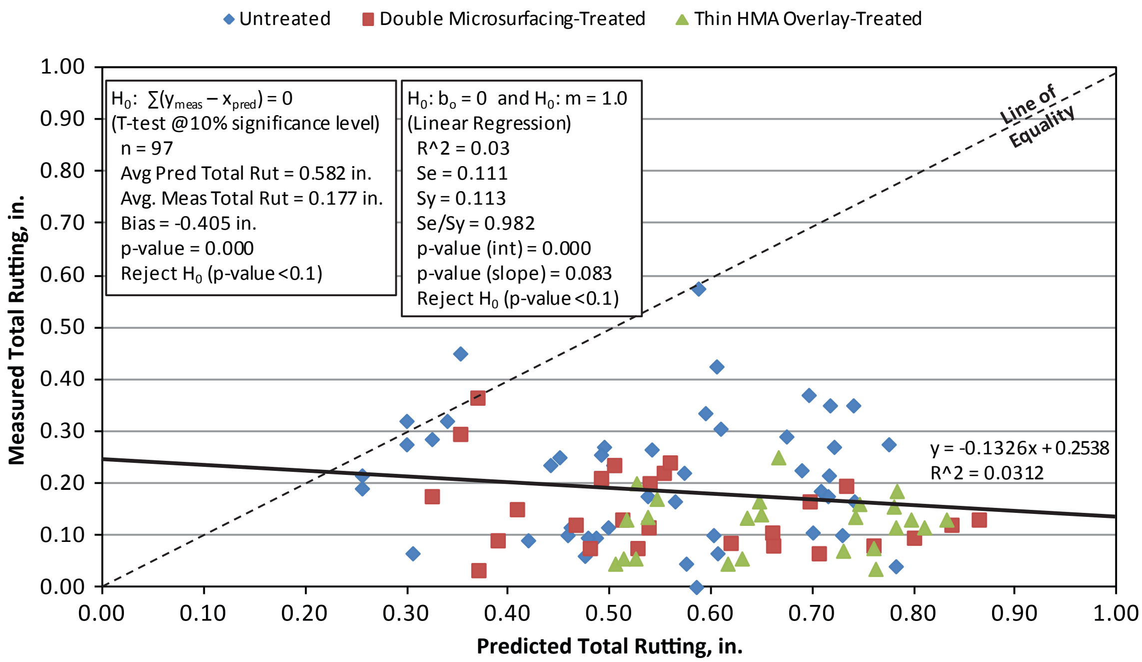


Figure 11. Predicted versus measured rutting.

Step 8: Eliminate Local Bias of Distress and IRI Prediction Models

Because the data presented in Figure 12 and Table 19 indicate high bias and low precision for each set of pavement sections, the data were reviewed to determine if certain factors (e.g., traffic, climate, pavement cross-section, or improvement year) caused these levels of bias and error. No specific factors were identified, but some data inconsistencies, possibly because of the use of different materials (e.g., rubblize-and-HMA overlay, reconstruction with HMA), were observed. These and other data that were found to be in error due to misalignment in the section limits were removed from the analysis.

To conduct the calibration, an optimization routine was developed in a Microsoft Excel spreadsheet. The routine included the MEPDG HMA rutting model and the various inputs required to calculate HMA rutting. For expediency, it was assumed that HMA rutting is 25% of the total rutting

Table 18. Summary of rutting model bias statistics.

Null Hypothesis	Parameter	Untreated Sections	Double Microsurface-Treated Sections	Thin HMA Overlay–Treated Sections
	Number	47	26	24
	Avg. predicted rutting, in.	0.546	0.566	0.668
	Avg. measured rutting, in.	0.221	0.148	0.112
	Bias (e_r), in.	-0.325	-0.418	-0.548
	R^2	0.00	0.11	0.01
	S_e	0.133	0.076	0.057
H_0: $\Sigma(y_{measured} - x_{predicted}) = 0$	*T*-test *p*-value	0.000	0.000	0.000
	Accept/reject H_0	Reject	Reject	Reject
H_0: $b_o = 0$	Regression *p*-value (intercept)	0.003	0.000	0.273
	Accept/reject H_0	Reject	Reject	Accept
H_0: $m = 1.0$	Regression *p*-value (slope)	0.868	0.100	0.581
	Accept/reject H_0	Accept	Accept	Accept

Note: Hypothesis testing performed at 10% significance level.

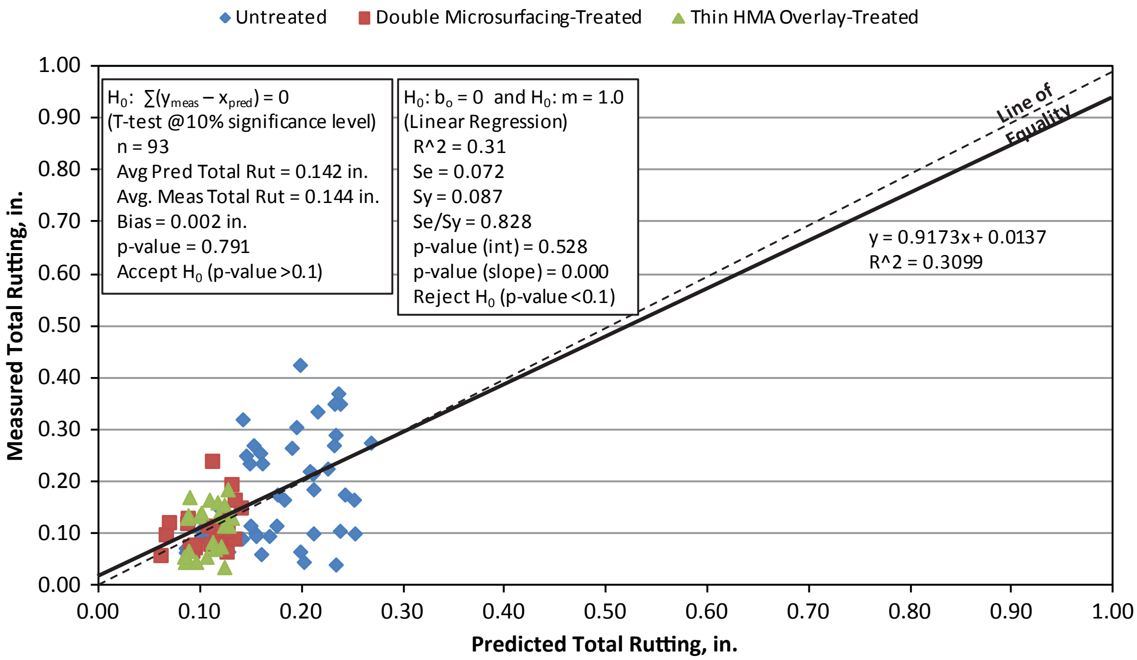


Figure 12. Modified predicted versus measured rutting.

(i.e., predicted total rutting was computed as four times the predicted HMA rutting). The Microsoft Excel Solver function was used to determine the optimal values of β_{r1}, β_{r2}, and β_{r3} that give the smallest SSE between the predicted and measured values of total rutting. The resulting plots of predicted versus measured total rutting are shown in Figure 12, and the corresponding bias statistics are provided in Table 19. Although hypothesis testing indicated an unacceptable level of bias for each group, the prediction capability and accuracy of each have been greatly increased, and the bias has been greatly reduced.

Step 9: Assess the Standard Error of the Estimate

As Table 19 indicates, the S_e value for the double-microsurfacing and thin HMA overlay sections was lower

Table 19. Modified summary of rutting model bias statistics.

Null Hypothesis	Parameter	Untreated Sections	Double Microsurfacing-Treated Sections	Thin HMA Overlay–Treated Sections
	Number	44[1,3]	25[2,3]	24[3]
	Avg. predicted rutting, in.	0.182	0.105	0.107
	Avg. measured rutting, in.	0.184	0.107	0.108
	Bias (e_r), in.	0.002	0.002	0.001
	R^2	0.15	0.14	0.09
	S_e	0.096	0.042	0.045
H_0: $\Sigma(y_{measured} - x_{predicted}) = 0$	T-test p-value	0.867	0.770	0.937
	Accept/reject H_0	Accept	Accept	Accept
H_0: $b_o = 0$	Regression p-value (intercept)	0.549	0.436	0.758
	Accept/reject H_0	Accept	Accept	Accept
H_0: $m = 1.0$	Regression p-value (slope)	0.009	0.071	0.158
	Accept/reject H_0	Reject	Reject	Accept

Notes: Hypothesis testing performed at 10% significance level. [1] Sample size from Step 7 reduced by three due to removal of data outliers. [2] Sample size from Step 7 reduced by one due to removal of data outlier. [3] Adjustments made to a few of the measured rutting values in Step 7 to correct for misalignment in section limits.

than the reasonable value reported for MEPDG rutting model (0.076 in. and 0.057 in., versus 0.10 in.), and S_e for the untreated sections was higher (0.133 in. versus 0.10 in.). As Table 19 shows, calibration of the rutting model for each set of sections resulted in lower S_e values than the reasonable value reported in the MEPDG rutting model. The errors of the calibrated coefficients appear to be statistically significantly lower than those of the nationally calibrated coefficients.

Step 10: Reduce Standard Error of the Estimate

Because the S_e values were lower than the reasonable values reported in the MEPDG rutting model, no further reductions were necessary.

Step 11: Interpretation of Results, Deciding on Adequacy of Calibration Parameters

Table 19 suggests some issues with the calibrated coefficients for the double-microsurfacing–treated sections, including the evident statistical bias with respect to the intercept value for the predicted versus measured relationship (i.e., the intercept is not zero) and the poor predictive capability of the calibrated models ($R^2 < 50\%$). Also, an acceptable model could not be developed for the microsurfacing-treated and the thin HMA overlay–treated sections because of the limited range of measured data. (Only about half of the sections exhibited total rutting values at or near the 0.25-in. criterion.)

CHAPTER 6

Using Modified Material and Pavement Structural Properties in MEPDG Models to Account for Preservation

The application of preservation treatments could result in changes in pavement material properties (e.g., modulus), pavement structural properties (e.g., thickness, moisture content), moisture and thermal profiles in the pavement system, and the level and rate of distress and roughness development over time. These changes will influence pavement performance and life. Therefore, by identifying the MEPDG inputs or modeling components that are affected by the treatment application, quantifying the changes attributed to treatment application, and using the adjusted values of these items in the MEPDG design analysis process, the effect of preservation treatment on pavement performance and life will be accounted for.

