NCHRP
REPORT 523

Optimal Timing of Pavement Preventive Maintenance Treatment Applications

TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

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SUBJECT AREAS
Maintenance

TRANSPORTATION RESEARCH BOARD

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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FOREWORD

By Amir N. Hanna
Staff Officer
Transportation Research
Board

This report describes a methodology for determining the optimal timing for the application of preventive maintenance treatments to flexible and rigid pavements. The methodology is also presented in the form of a macro-driven Microsoft® Excel Visual Basic Application—designated OPTime—available to users by accessing the NCHRP website (http://trb.org/news/blurb_detail.asp?id=4306). The methodology is based on the analysis of performance and cost data and applies to any of the treatments and application methods that are used by highway agencies. A plan for constructing and monitoring experimental test sections is also provided to assist highway agencies in collecting the necessary data if such data are not readily available. The report is a useful resource for state and local highway agency personnel and others involved in pavement maintenance and preservation.

Various preventive maintenance treatments are employed by highway agencies to restore pavement condition and retard future deterioration. For specific climate conditions and traffic levels, the performance of the restored pavement will depend not only on the type of maintenance treatment, but also on the existing pavement condition when these treatments are applied. However, these relationships are not well documented and a rational methodology for determining the optimal timing for applying a specific preventive maintenance treatment is not readily available. Without such a methodology, the optimal timing for the application of pavement treatments cannot be reasonably identified, leading to an application of the treatment at a less desirable time that also makes it more costly. NCHRP Project 14-14 was conducted to address this need.

Under NCHRP Project 14-14, "Guide for Optimal Timing of Pavement Preventive Maintenance Treatment Applications," Applied Pavement Technology, Inc., of Downers Grove, Illinois, was assigned the objectives of (1) developing a methodology for determining the optimal timing for the application of preventive maintenance treatments to flexible and rigid pavements; (2) presenting the methodology in the form of a user-oriented computational process to facilitate its use for the variety of pavement maintenance situations encountered by highway agencies; and (3) developing a plan, for use by highway agencies, to collect the data needed to support the proposed methodology. In this project, preventive maintenance referred to any planned strategy of cost-effective treatments to an existing roadway system that preserves the system, retards future deterioration, and maintains and improves the functional condition of the system (without substantially increasing structural capacity). To accomplish the project objectives, the researchers performed the following tasks:

1. Reviewed domestic and foreign literature pertaining to the timing, selection, and performance of preventive maintenance treatments of flexible and rigid pavements.

2. Identified appropriate preventive maintenance treatments for ranges of climatic conditions, traffic levels, and pre-treatment pavement condition.
3. Developed a methodology for identifying the optimal timing for application of preventative maintenance treatments that considers the cost-effectiveness and performance of maintenance treatments.
4. Presented the methodology in the form of an Excel spreadsheet to facilitate its use for the variety of pavement maintenance situations encountered by highway agencies.
5. Demonstrated the applicability of the methodology by using data from a limited number of projects to compare the impact of the timing of treatment application on the annual costs and service life.
6. Developed a plan for constructing and monitoring test sections for the purpose of collecting the data needed to support the developed methodology.

The methodology developed in this project provides a means for comparing the performance and costs associated with the application of specific treatments at different points in the age (or condition) of a pavement. The performance is measured by the cumulative improvement in pavement condition that occurs until pavement failure (i.e., major rehabilitation is required) or treatment failure (i.e., benefit is no longer realized) over the expected condition if no treatment were applied (do-nothing alternative). This improvement is measured by one or more pavement performance indicators (e.g., rutting, cracking, and roughness). The methodology allows the consideration of multiple condition indicators to which different levels of relative importance can be assigned to reflect the highway agency's perspective on these indicators. The methodology is presented in the form of a macro-driven Microsoft® Excel Visual Basic Application—designated OPTime—to facilitate its use. The methodology and a related user's guide are available on the NCHRP website (http://trb.org/news/blurb_detail.asp?id=4306).

The findings of this research pointed out the importance of preventive maintenance programs and the need for developing a guide for determining the optimal timing of maintenance treatment applications. However, because of the lack of sufficient data to develop such a guide, the research identified the need for establishing a database of the performance of preventive maintenance treatments and developed a plan for constructing and monitoring test sections to collect the relevant data.

The primary product of this research—a methodology for determining the optimal timing for the application of preventive maintenance treatments to flexible and rigid pavements—provides a viable approach for comparing the performance and costs associated with application of treatments at different ages. When combined with performance data obtained from in-service projects or otherwise estimated, this approach can be used to select an optimal application age. Such information should be useful to highway agencies and contracting firms involved in preventive maintenance and preservation activities.

CONTENTS

OPTIMAL TIMING OF PAVEMENT PREVENTIVE MAINTENANCE TREATMENT APPLICATIONS

SUMMARY

As highway agency budgets shrink, more and more highway agencies are moving toward a policy of pavement preventive maintenance and away from worst-first programming (in which pavements are allowed to deteriorate to a highly distressed condition before any restorative work is performed). Preventive maintenance is a systematic process of applying a series of preventive maintenance treatments over the life of the pavement to maintain a good condition, extend pavement life, and minimize life-cycle costs. Although pavement preventive maintenance is believed to result in lower agency costs, improved pavement conditions, and increased customer satisfaction, these programs continue to face many obstacles. Among these obstacles are lack of proof that preventive maintenance is cost effective and insufficient guidance on when preventive maintenance treatments should be applied. Consequently, highway agencies need a procedure that can help to demonstrate the cost-effectiveness of preventive maintenance treatments and to provide guidance on the optimal timing of such treatments.

PROJECT OBJECTIVES

The primary objective of this research was to develop a methodology for determining the optimal timing for the application of preventive maintenance treatments to flexible and rigid pavements. The methodology needed to be flexible enough to consider the variety of treatments that are used and the different ways of monitoring their performance. Also, the methodology needed to be useful both to agencies that already have a preventive maintenance program and to those considering the implementation of such a program.

A secondary objective of the research was to create a user-friendly tool to aid in the implementation of this methodology. Applicability of the methodology was tested using data from actual pavement projects. A plan for obtaining the data needed to support the proposed methodology was also developed to guide agencies not currently collecting preventive maintenance-related data.

FINDINGS

Researchers first contacted highway agencies in the United States and abroad to iden-tify the techniques that are being used to determine the optimal time to apply preventive maintenance treatments. It was found that there was almost no guidance available on this topic, and there was no indication of attempts to optimize the timing of treatment placement. Techniques used to determine the time to apply preventive maintenance included the following:

- A predetermined treatment schedule
- Time since a previous maintenance or rehabilitation event
- Maintenance surveys
- A pavement management system

Because of the lack of available information from highway agency practice, the research focused on defining a methodology that could be used by agencies interested in placing the right treatment on the right pavement at the right time. The methodology is based on the premise that if a specific treatment is applied to a pavement at different times in its life, it will provide different benefits. Conceptually, there is a timing "win-dow" during the life of the pavement in which the maximum benefit from the mainte-nance treatment is attained, that is, the treatment will provide little to no benefit if it is placed either too soon or too late. This concept requires the use of a meaningful mea-sure of benefit. Benefit is defined in this research as the difference in condition over time between the treated pavement and the performance of the same pavement if no treatment had been applied. This definition allows benefit to be negative or positive.

Because highway agencies use many different technologies and procedures to mon-itor and report on the performance of pavements, the methodology had to be flexible enough to include different measures of benefit. It was also necessary to address the fact that different measures of performance could be used by the same agency. For example, routinely collected monitoring information might include roughness, friction, and a measure of surface distress in the form of a composite index or single measures (e.g., rutting). Because the optimal time to apply a treatment is not solely when the greatest improvement in condition is realized but when the greatest improvement in condition is realized at the lowest cost, the methodology incorporates a comparison of benefit-cost ratios to identify the optimal timing. This comparison requires the ability to estimate the benefits and costs of applying a treatment at different times.

While the optimal timing methodology is conceptually simple, its application is complex. A Microsoft® Excel-based tool, OPTime, was developed to make the method-ology easy to apply. The resultant product is a versatile tool that allows users to ana-lyze existing pavement treatment performance data applied over a period of years to identify the optimal time to apply that treatment. Recognizing that agencies do not nec-essarily have data to analyze, the tool also has the capability to perform "what if" analy-ses with user-defined performance trends rather than with actual data.

Because state highway agencies (SHAs) do not necessarily have all the data needed to perform an analysis, a plan for generating such data was developed. The plan offers guidance on selecting treatments to study, constructing test sections, and monitoring performance over time.

Following the development of the optimal timing methodology and the analytical tool, the research team undertook a validation of the approach. Four SHAs (Arizona, Kansas, Michigan, and North Carolina) provided performance data for a range of treat-ments that were analyzed using OPTime. This analysis revealed the following findings:

- A wide range of performance measures are used to monitor pavement performance—not all of them clearly reflect the benefits of these treatments.
- Few SHAs are tracking all of the information that is needed to evaluate the effectiveness of treatments, such as pavement condition prior to treatment, the results of doing nothing, the pavement performance after treatment application, or defining measures of pavement performance that reflect the benefit of applying preventive maintenance.
- Agencies continue to use preventive maintenance treatments in "band-aid" applications; these uses should be distinguished from preventive applications.

Nonetheless, the validation effort demonstrated the soundness of both the analytical approach and the usefulness of OPTime.

The report includes background information to introduce the concepts of preventive maintenance and facilitate the initiation or advancement of a SHA's preventive maintenance program. It also includes a methodology that can be used by SHAs to analyze existing preventive maintenance-related data. The methodology is based on well accepted benefit and cost concepts and is presented on the OPTime Microsoft® Excel-based tool. The analytical tool provides SHAs the flexibility of investigating many "what if" timing scenarios if relevant data are not available. The report also includes a plan for the design and data collection efforts required to obtain the data needed for the methodology.

RECOMMENDATIONS

Guidance and useful tools are available to assist with the implementation of a successful preventive maintenance program. The following actions should further enhance this implementation:

- Identify specific objectives of the preventive maintenance program to guide both the selection of preventive maintenance treatments and the measures used to monitor performance.
- Select treatments that are considered preventive applications and define guidelines on their appropriate use.
- Determine the expected performance of pavements when no treatment is applied (the "do-nothing" case) and the expected treatment performance using existing data or data from test sections constructed specifically for this purpose.
- Estimate the optimal timing of specific preventive maintenance treatments using an analytical tool such as OPTime.

CHAPTER **1**

INTRODUCTION

PROBLEM STATEMENT

In many state highway organizations recognition of the importance of maintenance and particularly preventive maintenance is rapidly changing. During the decades of Interstate expansion (from the 1960s through the 1970s), SHAs were organized around construction. By the 1980s, the majority of the Interstate system was constructed and emphasis gradually shifted toward rehabilitation activities. In recent years, however, increased emphasis was placed on pavement preservation and preventive maintenance concepts and programs (*1*).

Many factors contributed to this changing paradigm. Probably the single largest factor was the realization that available funding levels—and doing business in the usual way—did not result in pavements that perform at the level of service demanded by the traveling public. The analyses of performance data in pavement management systems have helped to prove that point, as agencies could see the impact of allocating the limited available funds to pavement projects on a worst-first basis (i.e., funding and treatments are provided for pavements in the worst condition) (*2*). The result, in most cases, has been a gradual decline in the number of miles an agency could treat each year and a decrease in the overall condition of the pavement network.

The inability to provide an acceptable level of service to the public has been confirmed through public surveys. National studies and statewide surveys have consistently shown a desire for longer lasting, safer roads, with fewer disruptions from continual road work (*3, 4, 5*). For example, the results from a survey in Arizona have shown that the public would even be willing to pay higher taxes to meet improved levels of maintenance service, and spend more money now to save money on maintenance in the long term (*6*); public opinion surveys in Washington State revealed similar findings (*4*).

As it has become evident that rehabilitating pavements when they are near failure is not a cost-effective pavement management technique, the need for a better approach to optimize pavement condition and minimize the associated costs was recognized. The concept of "preventive maintenance," which refers to the application of one or more treatments to a pavement to retard or delay the development of pavement deterioration, subsequently emerged.

There are several difficulties associated with moving away from the worst-first approach used by most highway agencies.

In addition to funding and institutional issues, there are the not-so-insignificant problems of determining what treatment to apply to a pavement, when in the life of the pavement to apply this treatment, and what measurable improvement is obtained by the application of this treatment in comparison with other alternatives, including doing nothing. Although all are critical issues, the first step is the acceptance that preventive maintenance is an effective approach in preserving the agency's pavement investment.

When applied to the right pavement at the right time, proper preventive maintenance treatments are a cost-effective means of obtaining the desired life and performance of the pavement. Treatments applied too soon add little benefit and treatments applied too late are ineffective, failing to prolong the life of the pavement. Considering the annual magnitude of highway investments, the potential savings from following a cost-effective approach to meeting an agency's performance objectives for pavements are significant.

Unfortunately, little guidance is available about timing of the application of pavement maintenance treatments. Agencies at both the state and national levels have conducted research on whether preventive maintenance is an appropriate pavement preservation strategy; however, the wide range of chosen treatment timings has raised questions about the effectiveness of preventive maintenance. For example, some agencies have applied preventive maintenance treatments at the end of a pavement's life because funds were not available for the required rehabilitation. Preventive treatments are effective when applied to relatively young pavements in good condition. However, the poor performance of treatments applied at inappropriate timings could lead to the erroneous conclusion that preventive maintenance does not work. Fortunately, many agencies believe preventive maintenance works and have developed schedules to apply preventive maintenance treatments, although they do not claim to have identified the "optimal" timing for treatment applications. Such examples illustrate the importance of determining the window of time in which preventive maintenance treatments perform as they are intended.

This project is based on the premise that preventive maintenance is effective and there is a "best" time to perform it—an idea that is easy to accept. All pavements begin to deteriorate as they are exposed to traffic and environmental forces. For bituminous-surfaced (flexible) pavements, this deteri-

oration occurs in the form of rutting, cracking, loss of surface texture, increased roughness, and other deterioration. In concrete-surfaced (rigid) pavements, the initial deterioration may take the form of cracking, loss of surface texture, increased roughness, and the intrusion of water and incompressibles into joints and cracks. The concept of preventive maintenance stipulates that these deterioration modes can be anticipated and at least partially mitigated before they occur, thereby providing the following long-term benefits:

- A higher level of service resulting from improved pavement performance, reduced user costs, and increased safety;
- Delayed need for rehabilitation; and
- Life-cycle cost savings

OBJECTIVE AND SCOPE OF RESEARCH

The objective of this research was to develop a methodology for determining the optimal timing for the application of preventive maintenance treatments to flexible and rigid pavements to realize the greatest increase in performance at the least cost. The methodology was to consider the variety of treatments that are used and the different ways of monitoring pavement performance. It should be useful both to agencies that already have a preventive maintenance program and to those considering the implementation of such a program.

This research addresses a gap in preventive maintenance programs that has been recognized by highway agencies. In response to a November 2000 survey of SHAs, 12 respondents (out of 34) identified data collection and management and 6 identified improved models and guidance on project selection as the most important needs for their preventive maintenance program (7). The comments provided with the responses pointed out the lack of research that specifically correlates maintenance treatments to the extension of pavement life cycle, the lack of information on how often preventive maintenance treatments should be applied, the necessity to articulate definite cost savings and benefits, and the reliance on experience for determining appropriate preventive maintenance treatment timing.

RESEARCH APPROACH

The project objective was accomplished by completing the following six tasks.

Task 1. Collect and review information on the timing, selection, and performance of preventive maintenance treatments of flexible and rigid pavements. Highway agencies in North America, South Africa, and New Zealand were queried about their preventive maintenance experiences, particularly as they relate to treatment timing and project selection. Agencies reported that they consider a range of factors in their decision process, including environment, material type, surface thickness, pavement deterioration (type, severity, and extent), past and projected traffic, performance history, maintenance history, treatment costs and available budgets, and expected future performance. In some cases, the analysis is performed as part of the agency's pavement management process. However, there was no apparent rigorous analytical process for timing or selecting preventive maintenance treatments. A brief summary of the results of this data collection effort is found in Appendix A (not published herein).

Task 2. Identify appropriate preventive maintenance treatments for ranges of climatic conditions, traffic levels, and pre-treatment pavement conditions. Many factors were found to be important for identifying appropriate preventive maintenance treatments although ultimately the decision is based on "local" factors. General guidance is available on the conditions in which various treatments are appropriate. As described in Chapter 2, this guidance can be adapted by agencies to meet their needs.

Task 3. Recommend and describe a methodology that considers the cost-effectiveness and performance of maintenance treatments. The optimal timing methodology is described in Chapter 3. The process that led to its adoption is described in Appendix B (not published herein).

Task 4. Create a user-friendly analysis tool to facilitate use of the methodology for the variety of pavement maintenance situations encountered by highway agencies. The optimal timing methodology, designated OPTime, is a Visual Basic Application-driven Microsoft® Excel workbook provided on a CD-ROM. OPTime can be used to estimate the optimal time to apply a specific preventive maintenance treatment. Although OPTime does not use a true optimization strategy (i.e., all possible treatment application times and alternative treatments are not analyzed), it provides a simple analysis method that can be used to choose the most effective treatment timing from a set of user-chosen timing scenarios (i.e., a preventive maintenance treatment applied at many different user-chosen pavement ages). A User's Guide, found in Appendix C, http://trb.org/news/blurb_detail.asp?id =4306 offers specific instruction on the use of the tool.

Task 5. Demonstrate the applicability of the methodology and the suitability of the implementation tool using data from a limited number of projects or other means. The Arizona, Kansas, Michigan, and North Carolina DOTs all provided data and other resources to support the effort to evaluate the methodology using the analysis tool. Since the availability and type of data greatly differed between agencies, the collected data were also used to test the flexibility of the analysis tool. The results of this effort are discussed in Chapter 3.

Task 6. Develop a plan, for use by highway agencies, to collect the data needed to support the proposed methodology.

The preventive maintenance optimal timing methodology is based on analyzing an agency's performance data gathered from applying treatments to pavements at different times. Because many agencies do not have such data, a plan was developed to assist these agencies in establishing test sections and collecting such data. The plan is found in Appendix D.

ORGANIZATION OF THE REPORT

This report consists of four chapters. This chapter provides the introduction and research approach, describes the problem statement and research objective, and outlines the scope of the study. Chapter 2 describes the findings of the literature search and the preventive maintenance treatments, applicable to bituminous and concrete-surfaced pavements. Chapter 3 describes the methodology recommended for analyzing preventive maintenance data and identifying appropriate treatments and timing for specific situations. It also demonstrates the applicability of this methodology using data obtained from SHAs. Chapter 4 summarizes the significant conclusions of the project and presents suggestions for future research.

CHAPTER **2**

BACKGROUND AND LITERATURE SEARCH

INTRODUCTION

The first step in developing a methodology for determining the optimal timing of preventive maintenance was to review and assess previously completed work on this topic. As part of that effort, a literature search was performed and appropriate types of treatments used for preventive maintenance were identified. This chapter highlights the findings from the literature search and identifies important characteristics of preventive maintenance treatments.

The literature search focused on the topics relevant to preventive maintenance application timing, specifically the following topics:

- Concepts and implementation
- Case studies
- Measurement of benefit
- Maintenance costs
- Maintenance treatment selection and performance
- Treatment application timing
- Optimization methods

From approximately 200 records that were reviewed, only a few of the published reports specifically discussed treatment timing issues, and none provided any indication of rigorous research into the development of guidelines for the optimal timing of preventive maintenance. Nonetheless, a good deal of information was available for the other areas targeted in the literature search. Some of the findings regarding the concepts, implementation, and state agency experience (case studies) of preventive maintenance are highlighted in Chapter 1. A more detailed discussion of treatment selection, usage, and performance is presented later in this chapter. Benefit- and cost-related information is included in the discussion of the analysis approach described in Chapter 3. Finally, the published work on optimization approaches is summarized and presented in Appendix B.

Overview of Preventive Maintenance

Experience with preventive maintenance in the United States differs substantially among highways agencies. For example, Arizona (*8*) and Iowa (*9*) have constructed test sec-

tions to evaluate the performance of certain preventive maintenance treatments; Michigan, New York, and California have well-established preventive maintenance programs which are documented in comprehensive manuals. In light of this broad range of experience, it is noteworthy to review the status of pavement preservation in the United States. In 1999, transportation agencies in all 50 states, the District of Columbia, Puerto Rico, and six Canadian Provinces were surveyed about their preventive maintenance programs and practices; 41 agencies responded (*10*). All 41 respondents reported using preventive treatments. Eighty-five percent (36) of the respondents reported having established pavement preventive maintenance programs, and two respondents were in the process of establishing a program. Seventeen of the respondents reported having a program in place for more than 10 years, and one agency reported practicing preventive maintenance for the past 75 years.