Process Description

The application of a preservation treatment can result in changes in distress/roughness, material properties, structure cross-sections, and moisture and thermal profiles. Also, some preservation treatments can alter the distress/roughness level immediately upon application (e.g., the application of a thin HMA overlay would eliminate cracking, reduce the depth of rutting, and decrease IRI) and the rate and level of distress/roughness redevelopment. Therefore, it will be necessary to define the adjustment that should be made to each MEPDG performance parameter, recognizing the following:

- The empirical reflection cracking model may be used to predict the percentage of cracks (fatigue and thermal) or joints that propagate through the preservation treatment over time. This model uses a sigmoidal function with *a* and *b* fitting parameters that are a function of overlay (in this case, treatment) thickness, as well as *c* and *d* user-defined cracking progression parameters.
- A dynamic rutting model that uses the base rutting model and a subtraction term that represents the change in rutting due to the application of a preservation treatment may be used. As illustrated in Figure 13, for every preservation treatment that is applied to reduce rutting (to zero), a reduction of rutting by 0.25 in. is factored into the base model. Thus any rutting that occurs after treatment application is modeled as "base model rut depth minus 0.25 in." If a second treatment is applied, then the rutting that takes place after the second treatment is modeled as "base model rut depth minus 0.25 in. minus 0.25 in."
- A dynamic faulting model can be created and used in a manner similar to rutting.
- No adjustments to the overlay smoothness models are needed. The initial IRI in these models will be the value immediately upon preservation treatment application (as specified by the user). The other terms in the models (cracking and rutting) will be derived from their respective models.

The treatment application can have either an immediate or long-term effect on the properties of the surface layer material of the pavement. For example, applying a fog seal or rejuvenator to an HMA pavement or performing a surface recycle will immediately soften the HMA surface and lead to a reduced modulus value and influence flexibility and resistance to load and environment initially and over time. To properly account for the effects of the changes in material properties on performance, these changes must be quantified.

Some preservation treatments may not have an immediate effect on the properties of the surface layer material but may influence the long-term properties of that material. For example, placing a surface treatment on an HMA pavement protects the HMA surface layer from ultraviolet (UV) exposure, thus reducing the rate at which the binder in the surface layer hardens with time (i.e., protects against aging). The aging model in the MEPDG includes both a surface aging model and a viscosity-depth model for predicting binder viscosity at any time and any depth in the pavement structure.

A preservation treatment can also result in a change in the pavement structure cross-section. The thickness of the pavement surface layer may be reduced, as in the case of milling

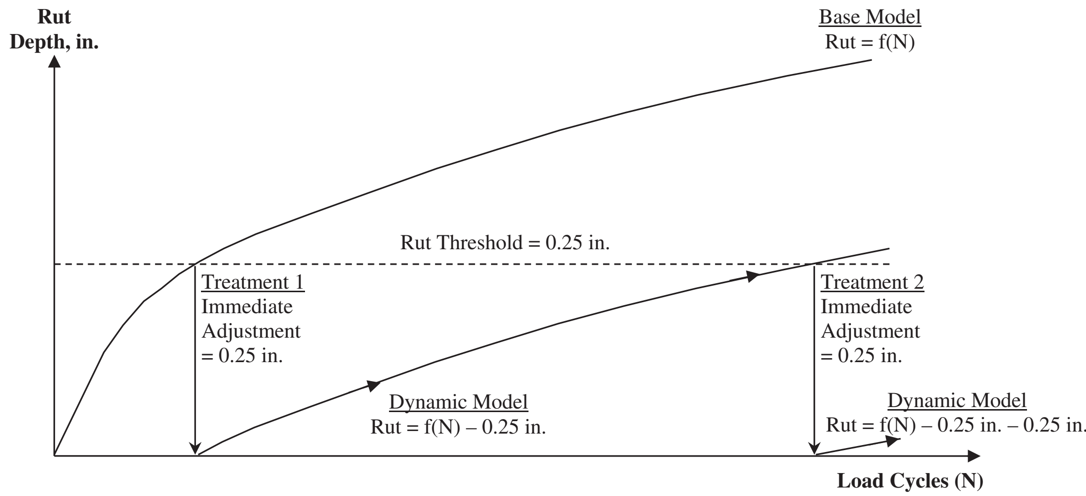


Figure 13. Concept of adjusting rutting model to account for preservation treatment effects.

of HMA or diamond grinding of PCC, or increased, as in the case of applying a surface treatment or thin HMA overlay. Although some treatments with large thicknesses are applied and treatments that are placed repeatedly over time could increase structural capacity, pavement preservation treatments are generally considered to have no effect on structural capacity. To model material characteristics and moisture and temperature regimes in the pavement structure, it is necessary to define the thickness and mechanistic properties associated with each preservation treatment.

The preservation treatment can also influence the moisture and thermal profiles of the pavement system over time, as modeled by the Enhanced Integrated Climate Model (EICM). Treatments that seal or waterproof a pavement may reduce the infiltration of surface water into the structure and foundation, thereby reducing the moisture content and increasing the resilient modulus of the underlying unbound materials. Similarly, thick treatments may influence the thermal characteristics throughout the pavement. To capture these effects, certain treated pavement structure inputs, such as the infiltration potential of the pavement (surface layer[s] and treated base layer[s]), the cross-slope and drainage path length of the treated pavement surface, and the surface shortwave absorptivity of the treatment, would need to be redefined.

Tables 20 and 21 list the likely effects of different preservation treatments on performance indicators for HMA- and PCC-surfaced pavements, respectively.

The process for determining the changes in material properties resulting from the application of preservation treatments and their effect on pavement performance is summarized as follows.

1. *Identify the Basic Pavement Structure and the Preservation Treatment Type:* The original/base design and corresponding use scenario are identified, together with the specific preservation treatment that will be considered for application at some time following construction.
2. *Identify Preservation Treatment Timing:* The timing for the preservation treatment application is identified based on specific schedule or thresholds for performance indicators (e.g., the amount of transverse cracking or rutting).
3. *Identify Baseline Material Properties of Pavement Structure and Treatment:* Key material properties of the base pavement structure and the preservation treatment (such as engineering and thermal properties [e.g., dynamic modulus, creep compliance, coefficient of thermal contraction] and volumetric properties [e.g., air voids, mix density, effective asphalt content]) are identified. Tables 22 through 24 list the specific preservation treatment material inputs.

   Several preservation treatments reduce or delay the infiltration of moisture through existing surface cracks and joints and may therefore increase the resilient modulus of the unbound and subgrade layers. However, this increase in stiffness will diminish over time. The resilient modulus for the unbound and subgrade layers may be determined from NDT (e.g., FWD backcalculation) or correlations with other tests (e.g., California bearing ratio [CBR] and *R*-value), or using values (AASHTO 2008).
4. *Quantify Treatment Effect on Pavement Thickness:* The effect of the preservation treatment on the existing pavement structure is quantified in terms of reduced or added structure thickness. For example, chip seals, microsurfacing, and overlays will add a layer to the pavement structure, but milling and diamond grinding will reduce the surface layer thickness.
5. *Identify Treatment Effect on Existing Layer Material Properties and on Moisture and Thermal Properties of Pavement Structure:* Short- and long-term effects of the preservation

Table 20. Possible effects of preservation treatments on performance indicators of HMA-surfaced pavements.

Treatment	Performance Indicator					
	Total Rutting (HMA and unbound)	Transverse Thermal Cracking	Fatigue Cracking (Bottom-up Alligator)	Fatigue Cracking (Top-Down Longitudinal)	Reflection Cracking (in overlays)	Smoothness (IRI)
Crack Filling/Sealing		(+)/+	☑	☑	(+)/+	☒
Fog Seal/Rejuvenator Seal	☑	☑	☑	☑	☑	
Sand/Scrub Seal	☑	☑	☑	☑	☑	☑
Slurry Seal	☑	(+)	☑	☑	☑	(+)
Microsurfacing	+	(+)	☑	☑	(+)	+
Chip Seals	(+)	(+)	☑	☑	(+)	(+)
Thin HMA Overlays	(+)	(+)	☑	☑	(+)	+
Ultrathin HMA Overlays	(+)	(+)	☑	☑	(+)	(+)
Ultrathin Bonded Wearing Course	(+)	(+)	☑	☑	(+)	(+)
Hot In-Place Recycling	+	+	+	+	+	+
Cold In-Place Recycling	+	+	+	+	+	+
Ultrathin Concrete Overlay	+	+	+	+	+	+

Notes: + or – = significant or long-term positive or negative impact; (+) or (–) = moderate or short-term positive or negative impact; ☑ = slight positive impact; ☒ = slight negative impact; blank cells designate no effect.

Table 21. Possible effects of preservation treatments on performance indicators of PCC-surfaced pavements.

Treatment	Performance Indicator							
	JPC Pavement				CRC Pavement			
	Crack/ Joint Faulting	Load Transfer Efficiency	Trans-verse Cracking	Crack/ Joint Spalling	Crack Spacing/ Width	Load Transfer Efficiency	Punchouts	Smoothness (IRI)
Crack Sealing/ Joint Resealing	☑		☑	+	☑	☑	☑	☒
Diamond Grinding	+							+
Diamond Grooving								
Partial-Depth Repair	☑			+				☑
Full-Depth Repair	+	+	+	+	+	+	+	☑
Load Transfer Restoration	+	+	(+)					☑
Cross-Stitching	+	+	(+)					☑
Thin HMA Overlay	(+)							+
Ultrathin Bonded Wearing Course	(+)							(+)

Notes: + or – = significant or long-term positive or negative impact; (+) or (–) = moderate or short-term positive or negative impact; ☑ = slight positive impact; ☒ = slight negative impact; blank cells designate no effect.

Table 22. Summary of asphalt binder material inputs (AASHTO 2008, Pierce et al. 2010).

Input	Level 1	Level 2	Level 3
Superpave Performance Grade Binder	AASHTO T 49	Same as Level 1	Superpave performance grade
Penetration/Viscosity Grade Binder	AASHTO T 49, T 53, T202, T 201, T 228, and TP 85	Same as Level 1	Penetration/viscosity grade

Table 23. Summary of HMA material inputs (AASHTO 2008, Pierce et al. 2010).