Regarding the condition of pavement when applying preventive maintenance treatments, 25 respondents said that pavements were in good condition, 22 said that they were in poor condition, and 1 respondent said they were in very poor condition (note that respondents identified all conditions in which maintenance treatment is applied). Some respondents noted that "preventative maintenance techniques are sometimes applied to poor roads when reconstruction budgets are limited," and "all pavements are treated, based on the assumption that even poor pavements will receive some benefit, however small."

The confusion about preventive maintenance stems in part from the fact that the condition in which a treatment is used—not the characteristics of the treatment—is what defines the treatment as "preventive." A treatment that is used to extend pavement life or improve functional performance may also be used to hold the pavement together until a rehabilitation or reconstruction project can be scheduled. Therefore, when using a treatment as a preventive application, the following three items must be considered:

- Existing distresses to be treated, or anticipated distresses to be prevented or slowed;
- Most appropriate treatments for existing conditions; and
- Timing the treatment for best results (i.e., maximizing performance while minimizing overall costs).

Thus, a thin overlay should not be considered a preventive maintenance treatment when it is applied to badly alligator-cracked pavement, neither should a slurry seal when it is placed on a cracked and oxidized surface. Selecting the appropriate treatment together with determining the appropriate timing of its placement constitutes a preventive maintenance strategy. These elements of preventive maintenance are captured in the following definition (*1*):

> *. . . the planned strategy of cost effective treatments to an existing roadway system and its appurtenances that preserves the system, retards future deterioration, and maintains or improves the functional condition of the system [without increasing structural capacity].*

Many factors should be considered when selecting the most appropriate preventive maintenance treatment for a given pavement. Some of those factors relate to the limitations of the treatments; important attributes or characteristics of some of the common preventive maintenance treatments are described later in this chapter. Constructibility and customer satisfaction are other factors to consider. Constructibility pertains to the availability of skilled contractors and suitable materials, environmental constraints, and other factors such as traffic control constraints and available lane closures that affect the placement of the treatments. Customer satisfaction pertains to traffic disruption, noise impacts, surface friction, and ride quality; it is becoming increasingly important for many agencies. While all these issues are important, this project focuses on performance attributes. These attributes include the treatment's expected life, the effect of the existing pavement condition on performance of the treatment, the effect of the treatment on the pavement condition, the effect of the climate on treatment performance, and the treatment cost.

Pavement Deterioration and Treatment Timing

Deterioration of a well designed and constructed pavement occurs as a result of the effects of the environment, the traffic loads, and the interaction between the two. However, initial deterioration results almost solely from environmental effects.

It is a fundamental tenet of treatment performance that the same treatment performs differently when applied at different times in the life of the pavement (or on pavements in varying condition). For example, placing a thin bituminous surfacing (such as a chip seal) on top of a 2-month old pavement may not increase the pavement's life because the pavement may show structural deterioration once the surfacing wears off. Similarly, placing the same treatment near the end of the pavement's life (i.e., when the surface is aged and worn and the pavement is exhibiting signs of structural deterioration) will have a minimal effect on pavement performance because the condition of the underlying pavement will control performance. Therefore, for a given pavement, there is an optimal age or condition (or a range of age or condition) where the benefit/cost (B/C) ratio associated with a chosen treatment is maximized; this is defined as the optimal timing for the treatment.

PREVENTIVE MAINTENANCE TREATMENTS FOR BITUMINOUS- AND CONCRETE-SURFACED PAVEMENTS

Different approaches are used to identify which pavement treatments are considered "preventive." For example, the Michigan DOT (MDOT) preventive maintenance program lists the 20 treatments shown in Table 1 (*11*). In Caltrans' Capital Preventive Maintenance (CAPM) program, grinding and removal and replacement of failed slabs are described for concrete-surfaced pavements, and thin overlays and "premium seal coats" (microsurfacing, polymer- and rubber-modified chip seals, modified binder open-graded hot-mix asphalt (HMA) blankets, and thin, hot-applied, gap-graded applications) are described for bituminous-surfaced pavements (*12*). In an FHWA course on pavement preservation, at least 11 bituminous-surfaced pavement treatments and 8 concrete-surfaced pavement treatments are described (*13*).

TABLE 1   Treatments included in MDOT's 1999 and 2000 Capital Preventive Maintenance program (*11*)

Concrete-Surfaced Pavements	Bituminous-Surfaced Pavements
Full depth concrete pavement repair	Bituminous overlay
Joint resealing	Surface milling and bituminous overlay
Crack sealing	Ultrathin bituminous overlay
Joint and surface spall repair	Crack treatment
Dowel bar retrofit	Overband crack filling
Diamond grinding	Microsurfacing
Underdrain outlet repair and cleaning	Chip seals
Concrete pavement restoration	Bituminous shoulder ribbons
Bituminous shoulder ribbons	Shoulder seals
	Paver placed surface seals
	Hot in-place bituminous recycling

Industry and agencies are constantly identifying new approaches to treating pavements, while discarding others that have been shown not to work for them. Key components in an agency's decision process for selecting a specific treatment are (1) determining timing and (2) understanding important attributes of the treatment. In a methodical approach to identifying appropriate treatments, the performance characteristics or attributes of the treatments must be considered because these alone determine if a treatment can serve its intended purpose.

Treatment Attributes

Treatments that are suitable for use by a given agency can be identified by considering the following factors or treatment attributes:

- Purpose of the treatment
- Applicability
  - Traffic
  - Environment
  - Pavement condition
- Contraindications
- Construction considerations
- Expected performance and cost
- Customer satisfaction

Purpose of the Treatment

The purpose of the treatment involves identifying pavement conditions that the treatment is meant to prevent or correct. For example, sealing cracks prevents moisture (and debris) from infiltrating the pavement structure. Some treatments may serve several purposes; a slurry seal can protect an HMA surface from environmental effects, improve surface friction, or seal minor cracks in the pavement surface. Any treatment considered for a preventive maintenance program should address one or more specific purposes so that the conditions of its use are clear. Because some of the preventive maintenance treatments are applied to pavement with little or no signs of deterioration, the purpose is not always to correct distress.

Applicability

The applicability or appropriateness of a treatment is determined by the overall condition of the pavement, traffic, and environment for which the treatment is suited. For example, some treatments require application at fairly warm temperatures to ensure good long-term performance, and their use is not recommended if a prolonged period of warm weather can-

not be forecast. Other factors that may influence the treatment selection process include the extent of snow plowing, the use of studded tires or chains, and the lane closure time available to complete the work.

Traffic is another important consideration as treatments perform differently under traffic loads. Many agencies differentiate appropriate treatments based on daily traffic counts or loads. This information can serve several purposes. For some treatments, the higher volume of traffic contributes to a likelihood of vehicle damage. Other treatments might be chosen because high-traffic volumes are anticipated and the treatment may reduce the likelihood of pavement deterioration.

The condition of the pavement cannot be ignored in determining appropriate treatments. While the concept of *preventive* maintenance implies that the pavement exhibits minimal distresses, the reality is that many treatments will be applied to pavements with some distress. It is important to know what distresses are present and how the different treatments will perform in relation to those distresses.

Contraindications

Conditions under which a specific treatment simply will not work or should not be used are considered contraindications for this treatment. For example, the need for a complete closure of the pavement, the requirement for cure time after application and before loads can be applied, the potential damage from early application of heavy loads, and the possible failure because of the presence of moisture during construction might all be considered contraindications to the use of certain treatments. While improvements in the technology of many preventive maintenance treatments help extend the conditions under which they can be used, familiarity with their limitations also helps to obtain the best possible performance.

Construction Considerations

Constructibility issues that need to be considered include the complexity of the construction of the treatment, the need for specialized or well-calibrated equipment, the local availability of qualified contractors, and the need for specialized materials. If a treatment's success relies on factors that are beyond the control of the agency, its application may be viewed as less feasible than a treatment that can be placed by most contractors using locally available materials.

Expected Performance and Cost

Another set of considerations relates to the performance and cost associated with a given treatment. An agency should be aware of both the expected performance of the treatment and

its cost to determine if that combination of performance and cost is acceptable. This information will also help compare different alternatives for reaching similar objectives. If adequate information about treatment performance is not readily available, agencies are strongly encouraged to generate preventive maintenance treatment performance data based on their own experience. In the interim, data required to perform certain analysis may be obtained from other sources, such as "expert" opinion or other agencies with comparable conditions.

Customer Satisfaction

There is a growing emphasis in highway agencies to pursue actions that improve customer satisfaction. Some of the attributes of interest to the traveling public include noise, roughness, absence from splash and spray, and traffic disruptions from road repairs. Different treatments affect these attributes in different ways, and an agency interested in improving customer satisfaction will consider these factors in the treatment selection process.

Characteristics of Selected Treatments

A list of pavement treatments that meet the definition of "preventive" maintenance is shown in Table 2; characteristics of treatments for bituminous- and concrete-surfaced pavements are presented in Tables 3 through 14 and maintenance of drainage features are shown in Table 15. This information includes estimates of the expected life and typical

TABLE 2 Typical pavement preventive maintenance treatments

1. Bituminous-Surfaced Pavements
Crack Filling/Crack Sealing
Fog Seals
Slurry Seals
Scrub Seals
Microsurfacing
Chip Seals
Thin Overlay
Ultrathin Friction Courses
2. Concrete-Surfaced Pavements
Joint/Crack Sealing
Diamond Grinding
Undersealing
Load Transfer Restoration
3. Maintenance of Drainage Features

cost of each treatment. Because the expected life estimates reported in these tables are based on the use of the treatment in both a preventive and reactive manner, there is a broad range for some of the reported lives. The costs also cover a wide range of applications and regional variations; users are encouraged to identify local, and more recent values for use in the analysis.