Input	Level 1	Level 2	Level 3
Unit Weight	AASHTO T 166	Not applicable	Typical value (default = 150 lb/ft^3)
Effective Binder Content	AASHTO T 308	Not applicable	Typical value (default = 11.6%)
Air Voids	AASHTO T 166	Not applicable	Typical value (default = 7%)
Poisson's Ratio	Not applicable	Reference temperature	Typical value (default = 0.35)
Dynamic Modulus	AASHTO TP 62	Binder properties and aggregate gradation	Same as Level 2
Indirect Tensile Strength	AASHTO T 322	Same as Level 1	Calculated internally
Creep Compliance	AASHTO T 322 at -4, 14, and 32°F	AASHTO T 322 at 14°F	Calculated internally
Thermal Conductivity	Not applicable	Not applicable	Typical value (default = 0.67 BTU/ft-hr-°F)
Heat Capacity	Not applicable	Not applicable	Typical value (default = 0.23 BTU/lb-°F)
Thermal Contraction	Not applicable	Mix and aggregate	Calculated internally

treatment on the existing surface layer material properties (i.e., changes in engineering or thermal properties, or volumetric properties of the HMA surface layer), on the moisture and thermal profiles of the pavement structure (e.g., drainage/infiltration potential, cross-slope, and drainage path length) are identified. However, the MEPDG considers only the effects of shoulder type, edge drains, and drainage layers (AASHTO 2008); it allows changes to the layer moduli of the unbound and subgrade layers and the surface shortwave absorptivity but not to the infiltration rate. These effects should be defined and considered.

6. *Identify Immediate Treatment Effect on Performance of Pavement Structure:* The immediate effect of the treatment on the performance of the existing pavement is determined (e.g., reducing rutting to zero or IRI value to a certain level).
7. *Establish MEPDG Reflection Cracking Model Coefficient and Dynamic Models for Rutting/Faulting:* The MEPDG reflection cracking model coefficient *d*, which governs the acceleration ($d > 1$) or delay ($d < 1$) in the formation of reflective cracks (from fatigue and transverse cracks in existing HMA pavement) in the preservation treatment, is determined. Also, a rut depth (or faulting for PCC pavement) model is proposed that modifies the MEPDG base model to account for the immediate change in rut depth (or faulting) by including an adjustment term.

Table 24. Summary of PCC material inputs (AASHTO 2008, Pierce et al. 2010).

Input	Level 1	Level 2	Level 3
Unit Weight	AASHTO T 121	Not applicable	Typical value (default = 150 lb/ft^3)
Poisson's Ratio	ASTM C469	Not applicable	Typical value (default = 0.20)
Coefficient of Thermal Expansion	AASHTO TP 60	Not applicable	Typical value (default = 5.5 x 10^{-6} in./in./°F)
Thermal Conductivity	ASTM E1952	Not applicable	Typical value (default = 1.25 BTU/ft-hr-°F)
Heat Capacity	ASTM D2766	Not applicable	Typical value (default = 0.28 BTU/lb-°F)
PCC Set Temperature	Not applicable	Not applicable	Internally calculated or user-defined
Ultimate Shrinkage	Not applicable	Not applicable	Internally calculated or user-defined
Reversible Shrinkage	Not applicable	Not applicable	User-defined
PCC Strength	AASHTO T 97, ASTM C469	AASHTO T 22	User-defined

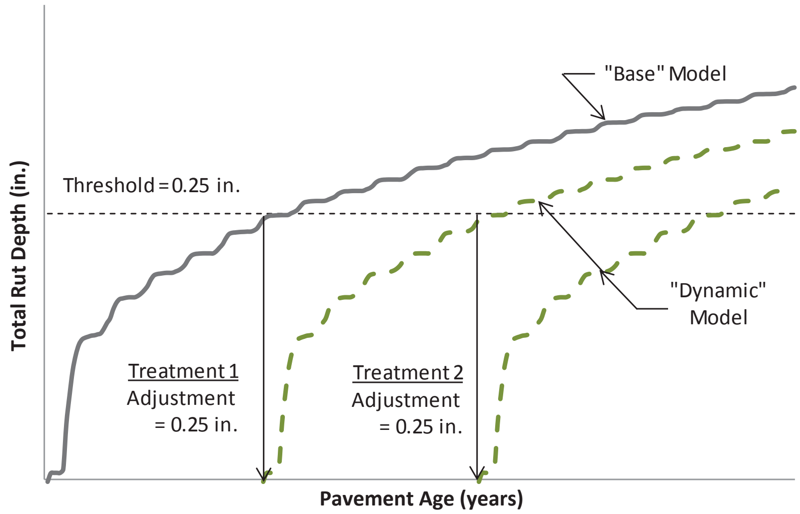


Figure 14. Concept of dynamic rut depth model.

The empirical reflection cracking model can be used to predict the percentage of cracks (fatigue and thermal) or joints that propagate through the preservation treatment over time. The MEPDG user-defined cracking progression parameters *c* and *d* can be adjusted to account for delaying or accelerating the progression of reflection cracking. The *MEPDG Manual of Practice* (AASHTO 2008) provides recommended values for *c* and *d*, but other values' parameters should be determined from calibration. Because the *d* parameter depends on overlay thickness and does not easily distinguish between fatigue and reflection cracking in the overlay, reliability of the reflection cracking model is set at 50% and cannot be changed by the user.

A dynamic rut depth model that uses the MEPDG base rut depth model and a subtraction term can be developed to consider the immediate rut depth change due to preservation treatment application. Figure 14 illustrates two preservation treatment applications, each of which reduces the rut depth to zero when the threshold value of 0.25 in. is reached. The dynamic rut depth model applies an immediate adjustment of 0.25 in., after which rut depth progresses as defined by the base model.

A dynamic faulting model can be developed in a manner similar to that described for the rut depth. The concept is illustrated in Figure 15.

No adjustments to the overlay smoothness models are required. The initial IRI in these models will be the value specified as an immediate adjustment corresponding to the preservation treatment. Table 25 lists the effects of various preservation treatments on IRI as reported in the literature.

8. *Perform Pavement ME Design Analysis:* The base design is analyzed using design inputs for traffic, climate, and

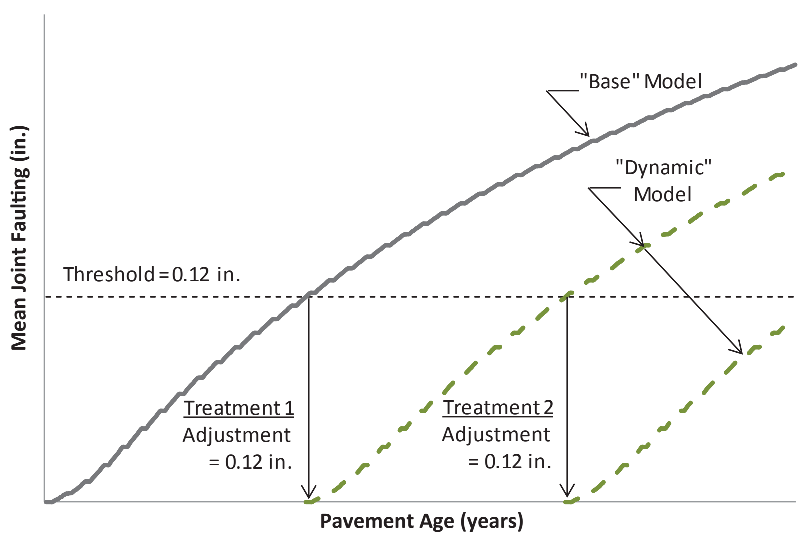


Figure 15. Concept of dynamic faulting model.

Table 25. Reported effects of preservation treatments on IRI.

Treatment Type	Before Treatment IRI, in./mi[1]	After Treatment IRI, in./mi[1]	Percent Improvement	Reference
Diamond Grinding	130 256	57 168	56 35	Battaglia 2010 Pierce and Muench 2009
Hot In-Place Recycling	109	78	29	Browning 1999
Microsurfacing	92	77	15	Ji et al. 2011
Milling	(2)	(2)	6	West et al. 2011
Thin HMA Overlay	(2)	(2)	18 to 36	Labi et al. 2005
Ultrathin HMA Overlay	162 154	99 89	39 42	Hanson 2001 Corley-Lay and Mastin 2007

Notes: [1] Values shown are based on the average IRI of individual projects reported in the reference publications. Actual IRI improvement may vary and depends on the IRI value prior to treatment application and agency design and construction practices. [2] Values were not provided.

materials properties, a specific design life, reliability levels for the individual performance indicators, and performance indicator threshold values for rehabilitation. Either the MEPDG performance prediction models or locally calibrated models can be used.

9. *Perform Pavement ME Design Analysis for Preservation-Treated Design:* A design analysis similar to that performed for the base design is performed for the preservation-treated design using the same base design parameters to consider the effects of the preservation treatment. The output from the base design (i.e., predicted distress and roughness levels) covering the period from original construction to the time when the first performance indicator threshold is reached is combined with the output from the preservation-treated design to produce the output for the specified design life. The effects of the treatment can then be evaluated in terms of (a) the immediate change in distress/roughness and their redevelopment, (b) the immediate or long-term change in the mechanistic properties of the pavement surface layer, (c) the immediate change in the pavement structural cross-section, and (d) the change in the moisture or thermal properties of the pavement surface layer and their effect on moisture or temperature profiles throughout the pavement structure.

Table 26 lists the data elements required for the design analysis of the baseline/untreated and preservation-treated alternatives.

Feasibility Assessment

Modifying material properties involves defining the types of effects of the application of a preservation treatment on a pavement (e.g., immediate and long-term changes in distress/roughness levels, material properties of the surface layer of the pavement, pavement structure cross-section, and moisture and thermal profiles of the pavement system). The design analysis uses the Pavement ME Design software to develop predicted distress/roughness values for a base design and a corresponding preservation-treated design, and then merges the two sets of predictions. This approach addresses only the cracking, rutting, faulting, and smoothness models included in the MEPDG. The level of effort required to implement this approach is fairly significant. Although some of the required inputs (e.g., typical treatment types and applications, distress/roughness threshold levels for preservation and rehabilitation treatments) can be easily obtained, other inputs must be obtained through collection and analysis of actual data. Examples of these inputs include the rate of redevelopment of distress/roughness, the change in the HMA surface layer dynamic modulus, and the change in pavement layer drainage and moisture characteristics following preservation. A major drawback to this approach is the complexity of accurately defining the changes in properties resulting from the application of different preservation treatments at different times during the life of the pavement.

This approach requires no modifications to the Pavement ME Design software and entails no added complexity in the use of the program. It simply involves design analysis computations for the original/base design, then performs the design analysis computations, repeats the process for the preservation-treated design, and merges the two sets of design outputs.

Examples of Implementation Process

Two hypothetical examples are presented to illustrate how modifying material properties could be used to account for preservation effects on performance. In one example, microsurfacing is applied to an existing HMA-surfaced pavement, and in another example, diamond grinding is performed on an existing PCC-surfaced pavement. When possible, actual inputs have been included and all assumptions have been clearly stated. These examples use inputs obtained from the Colorado DOT (CDOT) *Pavement Design Manual* (CDOT 2013) and *Standard Specifications for Road and Bridge Construction* (CDOT 2011). In these examples, “default” refers

Table 26. Data elements required for AASHTOWare Pavement ME Design analysis.