Overview of Treatments for Bituminous-Surfaced Pavements

With the exception of crack filling and crack sealing, treatments described in this section consist of a thin, uniform

TABLE 3 Characteristics of crack filling and crack sealing

CRACK FILLING AND CRACK SEALING	EVALUATION FACTORS			
	Climate	Traffic	Conditions Addressed	Contraindications
Description: These treatments are intended primarily to prevent the intrusion of moisture through existing cracks. Crack sealing refers to a sealant operation that addresses "working" cracks, i.e., those that open and close with changes in temperature. It typically implies high quality materials and good preparation. Crack filling is for cracks that undergo little movement. Sealants used are typically thermo-plastic (bituminous) materials that soften upon heating and harden upon cooling.	Treatment can perform well in all climatic conditions. However, sealants perform best in dryer and warmer environments that do not undergo large daily temperature changes.	Performance is not significantly affected by varying ADT or truck levels.	**Functional/Other** ■ Longitudinal cracking ■ Minor block cracking ■ Transverse cracking **Structural** Adds no structural benefit, but does reduce moisture infiltration through cracks. Only practical if the extent of cracking is minimal and if there is little to no structural cracking.	■ Structural failure (i.e., extensive fatigue cracking or high severity rutting) ■ Extensive pavement deterioration, little remaining life
Site Restrictions	None.			
Construction Considerations	Placement should be done during cool, dry weather conditions. Proper crack cleaning is essential to a good bond and maximum performance. Some agencies also use hot compressed air lance prior to sealing.			
Expected Life	2 to 6 years.			
Typical Costs	$1.00 to $5.00 per linear m ($0.30 to $1.50 per linear ft) for crack sealing, including routing; $1.00 per linear m ($0.30 per linear ft) for crack filling. Costs are slightly higher for small jobs.			

TABLE 4 Characteristics of fog seals

FOG SEALS	EVALUATION FACTORS			
	Climate	**Traffic**	**Conditions Addressed**	**Contraindications**
Description: Fog seals are placed primarily to seal the pavement, inhibit raveling, enrich the hardened/ oxidized asphalt, and provide some pavement edge-shoulder delineation. Fog seals are very light applications of a diluted asphalt emulsion placed directly on the pavement surface with no aggregate. Typical application rates range from 0.23 to 0.45 liters per m^2 (0.05 to 0.10 gal per yd^2).	Treatment performs well in all climatic conditions. Actual performance will vary according to factors that affect weathering and raveling of bituminous surfaces.	Increased ADT or truck levels can increase surface wear, particularly in states that permit studded tires.	**Functional/Other** ▪ Longitudinal, transverse, and block cracking (M) ▪ Raveling/weathering (loose material must be removed) ▪ Asphalt aging, oxidation and hardening ▪ Moisture infiltration **Structural** Adds no structural benefit, but can help reduce moisture infiltration through fatigue cracks (if their severity is low)	▪ Structural failure (such as significant fatigue cracking) ▪ Flushing/bleeding (M) ▪ Friction loss (M-H) ▪ Thermal cracking (H)
Site Restrictions	Not appropriate for surfaces with poor skid resistance, as it will lower the skid resistance even more.			
Construction Considerations	Typically, a slow-setting emulsion is used which requires time to "break," the pavement is sometimes closed for 2 hours for curing before being re-opened to traffic.			
Expected Life	1 to 2 years when placed in a preventive maintenance mode.			
Typical Costs	$0.36 to $0.54 per m^2 ($0.30 to $0.45 per yd^2) of pavement surface area.			

Note: L, M, and H define level of distress (L for low, M for medium, and H for high).

TABLE 5 Characteristics of slurry seals

SLURRY SEALS	EVALUATION FACTORS			
	Climate	**Traffic**	**Conditions Addressed**	**Contraindications**
Description: A mixture of well-graded aggregate (fine sand and mineral filler) and asphalt emulsion that is spread over the entire pavement surface with either a squeegee or spreader box attached to the back of a truck. It is effective in sealing low-severity surface cracks, waterproofing the pavement surface, and improving skid resistance at speeds below 64 km/h (30 mph). Thickness is generally less than 10 mm (0.4 in.).	Treatment performs effectively in all climatic conditions. However, best performance occurs in warm climates with low daily temperature changes.	Performance in terms of surface wear is affected by increasing ADT and truck traffic levels. Slurry mix properties (i.e., aggregate quality, gradation and emulsion content) can be modified to accommodate the higher traffic volumes.	**Functional/Other** ▪ Transverse, longitudinal and block cracking (L) ▪ Raveling/weathering (loose material must be removed) ▪ Asphalt aging, oxidation and hardening ▪ Friction loss ▪ Moisture infiltration **Structural** Adds no structural capacity; however, can temporarily seal cracks (if severity is low) or serve as a rut-filler (if the ruts are not severe and are stable)	▪ Structural failure (such as significant fatigue cracking and deep rutting) ▪ Thermal cracking (H) ▪ Can accelerate the development of stripping in susceptible HMA pavements
Site Restrictions	Pavement is often closed for several hours to allow the emulsion to cure.			
Construction Considerations	Surface must be clean. Aggregates must be clean, angular, durable, well-graded, and uniform (prefer 100% crushed). Avoid placement in hot weather (potential flushing problems) and premature opening to traffic. Do not place when freezing temperatures are expected.			
Expected Life	3 to 5 years when placed in a preventive maintenance mode.			
Typical Costs	$0.84 to $1.14 per m^2 ($0.70 to $1.00 per yd^2).			
Additional Information	Three slurry types with different aggregate gradations and application rates are used: Type I for lower traffic volume (3.3 to 5.4 kg/m^2 [6.1 to 10.0 lb/yd^2]) Type II for heavy traffic (5.4 to 8.1 kg/m^2 [10.0 to 15.0 lb/yd^2]) and Type III for irregular surfaced pavements (8.1 kg/m^2 [15.0 lb/yd^2]).			

Note: L, M, and H define level of distress (L for low, M for medium, and H for high).

TABLE 6   Characteristics of scrub seals

SCRUB SEALS	EVALUATION FACTORS			
	Climate	Traffic	Conditions Addressed	Contraindications
Description: A four-step process intended to rejuvenate the asphalt surface and to fill voids and surface cracks: (1) application of a layer of polymer-modified asphalt emulsion that is broomed into the voids and cracks of the pavement, (2) application of sand or small-sized aggregate, (3) a second application of polymer-modified asphalt (by brooming), and (4) rolling with a pneumatic-tired roller.	Can be effective in all climates, but works best in hot, arid climates.	Good performance has been observed on lower-volume roads (less than 7,500 ADT)	**Functional/Other** ■ Transverse, longitudinal and block cracking (L) ■ Raveling/weathering (loose material must be removed) ■ Moisture infiltration **Structural** Adds no structural capacity; however, can help seal cracks (if severity is low)	■ Structural failure (such as significant fatigue cracking) ■ Thermal cracking (H)
Site Restrictions	Do not apply on tight surfaces as this may reduce skid resistance of the pavement.			
Construction Considerations	Surface must be clean; special equipment is required for brushing.			
Expected Life	1 to 3 years when placed in a preventive maintenance mode.			
Typical Costs	$0.90 to $1.49 per m^2 ($0.75 to $1.25 per yd^2).			
Additional Information	Generally easy to apply and relatively inexpensive.			

Note: L, M, and H define level of distress (L for low, M for medium, and H for high).

TABLE 7   Characteristics of microsurfacing

MICROSURFACING	EVALUATION FACTORS			
	Climate	Traffic	Conditions Addressed	Contraindications
Description: Microsurfacing consists of a mixture of polymer-modified emulsified asphalt, mineral aggregate, mineral filler, water, and additives applied in a process similar to slurry seals. Used primarily to inhibit raveling and oxidation of the pavement surface. Also effective at improving surface friction, and filling minor irregularities and wheel ruts (up to 40 mm [1.6 in.] deep) in one pass.	Effective in all climate conditions. However, best performance occurs in warm climates with low daily temperature changes. May not set up quickly if applied in cool climates.	Very successful on both low- and high-volume roadways.	**Functional/Other** ■ Longitudinal and transverse cracking (L) ■ Raveling/weathering (loose material must be removed) ■ Bleeding (L-M) ■ Roughness (L) ■ Friction loss ■ Moisture infiltration **Structural** Adds limited structural capacity. Temporarily seals fatigue cracks (if severity is low) and can serve as a rut-filler (if the existing ruts are stable)	■ Structural failure (i.e., extensive fatigue cracking) ■ Extensive pavement deterioration, little remaining life ■ Thermal cracks (H) ■ Can accelerate the development of stripping in susceptible HMA pavements
Site Restrictions	None.			
Construction Considerations	Avoid placement in hot weather if there is potential for flushing problems. Placement in cool weather can lead to early raveling, not to be placed when freezing temperatures are expected.			
Expected Life	4 to 7 years when placed in a preventive maintenance mode.			
Typical Costs	$1.05 to $2.00 per m^2 ($0.90 to $1.70 per yd^2).			
Additional Information	Typical mix proportions: 82 to 90% aggregate, 1.5 to 3.0% mineral filler, and 5.5 to 9.5% residual asphalt.			

Note: L, M, and H define level of distress (L for low, M for medium, and H for high).

treatment applied to the pavement surface. If unsealed, the surface bituminous material loses volatiles as it is exposed to environmental forces, dries out, becomes brittle, begins to lose aggregate (raveling), and cracks. Thin surfacings seal the pavement surface slowing the aging process of the surface materials. These surfacings range from a fog seal (an asphalt emulsion without any aggregate) to a thin HMA over-lay; they cover the pavement surface without a structural contribution. Corrective measures, such as crack filling or crack sealing, can also improve long-term performance by keeping the pavement structure free from moisture infiltration, which otherwise could contribute to weakening the pavement. Additional characteristics of each of these treatments are summarized in Tables 3 through 11.

TABLE 8   Characteristics of chip seals

CHIP SEALS	EVALUATION FACTORS			
	Climate	Traffic	Conditions Addressed	Contraindications
Description: Asphalt (commonly an emulsion) is applied directly to the pavement surface (1.59 to 2.27 L/m^2 [0.35 to 0.50 gal/yd^2]) followed by the application of aggregate chips (8 to 27 kg/m^2 [15 to 50 lb/yd^2]), which are then immediately rolled to imbed chips (50 to 70 percent). Application rates depend upon aggregate gradation and maximum size. Treatment seals pavement surface and improves friction.	Treatment performs well in all climatic conditions.	With proper design and placement, chip seals can perform well on high-volume roads. However, use is primarily limited to lower-speed, lower-volume roads because of the propensity for loose chips to crack windshields.	**Functional/Other** ■ Longitudinal, transverse and block cracking ■ Raveling/weathering (loose surface material must be removed) ■ Friction loss ■ Roughness (L) ■ Bleeding (L) ■ Moisture infiltration **Structural** Adds almost no structural capacity. However, effective at sealing fatigue cracks (M) in comparison with other treatments.	■ Structural failure (i.e., extensive fatigue cracking and/or deep rutting) ■ Thermal cracking (H) ■ Extensive pavement deterioration, little or no remaining life ■ Can accelerate the development of stripping in susceptible HMA pavements
Site Restrictions	High-speed, high-volume roadways are often avoided, although a number of approaches are being used to extend the applicability of these treatments.			
Construction Considerations	Surface must be clean. Treatment should be placed during warm weather with chip spreader immediately behind asphalt distributor and rollers close behind the spreader. Approximately 2 hours required before roadway may be re-opened to normal speed traffic. Brushing is usually required to remove loose chips.			
Expected Life	4 to 7 years when placed in a preventive maintenance mode.			
Typical Costs	$0.90 to $1.08 per m^2 ($0.75 to $0.90 per yd^2) for a single application and $1.32 to $1.49 per m^2 ($1.10 to $1.25 per yd^2) for a double application.			
Additional Information	A second chip seal may be placed to achieve improve performance. Total thickness may approach 25 mm (1 in.).			