Data Category	Data Element
Analysis Parameters	• Untreated design strategy—typical pavement design • Preservation-treated design strategy—same typical pavement design, except with a specific preservation treatment included • Design life
Performance Criteria and Reliability	• HMA performance indicators—rut depth, reflection cracking, and IRI • PCC performance indicators—faulting and IRI • Design reliability (for individual distresses and smoothness)
Structure Properties	• Untreated design strategy—layer types, materials, and thicknesses • Preservation-treated design strategy—same as untreated • Surface shortwave absorptivity
Preservation Treatment Application Parameters	• Treatment timing – Distress, smoothness, and/or overall condition levels of original pavement at time of treatment application • Existing HMA layer material properties • Treatment effect on existing pavement structure – Removal depth of existing HMA surface (milling) – Treatment application thickness • Treatment effect (short- and long-term) on existing HMA surface layer material properties – Dynamic modulus • Treatment impact (short- and long-term) on moisture and thermal profile of existing pavement – Surface shortwave absorptivity – Unbound layer modulus
Performance Modeling Parameters	• Immediate adjustment of post-treatment performance levels – Post-treatment distress/smoothness measurements • Long-term adjustment of post-treatment distress level via rate of redevelopment of distresses/smoothness – Reflection cracking (for HMA-surfaced treatments) – Faulting (for PCC-surfaced treatments)

to the default values provided in the Pavement ME Design software.

Example 1: HMA Pavement Preservation

Step 1: Identify Baseline Pavement Design and Preservation Treatments

The specifics of the baseline pavement design are:

- Pavement type: Conventional flexible pavement
- Design period: 20 years
- Functional class: Principal arterial
- Traffic:
  - Truck traffic classification (TTC): Predominantly single-trailer trucks (TTC 1)
  - Two-way average annual daily truck traffic (AADTT): 450 (assumed)
  - Number of lanes in the design direction: two
  - Percent trucks in design direction: 50
  - Percent trucks in design lane: 95
  - Vehicle class distribution and growth: Default
  - Monthly adjustment: Default
  - Axles per truck: Default
  - Operational speed: 50 mi/hr
  - Axle distribution: Default
  - Axle configuration: Default
  - Lateral wander: Default
  - Wheelbase: Default
- Closest weather station: Cortez, CO

Table 27 lists the CDOT-recommended preservation treatments for HMA-surfaced pavements (CDOT 2013).

Step 2: Identify Preservation Treatment Timing

It is assumed that microsurfacing will be applied 10 years after original construction.

Step 3: Identify Baseline and Preservation Treatment Material Properties

The following material properties for the baseline pavement are based on CDOT's *Standard Specifications for Road and Bridge Construction* and *Pavement Design Manual*:

- HMA: Grading SX (CDOT designation)
  - Mixture volumetrics

Table 27. Recommended preservation treatments for HMA-surfaced pavements (CDOT 2013).

Treatment	Distress Types Addressed	Typical Thickness	Comments
Crack Sealing	High-severity linear cracks	Not applicable	—
Patching	Medium- to high-severity alligator cracking	Varies depending on depth of distress	—
Chip Seal	Cracking, surface aging	Varies depending on aggregate size and number of applications	Estimated performance life is 8 to 10 years.
Thin Overlay or Microsurfacing	Surface friction, hydroplaning, raveling, low-severity cracking, bleeding	0.4 to 0.5 in.	Estimated performance life is 4 to 7 years.
Leveling Course or Milling	Rutting	Varies depending on rut depth	—
Cold In-Place Recycling (w/HMA overlay)	Not specified	2 to 4 in.	Estimated performance life is 6 to 21 years.
Hot In-Place Recycling (w/HMA overlay)	Rutting, wearing, raveling, non-structural surface cracking, aging, poor frictional characteristics	<2 in.	Estimated performance life is 6 to 23 years.

    - Unit weight: 150 lb/ft^3 (default)
    - Effective binder content: 10%
    - Air voids: 4%
    - Poisson's ratio: 0.35 (default)
  - Mechanical properties
    - Dynamic modulus: Level 3
    - Gradation: 100% passing ¾ in., 95% passing ⅜ in., 65% passing No. 4, and 6% passing No. 200
    - Reference temperature: 70°F
    - Asphalt binder type: PG 64-28
    - Indirect tensile strength: 464.65 lb/in.^{2} (internally calculated)
    - Creep compliance: Level 3
  - Thermal properties
    - Thermal conductivity: 0.67 BTU/hr-ft-°F (default)
    - Heat capacity: 0.23 BTU/lb-°F (default)
    - Thermal contraction: 1.185×10^{-5} (internally calculated)
  - Surface shortwave absorptivity: 0.85 (default)
  - Endurance limit: Not applied (not recommended until calibrated)
  - Layer interface: Full friction
- Unbound base: Class 6
  - Aggregate type: Crushed stone
  - Poisson's ratio: 0.40
  - Coefficient of lateral earth pressure: 0.5 (default)
  - Resilient modulus: 38,721 lb/in.^{2} (CDOT median value)
  - Gradation (median of specification range): 100% passing ¾ in., 47.5% passing No. 4, 40% passing No. 8, and 7.5% passing No. 200
  - Liquid limit: 10
  - Plasticity index: 2
- Subgrade: A-2-6
  - Poisson's ratio: 0.40
  - Coefficient of lateral earth pressure: 0.50 (default)
  - Resilient modulus: 16,000 lb/in.^{2} (default)
  - Gradation: Default
  - Liquid limit: 15
  - Plasticity index: 5

Because the MEPDG and the Pavement ME Design software do not provide material inputs (e.g., dynamic modulus, indirect tensile strength [IDT], heat capacity) for microsurfacing, the microsurfacing material properties were assumed to be similar to those for HMA layers. Also, because microsurfacing could reduce the potential for moisture intrusion through any existing cracks, an increase of 5% was assumed for the resilient modulus of the base course and subgrade. (Actual changes would need to be quantified from in-service and laboratory testing.)

Step 4: Quantify Effect of Treatment Application on Pavement Thickness

Although the typical thickness of microsurfacing is 0.40 to 0.50 in., the minimum thickness of an overlay that can be considered in the Pavement ME Design software is 1 in. Therefore, the microsurfacing thickness was assumed to be 1 in.

Step 5: Identify Effect of Treatment Application on Existing Layer Material Properties

Microsurfacing will be analyzed as an additional thickness of HMA; no modification to the existing asphalt concrete (AC) material properties will be required.

Table 28. Baseline design inputs.

<table>
<tr><th>Data Category</th><th>Data Element</th></tr>
<tr><td>Analysis Parameters</td><td>▪ Design strategy—conventional flexible pavement
▪ Design life—20 years</td></tr>
<tr><td>Performance Criteria and Reliability</td><td>▪ New flexible pavement performance indicators and reliability (assumed values)
<table>
<tr><th>Condition</th><th>Limit</th><th>Reliability</th></tr>
<tr><td>Initial IRI</td><td>60 in./mi</td><td>—</td></tr>
<tr><td>Terminal IRI</td><td>170 in./mi</td><td>90</td></tr>
<tr><td>Top-down cracking</td><td>2,000 ft/mi</td><td>90</td></tr>
<tr><td>Bottom-up cracking</td><td>25%</td><td>90</td></tr>
<tr><td>Thermal cracking</td><td>1,000 ft/mi</td><td>90</td></tr>
<tr><td>Total rut depth</td><td>0.75 in.</td><td>90</td></tr>
<tr><td>HMA rut depth</td><td>0.25 in.</td><td>90</td></tr>
</table></td></tr>
<tr><td>Pavement Layers</td><td>▪ Layer types
o HMA (CDOT grading SX)
o Unbound base (CDOT Class 6)
o Subgrade (A-2-6)</td></tr>
</table>

Step 6: Identify Immediate Effect of Treatment Application on Existing Condition

It is assumed that the application of the microsurfacing will reduce the rut depth to zero and IRI to 90 in./mi.

Step 7: Determine Dynamic Model

The dynamic model will assume reductions of the rut depth to zero (see Figure 14) and the IRI to 90 in./mi with the application of the microsurfacing layer.

Step 8: Develop a Baseline Design

The material inputs defined for the project (see Table 28) were entered into the Pavement ME Design program. The analysis determined that a 15-in.-thick pavement (7-in. HMA grading SX [PG 58-28] plus 8-in. Class 6 aggregate base) will meet all of the performance criteria (HMA layer thickness rounded up to the nearest 0.5 in.).

The results of this analysis are listed in Table 29, and plots for IRI, rut depth, thermal cracking, and fatigue cracking (corresponding to 90% reliability) over time are shown in Figures 16 through 19, respectively. As seen in these figures, the critical distress for the baseline design is HMA rutting (i.e., HMA rut depth reaches the threshold value of 0.25 in. by the end of the 20-year design period), at which time a preservation treatment may be applied to reduce future rutting.

Step 9: Develop a Preservation-Treated Design

The MEPDG and the Pavement ME Design software can be used to estimate the change in the performance or pavement life due to the application of a preservation treatment (Figure 20) or determine the required baseline design thickness if a preservation treatment is applied. Such analysis would consider pre- and post-treatment application periods (i.e., 0 to 10 years and 10 to 20 years).

The analysis was made in two steps: one for a new conventional HMA pavement with a 10-year performance period and another for a 1-in. microsurfacing (assumed to be a 1-in. HMA overlay) of the existing HMA pavement. The condition of the pavement prior to application of the overlay would be taken as predicted performance of the pavement after 10 years.

Except for an assumed 5% increase in base and subgrade moduli, all HMA layer properties, unbound base thicknesses and properties, and subgrade layer properties were unchanged from the baseline design. Traffic volumes were adjusted to replicate the baseline design by using the same

Table 29. Baseline design predictions.