Note: L, M, and H define level of distress (L for low, M for medium, and H for high).

TABLE 9   Characteristics of thin hot-mix asphalt overlays

THIN HOT-MIX ASPHALT OVERLAYS	EVALUATION FACTORS			
	Climate	Traffic	Conditions Addressed	Contraindications
Description: Plant-mixed combinations of asphalt cement and aggregate applied to the pavement in thicknesses between about 19 and 38 mm (0.75 and 1.50 in.). Dense-graded, open-graded, and stone matrix mixes are used.	Treatment performs well in all climatic conditions. Actual performance will vary according to factors that affect weathering and raveling of bituminous surfaces.	Performance should not be affected by different ADT or percent trucks. Thin HMA overlays are not structural layers and as such should not be subjected to strain from loadings. Such layers may be subject to top-down cracking under certain combinations of loadings, environmental conditions, and pavement structures.	**Functional/Other** ■ Longitudinal and transverse cracking (L) ■ Raveling/weathering (loose surface material must be removed) ■ Friction loss ■ Roughness ■ Bleeding (L) ■ Block cracking (L; may perform better with additional milling) **Structural** Rutting (assumes rutting has stopped; requires use of separate rut-fill application)	■ Structural failure (i.e., fatigue cracking) ■ Extensive pavement deterioration, little remaining life ■ Thermal cracking (H)
Site Restrictions	Edge-shoulder drop-off should be considered. Surface should be uniform to ensure uniform compaction.			
Construction Considerations	Surface must be clean. A tack coat prior to overlay placement will help improve the bond to the existing surface. Thin HMA overlays dissipate heat rapidly and, therefore, depend upon minimum specified mix placement temperatures and timely compaction.			
Expected Life	7 to 10 years when placed in a preventive maintenance mode.			
Typical Costs	$2.09 to $2.39 per m^2 ($1.75 to $2.00 per yd^2) for dense-graded mixes; $1.50 to $1.70 per m^2 ($1.25 to $1.42 per yd^2) for open-graded mixes.			
Additional Information	While thin HMA overlays are considered a functional treatment, repetitive applications will impart some structural benefit to the pavement in the form of additional load-carrying capability.			

Note: L, M, and N define level of distress (L for low, M for medium, and H for high).

TABLE 10   Characteristics of ultrathin friction courses

ULTRATHIN FRICTION COURSES	EVALUATION FACTORS			
	Climate	Traffic	Conditions Addressed	Contraindications
Description: Relatively new treatment in the U.S. Consists of a gap-graded, polymer-modified 10 to 20 mm (0.4 to 0.8 in.) HMA layer placed on a tack coat formed by the application of a heavy, polymer-modified asphalt emulsion. Treatment effectively addresses minor surface distresses and increases surface friction.	Treatment should perform well in all climatic conditions.	Capable of withstanding high ADT volumes and truck traffic better than other thin treatments.	**Functional/Other** ■ Longitudinal, transverse and block cracking (L). Higher severities can be addressed with cold milling. ■ Raveling/weathering (loose surface material must be removed) ■ Friction loss (H) ■ Roughness (L) ■ Bleeding (L) **Structural** Provides some increased capacity and retards fatigue cracking. Not suited for rutted pavements.	■ Structural failure (i.e., significant fatigue cracking and/or deep rutting) ■ Extensive pavement deterioration, little remaining life ■ Thermal cracking (H)
Site Restrictions	Ultrathin overlays should only be placed on structurally sound pavements. Localized structural problems should be repaired prior to overlay application.			
Construction Considerations	Requires special paving equipment to place the mix and a license to apply it.			
Expected Life	7 to 10 years when placed in a preventive maintenance mode.			
Typical Costs	$3.00 to $3.59 per m^2 ($2.50 to $3.00 per yd^2), or about 50 percent more than thin, dense-graded HMA overlay.			
Additional Information	A proprietary treatment is known in the U.S. as "Novachip."			

Note: L, M, and H define level of distress (L for low, M for medium, and H for high).

TABLE 11   Characteristics of joint resealing and crack sealing

JOINT RESEALING AND CRACK SEALING	EVALUATION FACTORS			
	Climate	Traffic	Conditions Addressed	Contraindications
Description: Resealing of transverse joints and sealing of cracks in PCC pavements is intended to minimize the infiltration of surface water into the underlying pavement structure and to prevent the intrusion of incompressibles into the joint. A range of materials including bituminous, silicone, and neoprene are used in designed configurations.	Sealing of PCC pavement joints and cracks performs well in all climatic conditions. Sealant performance is affected by environmental conditions and the performance of sealed and unsealed pavement structures probably varies within environmental regions.	■ Performance is not affected by different ADT or percent trucks. ■ Silicone sealants that are not properly recessed are more likely to fail in the wheelpath.	**Functional/Other** ■ Longitudinal and transverse cracking (L) ■ Unsealed or partially sealed joints. **Structural** No direct structural benefit, but may reduce rate of structural deterioration. Sealing may also be beneficial on a structurally failing pavement to prolong the time until rehabilitation. Crack sealing is not an effective method of <u>repairing</u> cracked slabs, but may be useful in preventing further deterioration.	Different materials can be expected to perform for different durations. Material selection should be based on the expected time until next treatment.
Site Restrictions	Sealant reservoir should be clean and dry. Variable width reservoirs may cause a problem where backer rods are specified.			
Construction Considerations	Sealant performance is dependent on many construction factors, including material type and placement geometry, and application in a clean and dry environment.			
Expected Life	7 to 8 years.			
Typical Costs	$2.50 to $4.00 per linear m ($0.75 to $1.25 per linear ft) for hot-pour rubberized materials and from about $3.25 to $6.50 per linear m ($1.00 to $2.00 per linear ft) for silicone materials.			
Additional Information	While the merits of joint sealing in new construction is currently being questioned, this debate has not extended to the merits of keeping existing pavements sealed.			

Note: L, M, and H define level of distress (L for low, M for medium, and H for high).

TABLE 12 Characteristics of diamond grinding

DIAMOND GRINDING	EVALUATION FACTORS			
	Climate	Traffic	Conditions Addressed	Contraindications
Description: Diamond grinding is the removal of a thin layer of concrete (generally about 6.4 mm [0.25 in.]) from the surface of the pavement, using special equipment outfitted with a series of closely spaced diamond saw blades. The major applications for diamond grinding are to remove surface irregularities (most commonly joint faulting), to restore a smooth-riding surface, and to increase pavement surface friction (*14*).	Diamond grinding performance is not affected by climate. However, if studded snow tires or chains are used, surface wear may require more frequent grinding to restore friction.	Diamond grinding performance may be affected by traffic. Grinding may be used to remove faulting, which can reoccur due to the continued application of truck traffic. If grinding is used to restore friction loss caused by polishing of the pavement surface due to vehicle traffic, heavy volumes of traffic may cause the problem to reoccur.	**Functional/Other** ■ Roughness ■ Loss of skid **Structural** ■ Faulting	Diamond grinding is not appropriate if significant faulting or other signs of structural failure (such as pumping or corner breaks) are present. Diamond grinding may not be appropriate if materials-related distresses are present. Soft aggregate will wear much quicker and require more frequent grinding.
Site Restrictions	Disposal of the ground slurry should be addressed during project development.			
Construction Considerations	Typically constructed with a moving lane closure with traffic operating in the adjacent lanes. Often used in conjunction with other restoration techniques such as after the completion of load-transfer restoration.			
Expected Life	May reduce faulting for 8 to 10 years and roughness for at least 5 years.			
Typical Costs	Cost ranges from $1.50 to $6.50 per m^2 ($1.25 to more than $7.00 per yd^2) depending on the hardness of the aggregate.			

TABLE 13 Characteristics of undersealing

UNDERSEALING	EVALUATION FACTORS			
	Climate	Traffic	Conditions Addressed	Contraindications
Description: Undersealing is the pressure insertion of a flowable material beneath a PCC slab to fill voids between the slab and base, thereby reducing deflections and, consequently, deflection-related distresses such as pumping or faulting. It is most often performed at areas where pumping and loss of support occur, such as beneath transverse joints and deteriorated cracks. The voids being filled by this technique are generally less than 3 mm (0.12 in.) thick.	No studies are known to differentiate between the performance of undersealing in different environmental conditions.	Performance is not known to be affected by different levels of ADT or percent trucks.	**Functional/Other** Anticipates the development of roughness from faulting. **Structural** Fills voids that, if left unfilled, will lead to faulting and other structural deterioration. Performs best before faulting starts to develop.	Significant faulting, or other signs of structural failure (such as pumping, mid-panel cracking, or corner breaks), suggest structural failure requiring more extensive rehabilitation. Additional strategies, such as dowel retrofitting, may be required for pavements without load transfer.
Site Restrictions	Voids must be identifiable and contained for undersealing to work.			
Construction Considerations	Cement-fly ash grout is the most commonly used material, although asphalt has been used. Overfilling voids can contribute to worse problems than leaving them unfilled.			
Expected Life	Performance has been extremely variable.			
Typical Costs	Cost depends on the material used, the extent and size of the voids, and the size of the project. Cement-fly ash grout undersealing ranges from about $1.08 to $1.20 per m^2 ($0.90 to $1.00 per yd^2), while asphalt undersealing ranges from about $0.54 to $0.60 per m^2 ($0.45 to $0.50 per yd^2).			