Distress	Distress Criteria	Predicted Distress	Achieved Reliability
Terminal IRI, in./mi	170	138	99
Rut Depth – Total, in.	0.75	0.53	100
Rut Depth – HMA, in.	0.25	0.25	90
Bottom-Up Cracking, %	25	0.07	100
Top-Down Cracking, ft/mi	2,000	1,284	98
Transverse Thermal Cracking, ft/mi	1,000	27	100

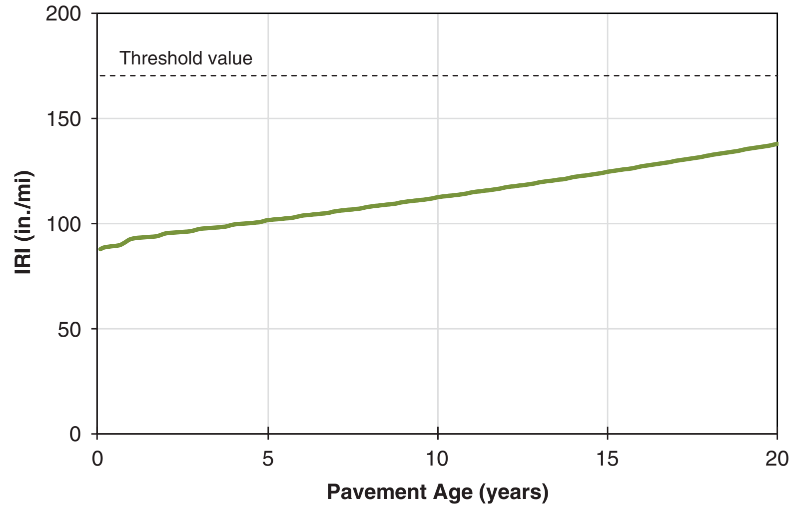


Figure 16. Predicted IRI (90% reliability) for baseline design.

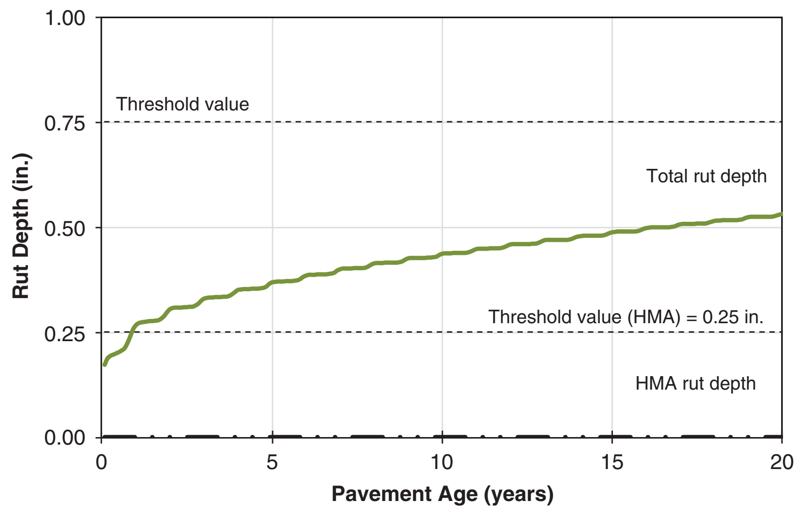


Figure 17. Predicted total rut depth (90% reliability) for baseline design.

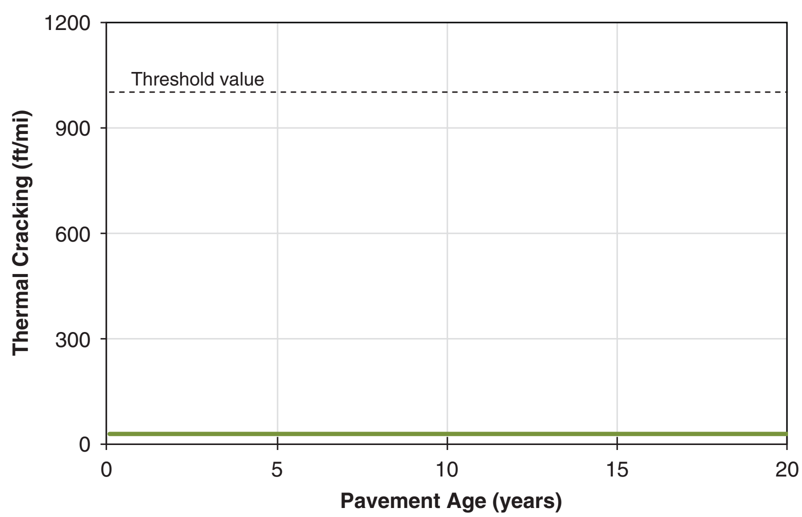


Figure 18. Predicted transverse thermal cracking (90% reliability) for baseline design.

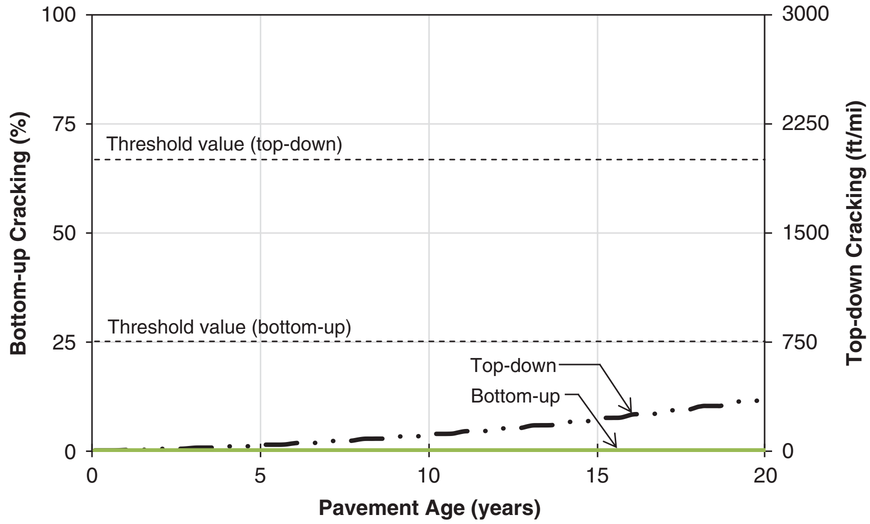


Figure 19. Predicted fatigue cracking (90% reliability) for baseline design.

traffic characteristics for the first period (Years 0 through 10) and projected traffic volumes for the second period (Years 11 through 20). In this manner, the baseline and preservation-treated designs experience the same traffic loadings. Table 30 lists the inputs for the preservation-treated design.

For these inputs, a 12-in.-thick pavement section is required to meet all performance criteria, consisting of 4-in. HMA grading SX (PG 58-28) and 8-in. Class 6 aggregate base; a 1-in.-thick overlay (microsurfacing) will be applied after 10 years. The predicted performance at 10 and 20 years is shown in Table 31. Plots for IRI, rut depth, thermal cracking, and total cracking (which includes reflective cracking and new bottom-up, top-down cracking) versus age are shown in Figures 21 through 24, respectively.

Figure 21 shows that, although an increase in IRI is predicted following the application of the treatment in Year 10, the predicted IRI remains below the threshold level over the 20-year design life. Figure 22 illustrates the predicted total rut depth at 90% reliability for the pavement (before and after preservation). The analysis assumes that the application of the 1-in. microsurfacing layer reduced the total rut depth (i.e., 0.50 in.) in Year 10 to zero. Figures 23 and 24 illustrate the predicted transverse thermal cracking and total cracking (at 90% reliability), respectively. The level of predicted cracking for the preservation-treated pavement is very low.

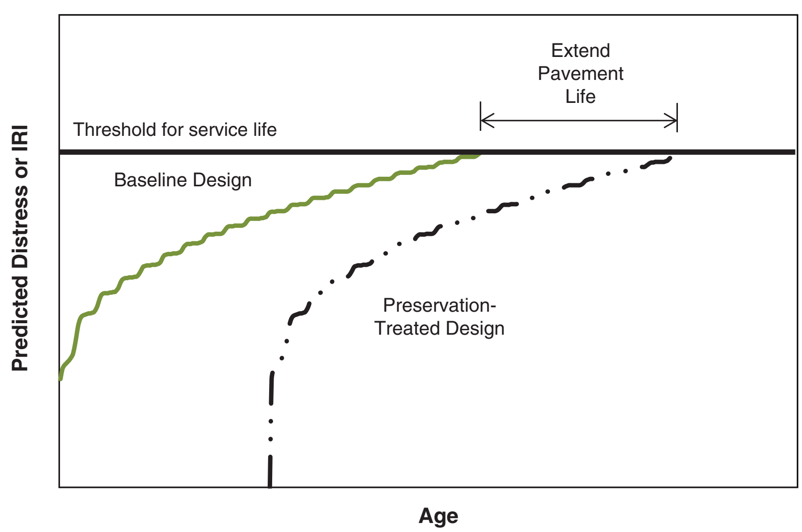


Figure 20. Illustration of the effect of preservation treatment application on pavement life.

Table 30. Preservation-treated design inputs.

<table>
<tr><th>Data Category</th><th>Data Element</th></tr>
<tr><td>Analysis Parameters</td><td>• New construction—conventional flexible pavement
– Design life—10 years
• HMA overlay (microsurfacing) of conventional flexible pavement
– Design life—10 years</td></tr>
<tr><td>Performance Criteria and Reliability</td><td>• New flexible pavement performance indicators and reliability (assumed values)
<table>
<tr><th>Condition</th><th>Limit</th><th>Reliability</th></tr>
<tr><td>Initial IRI</td><td>60 in./mi</td><td>—</td></tr>
<tr><td>Terminal IRI</td><td>170 in./mi</td><td>90</td></tr>
<tr><td>Top-down cracking</td><td>2,000 ft/mi</td><td>90</td></tr>
<tr><td>Bottom-up cracking</td><td>25%</td><td>90</td></tr>
<tr><td>Thermal cracking</td><td>1,000 ft/mi</td><td>90</td></tr>
<tr><td>Total rut depth</td><td>0.75 in.</td><td>90</td></tr>
<tr><td>HMA rut depth</td><td>0.25 in.</td><td>90</td></tr>
</table>
• HMA overlay (microsurfacing) of existing AC pavement performance indicators and reliability (assumed values)
<table>
<tr><th>Condition</th><th>Limit</th><th>Reliability</th></tr>
<tr><td>Initial IRI</td><td>90 in./mi</td><td>—</td></tr>
<tr><td>Terminal IRI</td><td>170 in./mi</td><td>90</td></tr>
<tr><td>Top-down cracking</td><td>2,000 ft/mi</td><td>90</td></tr>
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<tr><td>Total rut depth</td><td>0.75 in.</td><td>90</td></tr>
<tr><td>HMA rut depth</td><td>0.25 in.</td><td>90</td></tr>
</table></td></tr>
<tr><td>Pavement Layers</td><td>• Layer types—new construction
– HMA (CDOT grading SX)
– Unbound base (CDOT Class 6)
– Subgrade (A-2-6)
• Layer types—HMA overlay (microsurfacing)
– 1-in. HMA overlay (microsurfacing) (CDOT grading SX)
– New construction pavement section</td></tr>
</table>

Summary

Analysis was conducted to estimate the effects of applying a microsurfacing (modeled as a 1-in. HMA overlay) in Year 10 of a 20-year design. The baseline design resulted in a pavement section consisting of 7 in. of HMA over 8 in. of aggregate base. The preservation-treated design was evaluated at 10 years (both prior to and after the application of microsurfacing). The evaluation resulted in a pavement structure consisting of a 4-in. HMA layer on an 8-in aggregate base (with the 1-in. microsurfacing placed at Year 10).

There are a number of issues that require further consideration:

- The material properties and aging effects of the microsurfacing were assumed to be the same as those of an HMA layer. To better evaluate the effects of microsurfacing treatment (or other treatment application), the treatment material properties, the potential changes to the existing layer(s), and aging effects need to be quantified.
- Although the same cumulative number of trucks was assumed before and after the preservation application,

Table 31. Summary of distress prediction.

Distress	Distress Criteria	At 10 Years (prior to overlay/microsurfacing)		At 20 Years (10 years after overlay/microsurfacing)	
		Predicted Distress	Achieved Reliability	Predicted Distress	Achieved Reliability
Terminal IRI, in./mi	170	115	100	164	93
Total Rut Depth, in.	0.75	0.50	100	0.40	100
HMA Rut Depth, in.	0.25	0.18	100	0.06	100
Bottom-Up Cracking, %	25	0.16	100	1.45	100
Top-Down Cracking, ft/mi	2,000	1,635	94	1,394	97
Transverse Thermal Cracking, ft/mi	1,000	27	100	27	100

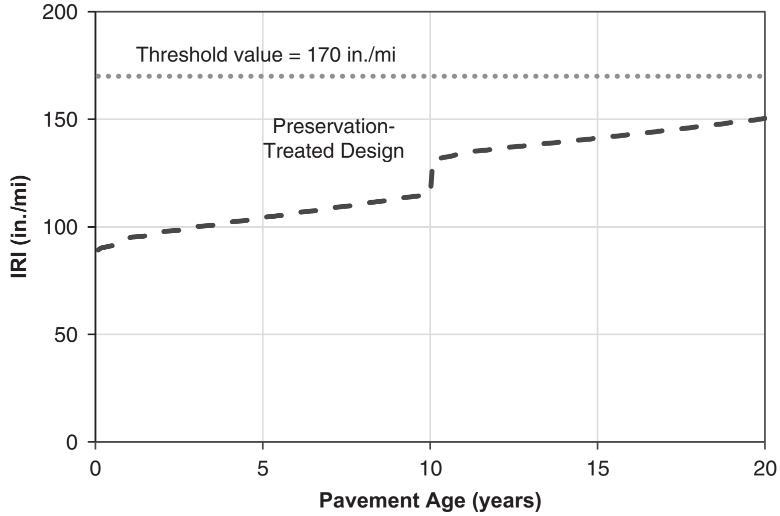

Figure 21. Predicted IRI.

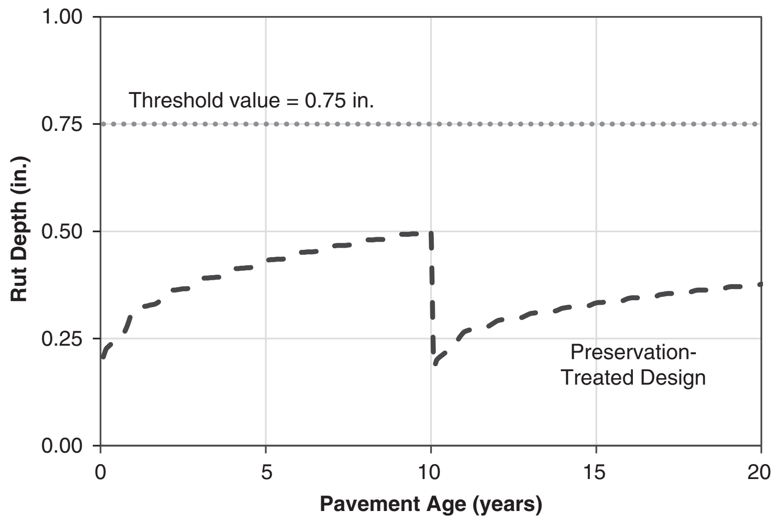

Figure 22. Predicted rut depth.

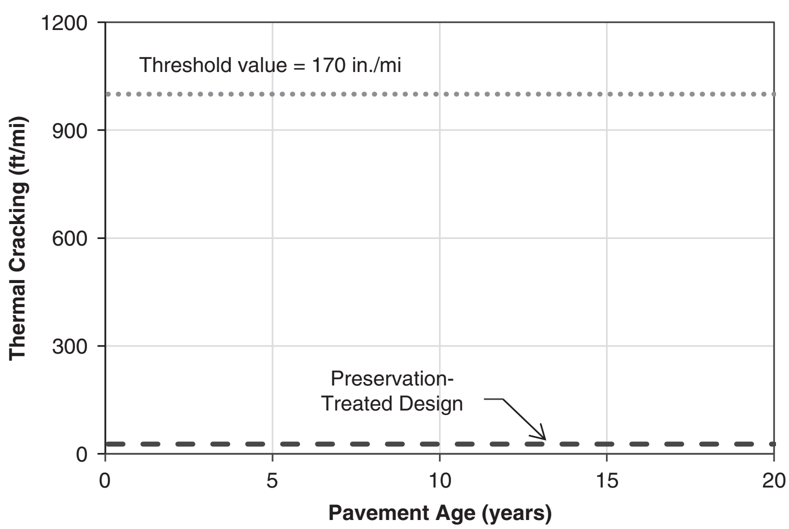

Figure 23. Predicted transverse thermal cracking.

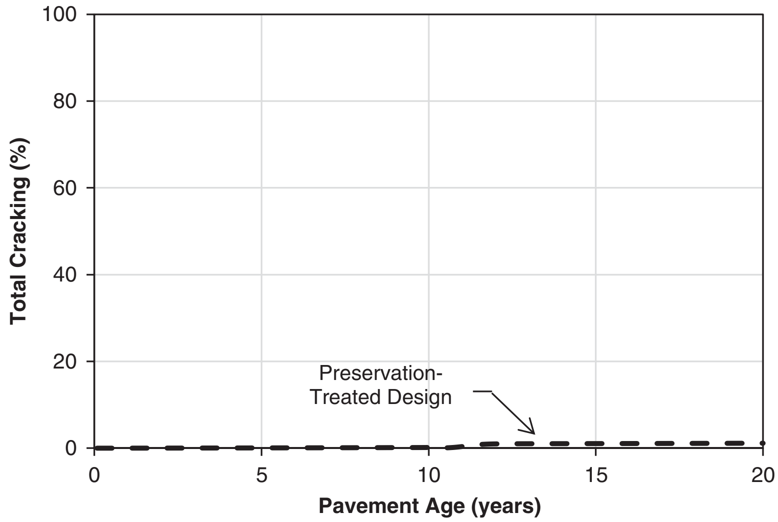

Figure 24. Predicted total cracking.

conducting the analysis in two separate periods may not fully quantify the effects of repeated load applications and aging/climatic effects.

- Increasing the resilient modulus of the unbound and subgrade layers to account for the reduction in moisture infiltration may not lead to appropriate consideration of the effect of a preservation treatment application. Although sealing of surface cracks and joints will minimize moisture infiltration, the effect of crack sealing on unbound and subgrade layer characteristics has not been established or considered in the EICM.

To illustrate the potential effects of the microsurfacing treatment on the fatigue characteristics of the existing asphalt layer, analysis was conducted considering a softening or rejuvenating effect of the treatment on the top portion of the existing asphalt layer. Within the MEPDG, increasing the effective asphalt content by volume (V_{be}) and lowering the percent air voids in the asphalt mixture (V_a) will reduce the amount of predicted fatigue cracking but will increase rutting in the asphalt layer (ARA, Inc. 2004).

For this analysis, 10% and 25% higher V_{be} values (and corresponding 10% and 25% lower V_a values) were assumed for the existing asphalt layer. These changes resulted in very slight changes in the predicted distresses.

Example 2: PCC Pavement Preservation

Step 1: Identify Baseline Pavement Design and Preservation Treatments

The specifics of the baseline pavement design are as follows:

- Pavement type: JPC pavement
- Design period: 30 years
- Functional class—principal arterial
- Traffic:
  - TTC, predominantly single-trailer trucks (TTC 1)
  - Two-way AADTT: 3,000 (assumed)
  - Number of lanes in the design direction: two
  - Percent trucks in design direction: 50
  - Percent trucks in design lane: 95
  - Vehicle class distribution and growth: default
  - Monthly adjustment: Default
  - Axles per truck: Default
  - Operational speed: 60 mi/hr
  - Axle distribution: Default
  - Axle configuration: Default
  - Lateral wander: Default
  - Wheelbase: Default
- Closest weather station: Denver, CO

Table 32 lists the recommended CDOT preservation treatments for JPC-surfaced pavements.

Step 2: Identify Preservation Treatment Timing

Diamond grinding treatment will be applied 20 years after original construction.

Step 3: Identify Baseline and Preservation Treatment Material Properties

The material properties and other parameters for the baseline pavement are based on the CDOT's *Standard Specifications for Road and Bridge Construction* and *Pavement Design Manual*:

- PCC
  - Unit weight: 150 lb/ft^3 (default)
  - Poisson's ratio: 0.20 (default)

Table 32. Recommended preservation treatments for JPC pavements (CDOT 2013).