*Overview of Treatments
for Concrete-Surfaced Pavements*

The preventive maintenance treatments for concrete-surfaced pavements function in a different manner than those for bituminous-surfaced pavements. The identified treatments can be used to anticipate and mitigate more serious deterioration. Benefits of these treatments include reduced roughness, improved skid resistance, and protection against distresses accelerated by the presence of subsurface moisture (such as pumping, faulting, and corner breaks). Key characteristics of the concrete pavement treatments are summarized in Tables 11 through 14.

TABLE 14 Characteristics of load transfer restoration

LOAD TRANSFER RESTORATION	EVALUATION FACTORS			
	Climate	Traffic	Conditions Addressed	Contraindications
Description: Load transfer restoration (LTR) is the placement of load transfer devices across joints or cracks in an existing jointed PCC pavement to restore load transfer at these locations. Poor load transfer can lead to pumping, joint faulting, and corner breaks.	LTR has been used in all climatic regions.	The need for LTR increases with an increased ADT and percent trucks. Low-volume jointed concrete pavements that are not doweled may not need LTR.	**Functional/Other** Can prevent the development of a rough ride caused by faulting. **Structural** Most effective on jointed concrete pavements that have poor load transfer at joints and/or transverse cracks but also have significant remaining structural life. The optimum time to apply this technique is when the pavement is just beginning to show signs of structural distress, such as pumping and the onset of faulting.	Significant faulting, or other signs of structural failure (such as pumping, mid-panel cracking, or corner breaks). Pavements with little remaining life or materials-related distresses.
Site Restrictions	Can be performed with a single lane closure.			
Construction Considerations	Agencies have experimented with different retrofit patterns. Two to four bars per wheelpath is typical. Care must be given to the selection of the patch material and isolation of the joint. Often performed in conjunction with diamond grinding.			
Expected Life	A minimum expected life is 9 to 10 years (*15*). However, many load-transfer restoration projects have been in place around 20 years with little or no distress present (Puerto Rico) (*16*).			
Typical Costs	For production jobs, the typical costs are $25 to $35 per dowel.			
Additional Information	Repetitive applications will impart some structural benefit to the pavement in the form of additional load-carrying capability.			

TABLE 15 Maintenance of drainage features

MAINTENANCE OF DRAINAGE FEATURES	EVALUATION FACTORS			
	Climate	Traffic	Conditions Addressed	Contraindications
Description The following activities are used as needed to improve or enhance the drainage capabilities of the existing pavement: • Install/maintain reference markers at outlet locations. • Clear debris and vegetation at outlets and at culverts. • Inspect edge drain pipe using video equipment. • Flush/rod edge drain system with high pressure equipment. • Clean ditches and re-establish depths and grades. • Restore cross slopes through milling or surface leveling (HMA pavements only). • Regrade the shoulder to remove any buildup of dirt and debris. • Clean closed drainage systems, including drainage inlets, catch basins, and manholes.	Maintenance of drainage features is not limited by climate or traffic conditions.		Drainage maintenance does not address specific pavement condition. However, timely maintenance of drainage features helps to prevent the development of more serious deterioration.	There are no contraindications for the maintenance of drainage features.
Site Restrictions	There are no site restrictions; this activity is performed entirely off the main roadway.			
Construction Considerations	Drainage maintenance should be performed on a regular basis or whenever conditions warrant.			
Typical Costs	Costs depend on activity and frequency.			
Additional Information	The manner in which this activity is carried out varies widely among highway agencies. However, there is a far greater chance that the work will be completed if it is a programmed activity rather than one left for maintenance forces to do if all other activities have been completed.			

Maintenance of Drainage Features

Maintenance of drainage features for both bituminous-surfaced and concrete-surfaced pavements are described in Table 15. Drainage impacts pavement performance in many ways. Poor surface drainage can lead to such undesirable conditions as splash and spray and or slippery pavements. Poor subsurface drainage can ultimately contribute to the reduced structural performance of the pavement. While the maintenance of features such as drainage outlets, headwalls, and edge drains may not be part of a pavement preventive maintenance program, the importance of performing routine maintenance of these features cannot be overemphasized. Drainage features are incorporated in a pavement structure to prevent the development and acceleration of moisture-related deterioration; failure to maintain these features in operable condition can contribute to the loss of pavement serviceability.

SUMMARY

The literature search performed for this project shows that there is little work being done on the timing of preventive maintenance treatments. However, there is a general consensus on the concepts and definition of preventive maintenance, and on the treatments used in preventive maintenance programs. Important attributes of preventive maintenance treatments may be considered for selecting treatments to be included in a preventive maintenance program and for determining when such treatments should be applied.

CHAPTER **3**

RESEARCH RESULTS

INTRODUCTION

There is a need to identify when it is "best" to apply preventive maintenance treatments. Treatment performance is greatly dependent on the condition of the pavement at the time of treatment application, and different types of treatments are likely only to be effective when placed at certain times in a pavement's life. When placed at the right time, a preventive maintenance treatment becomes a cost-effective means of attaining the desired life and performance of the pavement. Treatments applied too soon add little benefit and treatments applied too late are ineffective; however, there is little guidance available on this topic.

There are no studies that have successfully determined how to identify the optimal time to apply preventive maintenance treatments; although a number of completed studies have examined this issue and other research continues to study it. These include the studies of maintenance effectiveness under the Specific Pavement Studies (SPS-3 and SPS-4) effort (*17, 18*), and field studies by the DOTs in Iowa (*9*), Arizona (*19*), Texas (*20, 21*), and South Dakota (*22*).

The primary objective of this project was to determine an approach for identifying the optimal timing for the application of preventive maintenance treatments. This chapter describes a methodology for determining the optimal time to apply preventive maintenance by analyzing pavement performance and cost data. The methodology is presented as a Microsoft® Excel-based software designated OPTime. The results of an evaluation of OPTime (and the analysis methodology) with data provided by state highway agencies is also described.

INTRODUCTION TO THE METHODOLOGY USED TO DETERMINE OPTIMAL TIMING

One of the initial challenges in this project was to attach some physical meaning to "optimal" timing in the context of preventive maintenance treatment applications. It could potentially mean to provide the smoothest ride for the least money, to prolong the need for rehabilitation, or to meet some other objective. While the concept of "optimal" timing seems closely linked to cost-effectiveness, the definition of cost-effectiveness also varies among agencies. Ulti-mately, a methodology very similar to the cost-effectiveness analyses used in pavement management systems was selected.

Overview of the Analysis Approach

The approach is built on a number of fundamental concepts. It assesses the effectiveness of a particular preventive maintenance application in terms of both the *benefit* it provides and the *cost* required to obtain that benefit. In this methodology, *benefit* is defined as the quantitative influence on pavement performance as measured by one or more condition indicators. Costs that may be included in the analysis include the following:

- The agency cost to construct the treatment,
- Work zone-related user delay costs,
- The cost of a rehabilitation activity that would be considered at the point when the preventive maintenance treatment is considered failed, and
- The cost of scheduled routine maintenance.

In the optimal timing methodology, the benefits associated with the use of a preventive maintenance treatment are evaluated in conjunction with its associated costs. The optimal application of a preventive maintenance treatment occurs at the point at which the benefit per unit cost is greatest.

Pavement Performance

The computation of the benefit associated with an applied preventive maintenance treatment requires knowledge of the anticipated performance of the pavement. The effect of a treatment on performance is determined by the change in condition indicators, such as International Roughness Index (IRI), present serviceability index (PSI), or other custom-defined measure of performance.

Condition Indicators

The ability of treatment to preserve pavement condition and retard future deterioration is measured by changes in the condition indicators that define pavement performance. Condition

indicators used in the optimal timing methodology should have the following characteristics:

- Be measurable (able to be tracked over time),
- Indicate pavement performance (especially functional performance for preventive maintenance), and
- Change value following the application of a preventive maintenance treatment.

Condition monitoring data are needed for all condition indicators that are used in the analysis; the methodology permits the analysis of multiple condition indicators.

Do-Nothing Relationships

The benefit associated with the application of a preventive maintenance treatment at any given time is based on the improvement in condition compared with that for the "do-nothing" alternative. The do-nothing alternative defines the performance over time (in terms of the condition indicator) that would be expected if only minor routine maintenance were conducted. In a plot of pavement condition versus time, the baseline performance relationship is referred to as a do-nothing curve. If benefit is defined in terms of multiple distress types, a do-nothing performance curve is required for each relevant condition indicator. The best source for this information is existing pavement management systems, although the necessary relationships can also be approximated without the assistance of a pavement management database.

Post-Treatment Relationships

Determining optimal timing also requires an understanding of how performance is changed once the preventive maintenance treatment has been applied. A separate performance relationship (condition versus age) is needed for each unique combination of condition indicator and treatment application age; it is generally assumed that this relationship changes depending on when the treatment is applied. For example, if performance is measured by 3 indicators for a treatment applied at 5 ages, 15 (3×5) different performance relationships must be defined.

Benefit Associated with Individual Condition Indicators

Benefit is the quantitative influence on condition indicators resulting from the application of a preventive maintenance treatment. Using this definition, different types of benefit may be associated with an application of a given preventive maintenance treatment. For example, applying a chip seal could result in benefits in the form of improved friction, retarded

oxidation, or reduced rutting. For a specific condition indicator, the benefit is determined by the difference in computed areas associated with the post-treatment condition indicator curve and the do-nothing curve. For condition indicators that decrease over time (e.g., serviceability, friction, or a typical composite index) the area under the curve becomes relevant to benefit computations, while for condition indicators that increase over time (e.g., roughness, cracking, rutting, faulting, and spalling) the area above the curve becomes relevant. Figure 1 illustrates the benefit resulting from the application of a preventive maintenance treatment. As shown in the figure, a defined lower benefit cutoff value limits the areas.

The benefit (difference in areas) is generally *positive,* as a preventive maintenance treatment should improve condition or extend the time until the pavement needs rehabilitation; however, negative benefits may result (e.g., the decrease in friction that follows the application of a fog seal).

As different condition indicators are expressed in different units, the methodology normalizes all individual condition indicator benefit values by dividing the benefit area by the original do-nothing area. The result is that all individual benefit values are similarly expressed in units of percent. For example, if the do-nothing and benefit areas in Figure 1 are calculated to be 30 and 12, respectively, the individual benefit value associated with the condition indicator would be $^{12}/_{30} = 0.4$, or 40 percent.

Benefit Weighting Factors

When more than one condition indicator is included in the analysis, a method is needed to combine the individual benefit values associated with the different indicators. This is done by using *benefit weighting factors* and a normalization process.