<table>
<tr><th>Treatment Type</th><th>Distress Types Addressed</th><th>Typical Thickness</th><th>Comments</th></tr>
<tr><td>Joint/Crack Resealing</td><td>Cracking, joint seal damage</td><td>Not applicable</td><td>1 to 4 years (typical)</td></tr>
<tr><td>Diamond Grooving</td><td>Macrotexture</td><td>Not applicable</td><td>—</td></tr>
<tr><td>Diamond Grinding</td><td>Faulting, roughness, macrotexture, pavement/tire noise, curling and warping, cross-slope</td><td>0.25 in.</td><td><table><tr><th>ADT, veh/day</th><th>IRI, in./mi</th></tr><tr><td><3,000</td><td>90</td></tr><tr><td>3,000 to 10,000</td><td>76</td></tr><tr><td>>10,000</td><td>63</td></tr></table></td></tr>
<tr><td>Partial-Depth Repair</td><td>Localized surface distress</td><td>Not applicable</td><td>—</td></tr>
<tr><td>Full-Depth Repair</td><td>Severe spalling, joint/crack deterioration, full-depth cracks that divide a panel into two or more parts</td><td>Not applicable</td><td>—</td></tr>
<tr><td>Cross-Stitching</td><td>Poor load transfer at longitudinal joints</td><td>Not applicable</td><td>—</td></tr>
<tr><td>Slab Stabilization</td><td>Loss of support, faulting, corner breaks, settled slabs</td><td>Not applicable</td><td>—</td></tr>
<tr><td>Dowel-Bar Retrofit</td><td>Poor load transfer at transverse joints</td><td>Not applicable</td><td>—</td></tr>
</table>

  - Thermal properties
    - Coefficient of thermal expansion: 5.5 in./in./°F × 10^{-6} (default)
    - Thermal conductivity: 1.25 BTU/hr-ft-°F (default)
    - Heat capacity: 0.28 BTU/lb-°F (default)
  - Mix
    - Cement type: Type I
    - Cementitious material content: 500 lbs/yd^3
    - Water-to-cement ratio: 0.42
    - Aggregate type: Limestone
    - PCC zero-stress temperature: Calculated
    - Ultimate shrinkage: Calculated
    - Reversible shrinkage: 50% (default)
    - Time to develop 50% of ultimate shrinkage: 35 days (default)
    - Curing method: Curing compound
  - Modulus of rupture: 650 lb/in.^{2}
  - Surface shortwave absorptivity: 0.85
  - Joint spacing: 15 ft
  - Sealant type: Liquid sealant
  - Doweled joints: No dowels
  - Widened slab: No
  - Tied shoulders: No
  - Erodibility index: Fairly erodible
  - PCC-base contact friction: Full friction with friction loss at 240 months
  - Permanent curl/warp effective temperature difference: −10°F
- Unbound base: Class 6
  - Aggregate type: Crushed stone
  - Poisson's ratio: 0.40
  - Coefficient of lateral earth pressure: 0.5 (default)
  - Resilient modulus: 38,721 lb/in.^{2} (CDOT average value)
  - Gradation (median of specification range): 100% passing ¾ in., 47.5% passing No. 4, 40% passing No. 8, and 7.5% passing No. 200
  - Liquid limit: 10
  - Plasticity index: 2
- Subgrade: A-2-6
  - Poisson's ratio: 0.40
  - Coefficient of lateral earth pressure: 0.50 (default)
  - Resilient modulus: 16,000 lb/in.^{2} (default)
  - Gradation: Default
  - Liquid limit: 15
  - Plasticity index: 5

Step 4: Quantify Impact of Treatment Application on Pavement Thickness

The diamond grinding application is assumed to reduce the thickness of the existing PCC by 0.25 in.

Step 5: Identify Impact of Treatment Application on Existing Layer Material Properties

Diamond grinding is assumed to have no effect on the existing pavement layer material properties.

Step 6: Identify Immediate Impact of Treatment Application on Existing Condition

It is assumed that diamond grinding will reduce faulting to zero and IRI to 90 in./mi.

Table 33. Baseline design inputs.

Data Category	Data Element
Analysis Parameters	• Design strategy—jointed plain concrete pavement • Design life—30 years
Performance Criteria and Reliability	• New concrete pavement performance indicators and reliability (assumed values) <table><tr><th>Condition</th><th>Limit</th><th>Reliability</th></tr><tr><td>Initial IRI</td><td>60 in./mi</td><td>—</td></tr><tr><td>Terminal IRI</td><td>170 in./mi</td><td>90</td></tr><tr><td>JPC pavement transverse cracking</td><td>15%</td><td>90</td></tr><tr><td>Mean joint faulting</td><td>0.12 in.</td><td>90</td></tr></table>
Pavement Layers	• Layer types – PCC – Unbound base (CDOT Class 6) – Subgrade (A-2-6)

Table 34. Summary of baseline design condition prediction.

Distress	Distress Criteria	Predicted Distress	Achieved Reliability
Terminal IRI, in./mi	170	149	97
Mean Joint Faulting, in.	0.12	0.12	90
Transverse Cracking, % slabs	15	4.4	100

Step 7: Determine Dynamic Model

The dynamic model will incorporate resetting the faulting to zero (see Figure 15) and the IRI to 90 in./mi upon diamond grinding application.

Step 8: Develop a Baseline Design

The material inputs listed in Table 33 were entered into the Pavement ME Design software program.

The analysis determined that a 16-in.-thick pavement (10-in. PCC on 6-in. Class 6 aggregate base) will meet all of the performance criteria. The results of this analysis are listed in Table 34, and the predicted IRI, faulting, and panel crack predictions are shown in Figures 25 through 27, respectively (at a 90% reliability level).

In this example, the level of faulting controls the recommended pavement design. IRI is predicted to reach a maximum value of 149 in./mi, the mean joint faulting is at the threshold

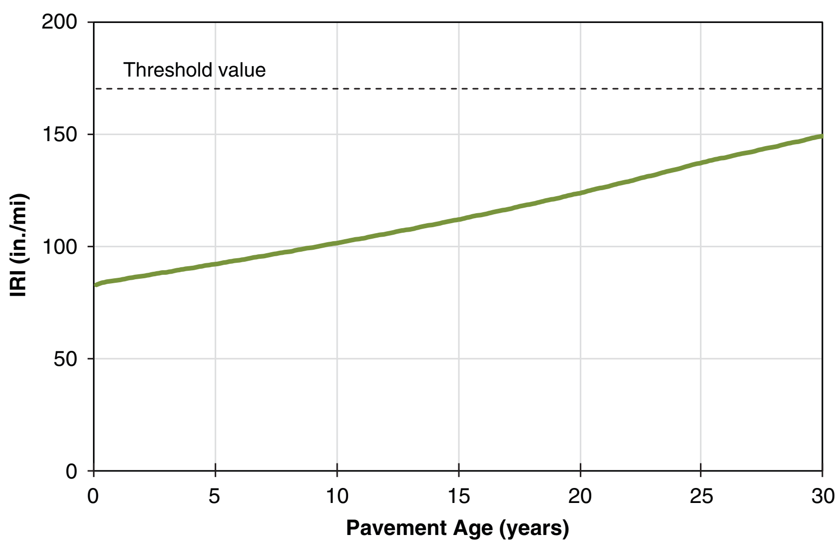

Figure 25. Predicted IRI for baseline design.

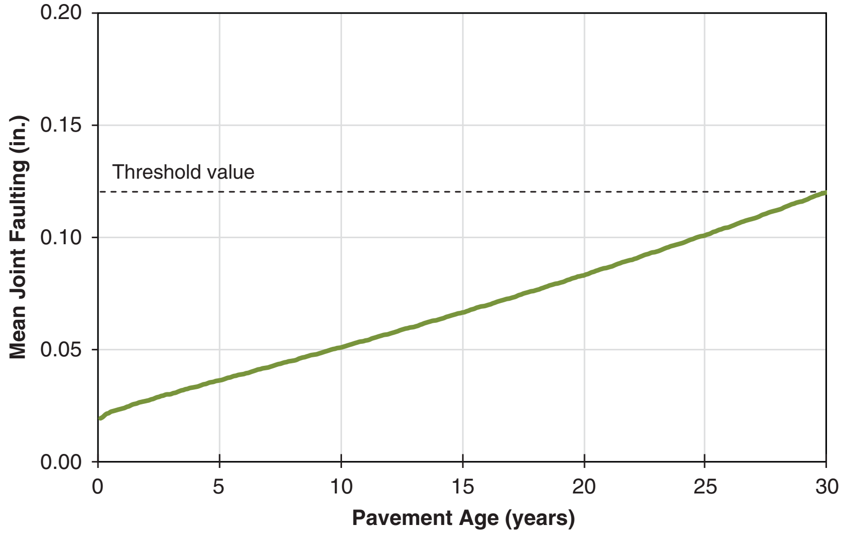

Figure 26. Predicted joint faulting for baseline design.

value of 0.12 in., and transverse slab cracking is estimated to reach approximately 4% (all at 90% reliability).

Step 9: Develop a Preservation-Treated Design

No changes to the material inputs were assumed. The analysis considered pre- and post-preservation periods (i.e., 0 to 20 years and 20 to 30 years). For this example, the PCC thickness was reduced by 0.25 in. for the 20- to 30-year period, and the initial IRI was reduced to 90 in./mi.

The analysis showed that a 15-in.-thick pavement (9-in. PCC on 6-in. Class 6 aggregate base) will meet all of the performance criteria if diamond ground after 20 years. The predicted performance at 20 and 30 years is listed in Table 35, and the predicted IRI, faulting, and panel cracking are shown in Figures 28 through 30, respectively. Figure 28 shows that the predicted IRI remains below the threshold level over the 30-year design life, and Figures 29 and 30 show that mean joint faulting and transverse cracking stay below the respective threshold levels before and after diamond grinding over the 30-year period.

Summary

Analysis was conducted to estimate the effects of applying a diamond grinding treatment (modeled as a reduction in thickness and resetting IRI to 90 in./mi) in Year 20 of a 30-year design. The baseline design resulted in a pavement

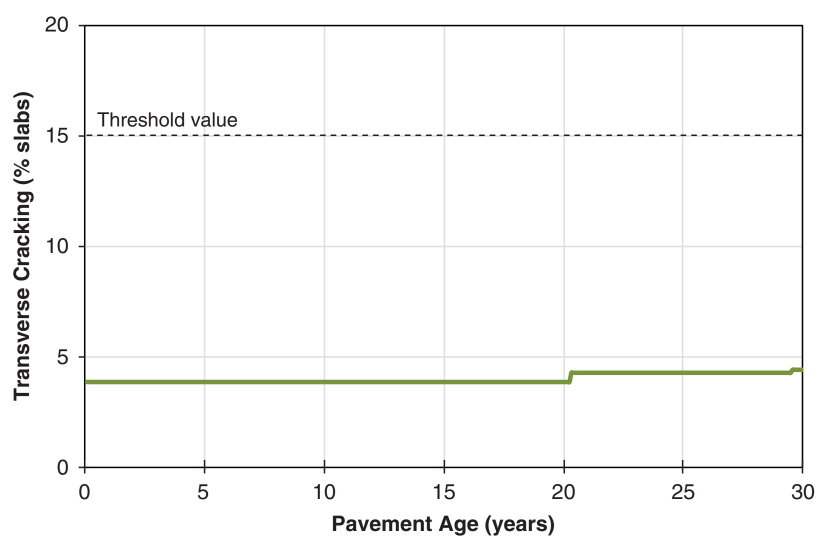

Figure 27. Predicted slab cracking for baseline design.