Computation of Overall Benefit

Benefit weighting factors are used to differentially weight the computed individual benefits associated with each included
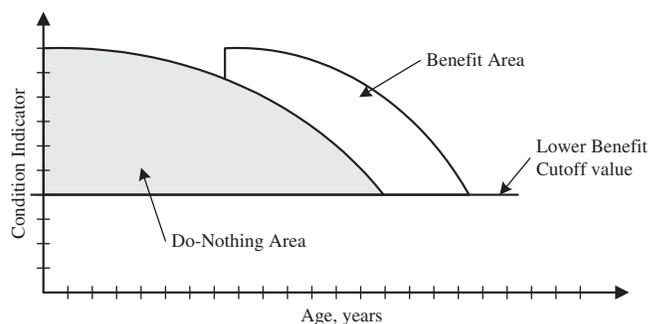
Figure 1. Conceptual illustration of the do-nothing and benefit areas.

condition indicator. Each condition indicator is assigned an integer weighting factor between 0 and 100, where all the entered weighting factors must total 100 for a given analysis. Each chosen weighting factor is then converted to an associated *weighting percentage* by dividing each individual weighting factor by 100 (i.e., the total of all assigned benefit weighting factors). The individual contributions to the overall benefit are then determined by multiplying the benefit weighting factor percentages by the individual benefit values. This approach is explained with the following example.

Assume that a particular preventive maintenance treatment timing results in individual benefit values of 27 percent for rutting, 12 percent for cracking, and 47 percent for friction. That is, the preventive maintenance treatment application increases performance by 27, 12, and 47 percent over the do-nothing benefit area performances for rutting, cracking, and friction, respectively. Next, assume that the agency chooses benefit weighting factors of 60, 30, and 10 for rutting, cracking, and friction, respectively (note that these factors add up to 100). Overall benefit contributions are then determined by multiplying the benefit weighting factor percentages by the individual benefit values (e.g., for rutting 27 percent × 60 = 16.2 percent). The total overall benefit contribution is then the total of those values calculated for each individual condition indicator. In this example, the total overall benefit contribution is 24.5 percent (see Table 16). The total benefit values computed for different timing scenarios are then used in combination with costs to compare the effectiveness of the different timing scenarios.

Selecting Benefit Weighting Factor Values

Selecting benefit weighting factors that correctly represent the relative importance of different condition indicators is a difficult task. Because each condition indicator is expressed in different units, an incremental change in the magnitude of one indicator does not necessarily provide the same effect as an incremental change of equal magnitude in another condition indicator. For example, a 10 percent increase in the area (benefit) associated with roughness is not likely to have the same impact on performance as a 10 percent increase in the friction area. Although the selection of benefit weighting factors is a subjective process that requires engineering judg-

ment, an investigation can be conducted to provide feedback on multiple condition indicators used in the analysis. Some general steps that can be followed to gather feedback for use in the factor selection process are described in this section.

Initial Selection of Benefit Weighting Factors. Engineering judgment is a good starting point in the process of selecting relative weights associated with each performance measure. The initially selected weights represent attempts to quantify the relative purpose or benefit of applying the treatment. For example, if the use of a slurry seal is proposed to reduce or eliminate a historical problem with raveling and low friction characteristics, and if the agency feels that the problems with raveling and low friction are of equal importance, then initial benefit weighting factors of 50 would be appropriate for both. However, if the preventive pavement program is primarily being driven by a desire to improve friction characteristics, this difference in purpose may be reflected by assigning a much larger factor to friction (e.g., 80 for friction and 20 for raveling).

Analyze Each Condition Indicator Separately. The initial selection of benefit weighting can be improved by investigating the sensitivity of the results. This can be accomplished by analyzing the effects of one condition indicator at a time (set the associated benefit weighting factor for one of the condition indicators to 100 and all other benefit weighting factors to 0). The effects on treatment timing can then be interpreted to identify the condition indicators that are relatively more important than others.

To demonstrate the importance of the benefit weighting process, assume an individual analysis of three different condition indicators (rutting, cracking, and friction). When the optimal timing results are relatively similar (e.g., 3, 4, and 4 years of age, respectively), the weighting process is less important than if the optimal treatment times are substantially different. The weighting process will be completed by considering a weighted average of the benefits associated with each condition indicator (the overall optimal timing will still be in a range from 3 to 4 years). However, if the individual analysis results show a wider range of optimal timings (e.g., 4, 2, and 7 years, respectively), the effect of assigned weighting factors on the final optimal timing cannot be easily assessed. In such cases, investigations similar to that described

TABLE 16 Example computation of overall benefit

Condition Indicator	Individual Benefit Values, %	Assigned Benefit Weighting Factor	Benefit Weighting Factor Percentage	Overall Benefit Contribution, %
Rutting	27	60	60/100 = 0.6	16.2
Cracking	12	30	30/100 = 0.3	3.6
Friction	47	10	10/100 = 0.1	4.7
TOTAL	**—**	**100**	**1.0**	**24.5**

in the following subsection are needed to determine appropriate weighting factors.

Trials of Different Combinations of Benefit Weighting Factors. Useful feedback may be obtained by conducting a series of analyses in which different combinations of weighting factors are investigated. For example, the selection of initial weighting factors as the baseline (e.g., 60 for rutting, 30 for cracking, and 10 for friction) indicates that controlling rutting appears to be the most important purpose of the treatment, and the overall optimal timing is thus likely to be closer to the age associated with the individual analysis in which only rutting was considered (i.e., 4 years) than to the ages associated with the other condition indicators (i.e., 2 or 7 years).

Conducting a simplified sensitivity analysis of different combinations of benefit weighting factors should provide information to support the initial choices for weighting factors or to help make appropriate changes to the individual factors. Continuing with the example above, assume that the results summarized in Table 17 are obtained by conducting a series of targeted analyses. A simultaneous interpretation of such "what if" scenario results—combined with the optimal timings estimated by conducting the separate condition indicator analyses—should provide a good indication of the benefit weighting factors that are best for a specific analysis.

Because the process for determining appropriate benefit weighting factors is very similar to that used by agencies to develop composite distress indices, many agencies may already have processes that can be adapted. Regardless of the method used to select the weighting factors, it is recommended that an agency regularly review the selected factors whenever additional (or more accurate) performance data become available (i.e., whenever performance relationships are updated). This review will greatly increase the chances of obtaining more accurate analysis results.

Cost Considerations

The second fundamental aspect of the proposed methodology is the inclusion of costs that are impacted by the application of preventive maintenance activities. The current methodology allows the user to consider preventive maintenance treatment costs (agency costs), rehabilitation costs, work zone-related user delay costs, and other routine maintenance costs. The user can select one or more of these available cost types to include in an analysis. The details associated with each of these cost types are described as follows.

Treatment Costs

Treatment costs include all agency costs associated with the placement of a preventive maintenance treatment. These include design, mobilization, materials, construction, and traffic control costs. Although the analysis methodology allows these costs to be omitted, it is highly recommended that treatment costs be included in any analysis.

Rehabilitation Costs

Because the application of preventive maintenance is expected to prolong the need for major rehabilitation, the inclusion of rehabilitation costs is an option in the analysis approach. As the cost of a required rehabilitation activity can be large in relation to the cost of a preventive maintenance treatment, the timing of the expected rehabilitation activity can have a significant impact on a pavement's overall life-cycle cost (LCC).

Work Zone-Related User Delay Costs

The methodology considers only user costs associated with work zone delays (i.e., the cumulative delay cost recognized by all users subjected to the work zone during construction of the treatment). This approach favors treatments that provide some benefit but can be placed comparatively quickly with little disruption to the traveling public. The methodology does not include other common types of condition-sensitive user costs (e.g., vehicle operating costs, discomfort, and accident costs) because the difference in pavement condition for preventive maintenance candidates is expected to be relatively small.

The cumulative delay cost is computed as a function of the average number of vehicles per day (AADT), work zone duration, average vehicle delay time, and cost per delay time per vehicle.

TABLE 17   Example of optimal timings resulting from conducting a series of analysis sessions with different benefit weighting factors

Rutting Weighting Factor	Cracking Weighting Factor	Friction Weighting Factor	Resulting Estimated Optimal Timing, age
60	30	10	5
60	25	15	6
60	35	5	4
70	20	10	4
50	40	10	3

In general terms, user costs are defined as non-agency costs that are borne by the users of a pavement facility, and typically consist of the following:

- Vehicle operating costs (VOC)—Costs induced because of increased wear and tear on a vehicle when using a pavement (because of stopping/starting or excessive pavement roughness) during normal operations. Normal operations are periods in which a pavement facility is free of construction, maintenance, or rehabilitation activities that would otherwise affect the capacity. Costs in this category are generally related to pavement roughness, and therefore do not begin to accrue until after the pavement has reached a higher level of roughness (e.g., an IRI of about 2.7 m/km [170 in./mi], or a present serviceability rating [PSR] of about 2.5).
- User delay costs—Additional costs caused by time delays in traveling over a pavement facility as a result of the following:
  – Reduced speed to enter the work zone (or even a complete stop, if there is queuing),
  – Reduced speed through the work zone; and
  – Use of alternate routes to avoid the work zone.
- Crash costs—Costs associated with fatalities or injuries that result from crashes on a pavement facility.

The inclusion of user costs as part of a life-cycle cost analysis (LCCA) is a controversial issue. While there is general agreement that traffic delays increase user costs, the actual costs are difficult to quantify and they are not costs borne directly by the highway agency. When user costs are included in an analysis, they often overwhelm the direct agency costs, particularly for high-volume facilities. Some highway agencies choose not to include user costs in an LCCA while others choose to compute direct costs and user costs separately and include user costs as an additional evaluation criteria when evaluating competing construction bids (often referred to as A + B contracts).

For most pavement facilities in fair or good condition (e.g., pavements with a PSR of 2.5 or greater), user costs during normal operations are minimal; consequently, the user costs associated with the placement of work zones for pavement maintenance or rehabilitation activities are of the greatest concern in this project. Of the three types of user costs, only user delay costs are incorporated into the optimal timing methodology because they are generally significantly larger than the vehicle operating costs or the crash costs; there is a dearth of statistical data to support crash rates in work zones, and there is controversy associated with crash cost rates.

Estimating User Delay Costs. The 1998 FHWA report, *Life-Cycle Cost Analysis in Pavement Design* (*23*), outlines the steps for estimating work zone user delay costs. The process requires at least the following information:

- General project inputs (e.g., project length, number of lanes);
- Traffic data (e.g., 2-way average daily traffic [ADT], directional split, hourly traffic distribution);
- Work zone closure data (e.g., time period(s) in which the closure is in place, duration of the work zone closure, number of available lanes, posted and work zone speed limits, vehicle capacity, queue dissipation rates); and
- Value of time delay costs (for passenger, single unit, and commercial vehicles).