Table 35. Summary of distress prediction.

Distress	Distress Criteria	At 20 Years (prior to grinding)		At 30 Years (10 years after grinding)	
		Predicted Distress	Achieved Reliability	Predicted Distress	Achieved Reliability
Terminal IRI, in./mi	170	140	98	163	93
Mean Joint Faulting, in.	0.12	0.11	94	0.09	99
Transverse Cracking, % slabs	15	4.49	100	4.39	100

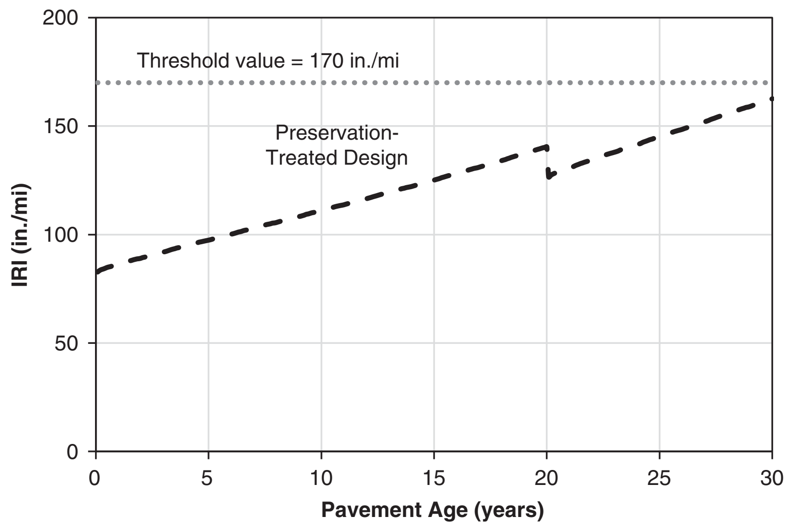

Figure 28. Predicted IRI.

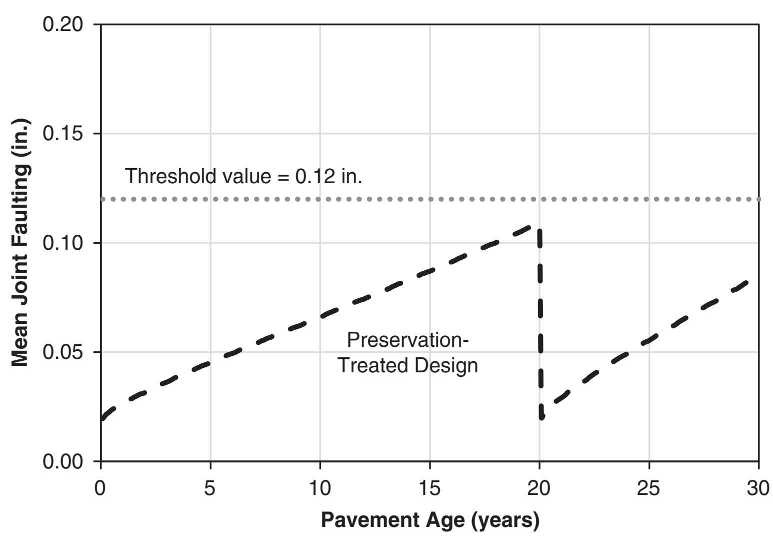

Figure 29. Predicted joint faulting.

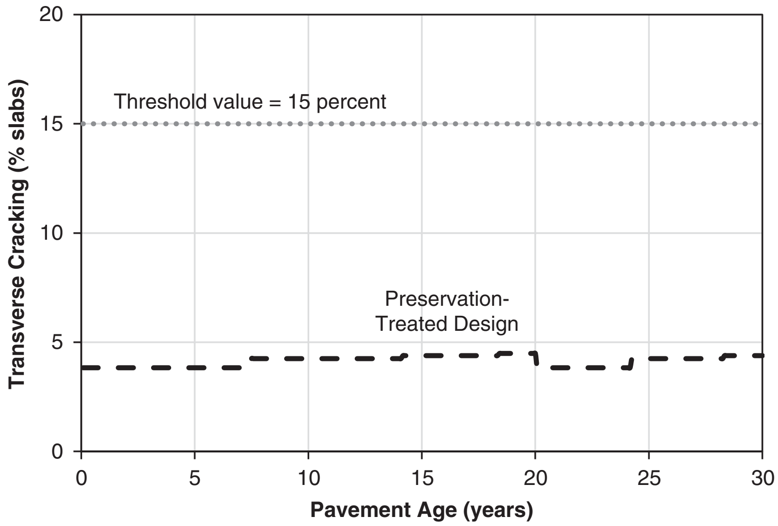

Figure 30. Predicted transverse cracking.

section consisting of 10 in. of PCC over 6 in. of crushed stone base. The preservation-treated design was evaluated at 20 years (prior to grinding) and 10 years thereafter. The evaluation resulted in a pavement structure consisting of a 9-in. PCC layer on a 6-in. aggregate base, with the diamond grinding occurring at Year 20. Although the same cumulative number of trucks was assumed before and after the preservation application, conducting the analysis in two separate periods may not fully quantify the effects of repeated load applications.

CHAPTER 7

Summary and Recommendations for Research

Summary

This research was initially intended to develop procedures for incorporating pavement preservation treatments into the MEPDG design analysis process. However, in reviewing the data available from several SHAs, it was determined that sufficient data were not available to achieve this objective. The project objective was modified to focus on identifying and describing processes for developing such procedures.

The research included a review of information relevant to pavement preservation and pavement design (primarily as related to the MEPDG) and interviews with representatives of selected SHAs and pavement industry groups to assess pavement preservation and pavement design practices and availability of data to support the development of procedures for incorporating preservation into the MEPDG. Also, the LTPP and other test sections used in the development and calibration of the MEPDG performance prediction models were identified and examined to determine if any preservation treatments were applied to those sections and thus already accounted for in these models. Based on this work, three approaches that would allow the consideration of preservation in the MEPDG design and analysis procedures were identified and illustrated by examples.

Pavement Preservation State of the Practice

Although there is growing use of pavement preservation by state highway agencies, there is a lesser tendency to apply these treatments to high-volume roads and in severe climates. The most commonly used preservation treatment types for HMA-surfaced pavements are crack sealing/filling, microsurfacing, thin HMA overlay, and drainage maintenance. For PCC pavements, diamond grinding, partial- and full-depth repair, joint resealing, load transfer retrofit, and drainage maintenance are commonly used. These treatments, and variants thereof, are appropriate candidates for incorporating into the MEPDG design.

Many studies on pavement preservation performance have been conducted over the past 20 years. Early studies generally focused on subjective, experience-based estimates of performance or on historical records (treatment application frequency) as a basis for estimating performance. More recent studies have focused on objective measures of performance involving the collection and analysis of time-series performance data from in-service pavement sections or experimental test sections.

Treatment performance can be assessed in terms of treatment service life, pavement life extension, and performance benefit area. Historical data on how the structural and performance indicators are influenced by preservation are needed for considering preservation in the design process.

SHAs have evaluated preservation treatment performance, although there were some issues with tracking the locations of preservation treatment projects in the databases and the reliability of the collected data. However, some agencies established performance models that often focused on just one performance parameter (e.g., IRI). Specific types of data in adequate amounts and format are needed to support consideration in the design process.

MEPDG Evaluation, Implementation, and Use

Many SHAs have been or are currently engaged in the evaluation, implementation, and use of the MEPDG process. At least three studies have addressed the design of pavements considering the effects of preservation. In one of these studies, the developed ME-based flexible pavement design program (CalME) allows a user to schedule one or more predefined M&R or preservation treatments as part of the design, and accounts for their effects on material and pavement structure mechanical properties.

The investigation of the LTPP pavement sections used in developing and calibrating the MEPDG models indicated some degree of influence on the models by preservation treatments. However, incorporating preservation directly into the MEPDG will remain a difficult task because of the lack of specific information on the effects of preservation.

Approaches for Incorporating Preservation into the MEPDG

Three approaches for considering preservation in the design and analysis procedures were identified. Each approach has distinct advantages and disadvantages influencing its potential for implementation and use. One approach accounts for all aspects of structural and functional performance. Another approach builds off the calibration/validation process outlined in the AASHTO *Local Calibration Guide* (AASHTO 2010) but requires a substantive set of preservation-treated test sections and the collection of time-series performance data to support development of calibrated models. A third approach considers the changes in pavement materials and structure properties resulting from treatment application but involves a high level of complexity to accurately define the immediate and long-term changes resulting from a treatment application.

Several SHAs indicated a lack of the data needed to fully develop and validate the alternative approaches. A few states have several years of network-level preservation treatment performance data, but there are various issues with the data (e.g., inaccurate; hard-to-access location, cross-section, and history information; incompatibilities with MEPDG parameters) that would make their use questionable. A few states have good but limited project-level data available in terms of the quantity of pavement sections or the time-series performance.

Preservation treatments have not typically been considered in the pavement design process because of the insignificant contributions to pavement structural capacity and the inability to quantify their effects. The inability to accurately quantify both initial and long-term effects of preservation treatments on performance makes their inclusion in pavement design and analysis procedures difficult.

Recommendations for Future Research

The information and findings from this study advance the goal of considering the effects of preservation in the pavement design process. However, further research is needed to fully develop and validate one or more of the approaches presented in this report, including the following:

- *MEPDG Performance Model Calibrations for Preservation.* There is a need to perform calibrations of the MEPDG models using data from the SPS-3 and SPS-4 test sections and other test sections and to develop calibration factors for the various flexible and rigid pavement preservation treatments.
- *LTPP Pavement Materials and Structure Properties.* There is a need to evaluate in situ and laboratory testing data for the various SPS-3 and SPS-4 test sections to determine effects of preservation treatments on surface permeability, asphalt aging with depth, and structural response.
- *Evaluate the Pavement ME Design Software Ability to Incorporate Preservation in the Design.* Research is needed to develop procedures for incorporating the effects of preservation in the models contained in the Pavement ME Design software.
- *Evaluate the Effects of Preservation on Material Properties.* Actual data on the effects of preservation treatments on HMA surface layer material properties and the moisture and thermal profile of the existing pavement are limited. Further research is needed to provide direct inputs for use into the MEPDG procedures.

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Appendices A Through I

Appendices A through I are not published herein; they are available on the report summary web page, which can be found by searching for *NCHRP Report 810* at www.TRB.org.

Abbreviations and acronyms used without definitions in TRB publications:

A4A	Airlines for America
AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
MAP-21	Moving Ahead for Progress in the 21st Century Act (2012)
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation

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