With these inputs, the movement of vehicles through the work zone can be analyzed, yielding information on user delay times (including delays because of the possible development of queues) which can be converted to user delay costs. The analysis can be conducted by several computer programs (e.g., MicroBENCOST, QueWZ). It is somewhat complex and requires inputs that may not be readily available for the analysis of most projects. Consequently, a more simplified procedure is needed for this methodology.

To include user costs in the analysis, an easy method is needed to compute the time delays for vehicles traveling through the work zone. If this value is estimated, then the entire calculation process becomes straightforward. Table 18 lays out the calculation routine for the incorporation of user delay costs, with each of the columns in that table defined following the table.

- Column A: The classification of vehicles using the facility (the 1998 FHWA report recommends just three classes: passenger cars, single-unit trucks, combination trucks) (*23*).
- Column B: The approximate number of vehicles in each of three categories that are affected by the work zone; this is largely influenced by the length of time that the work zone is in place (if the work zone is periodic, then it is the vehicles that pass through the zone only during that period).
- Column C: The delay cost rate for each vehicle classification (ranges are provided in the 1998 FHWA report) (*23*).
- Column D: The average additional delay time for each vehicle that is affected by the work zone. This value is estimated for each project, and is strongly related to the physical length of the work zone, the number of lanes that are closed (and the capacity of those that remain open), and whether or not a queue is expected to form.
- Column E: The total cost for each vehicle classification, which is the product of column B, column C, and column D (making sure all units are consistent).

This simplified process introduces several sources of error. One obvious source of error is the accuracy of the user's estimates. Although these errors may be significant, these estimates can be used to make meaningful comparisons of the relative effects. Another source of error arises if the work zone

TABLE 18   Calculation of user delay cost

Column A	Column B	Column C	Column D	Column E
Vehicle Classification	Total Number of Vehicles Affected By Work Zone[1]	Delay Cost Rate, \$/hr[2]	Average Additional Delay Time, hour/vehicle[3]	Total Cost
Passenger Cars	15	\$10 to \$13		Col. B* Col. C* Col. D
Single-Unit Trucks	6	\$17 to \$20		Col. B* Col. C* Col. D
Combination Trucks	1	\$21 to \$24		Col. B* Col. C* Col. D
TOTAL	(sum column B)			(sum column E)

[1] Only the number of vehicles in each category affected by the placement of the work zone over its entire duration.

[2] From 1998 FHWA LCC report, p. 23 (note: 1996 values) (*23*).

[3] The delay time for each vehicle is estimated on a project by project basis (it is the same for each vehicle category). This includes all delay times associated with the work zone, including speed change delay (going from posted speed limit to work zone speed limit), work zone speed delay (delay associated with slowing down to the work zone speed limit to traverse the work zone), stopping delay (time delay if a queue forms), and queue speed delay (time delay it takes to traverse the queue).

produces a queue that generates considerable delay costs. These costs may not be accurately accounted for in the user's estimate of the number of vehicles affected by the work zone. However, because work zones associated with most preventive maintenance treatments are of relatively short duration and short length, queues are less likely to form and the error associated with this item is reduced.

Additional Routine Maintenance Costs

Different pavement structures and surfacing approaches require different needs for routine maintenance. These needs are addressed in the methodology as a recurring cost for which the timing is not optimized. An example of such an activity is pothole patching that may influence long-term performance but does not fit the preventive maintenance model because it is only done once the distress appears (i.e., its timing cannot be optimized).

When choosing to include the costs of routine/reactive maintenance activities in an analysis, the do-nothing performance curves must account for the expected effect of this maintenance on performance. The routine maintenance schedule (and costs) must be estimated and included in the analysis.

Determination of Optimal Timing

The optimal time to apply a treatment is based on an analysis of benefit and costs. That application timing that maximizes benefit while minimizing costs (i.e., that with the largest B/C ratio is the most effective timing scenario.

To make the actual values of the B/C ratios more meaningful, the concept of an Effectiveness Index (EI) is introduced. The EI normalizes all individually computed B/C ratios to a 0 to 100 scale by comparing all B/C ratios with the maximum individual B/C ratio (i.e., the ratio associated with the optimal timing scenario). The maximum individual B/C ratio is assigned an EI of 100, and all other B/C ratios are represented as a fraction of the maximum EI. The EI is computed for each timing scenario using equation 1.

$$EI_i = \left[\frac{(B/C)_i}{(B/C)_{max}} \right] \times 100 \qquad \text{(Eq. 1)}$$

where:

EI_i = EI associated with the *i*th timing scenario (dimensionless).

$(B/C)_i$ = B/C ratio associated with the *i*th timing scenario.

$(B/C)_{max}$ = Maximum of all of the B/C ratios associated with the different timing scenarios.

i = Index associated with the current timing scenario.

DETAILED CALCULATION PROCEDURES OF THE ANALYSIS APPROACH

This section describes a step-by-step procedure for (1) computing benefit and costs within the methodology and (2) using the results to determine the most effective treatment timing. An example is also presented to illustrate the concepts.

Step 1: Analysis Session Setup

The first step in the optimal timing analysis process is to select the particular treatment and the specific treatment application ages that will be used in the analysis.

Treatment Selection

Agencies use a broad range of treatments in pavement preservation and rehabilitation programs. However, preventive maintenance, which is a subset of these two pavement activity categories, considers treatments that can be applied to a pavement in good condition to preserve condition and prevent or delay future deterioration. The treatments shown previously in Table 2 fit this definition of preventive maintenance and will provide benefits when used in the appropriate conditions. The user should, however, carefully consider whether these benefits can be measured using available performance evaluation procedures. For example, crack sealing or maintaining drainage features may be a cost-effective means of maintaining or improving pavement condition, but performance measures such as IRI, cracking indices, rutting, and faulting may reveal only subtle (or even no) differences when compared with control sections.

Furthermore, while the analysis method permits users to analyze performance results from any specified treatment, the approach does not work well for treatments applied when the pavement is deteriorated and rehabilitation is required. The current approach allows the analysis of a single application of one preventive maintenance treatment but not that of a series of preventive maintenance treatments.

Selection of Application Ages

The optimal time to apply a selected preventive maintenance treatment is estimated by conducting analysis for different *timing scenarios* in which the treatment is applied at different pavement ages.

Step 2: Selection of Benefit Cutoff Values

The concept of optimal timing stipulates that treatments applied too soon or too late do not necessarily provide added benefit. Benefit cutoff values are defined as the *y*-axis (condition indicator) boundary conditions for the performance curves that define the upper and lower limits for the benefit area calculations. The specific definitions of the upper and lower benefit cutoff values are as follows:

- Upper benefit cutoff value—The upper benefit cutoff value is the *upper* limit to the benefit area computations (i.e., no area above the upper benefit cutoff level is included in the benefit computation). For a condition indicator relationship that increases over time (e.g., IRI), this value also serves as the benefit cutoff value that is used in determining the analysis period (i.e., the age at which the performance curve reaches the benefit cutoff value). For a condition indicator relationship that decreases over time (e.g., friction number), the upper benefit cutoff value defines a "ceiling" that limits the benefit credited to the application of the treatment. For example, assume that an agency associates excellent

roadway friction with a friction number of 60 (i.e., FN40R = 60). If the application of a particular treatment is found to result in friction numbers greater than 60, the area above the upper benefit cutoff value of 60 would not be included in the benefit calculations.

- Lower benefit cutoff value—The lower benefit cutoff value is the *lower* limit to the benefit area computations (i.e., no area below the lower benefit cutoff level is counted as a benefit). For a condition indicator relationship that decreases over time this value also serves as the benefit cutoff value in determining the analysis period (in the same manner as described for the upper benefit cutoff).

Figure 2 illustrates how upper and lower benefit cutoff values limit the area calculations for both decreasing and increasing do-nothing condition indicator curves. In this example, the decreasing relationship is limited by both the upper and lower benefit cutoff values and the increasing relationship is limited only by the upper benefit cutoff value.

Benefit cutoff values are unique to an agency, and perhaps even to a given project, and their determination is not straightforward. In general, agencies should consider benefit cutoff values that relate to the following identifiable condition levels:

DECREASING RELATIONSHIP

INCREASING RELATIONSHIP
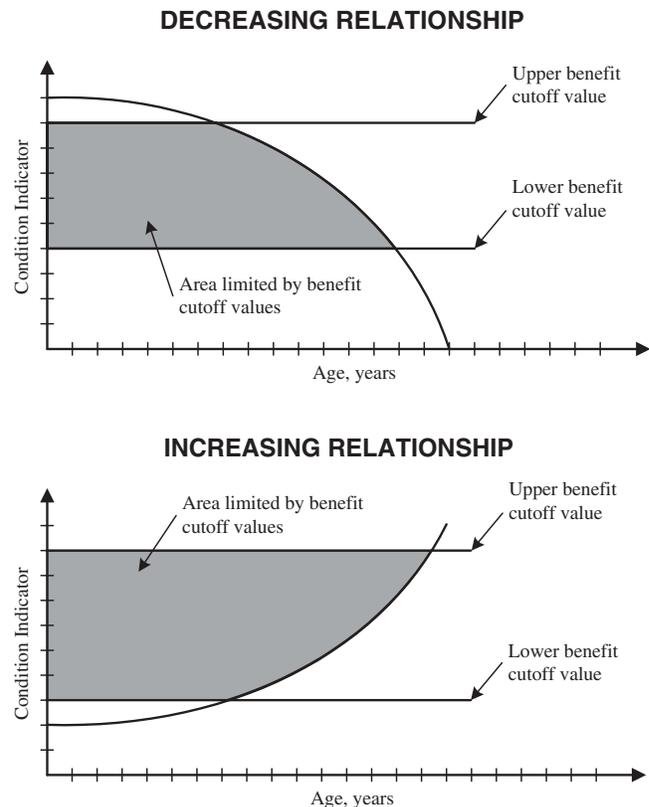
Figure 2. Illustration of the application of upper and lower benefit cutoff values on both decreasing and increasing condition indicators for the do-nothing case.

- Pavement failure (rehabilitation trigger)—the condition level at which a major rehabilitation is required.
- Treatment failure—the condition level at which a treatment is considered failed (i.e., the benefits of the preventive maintenance treatment are no longer being realized).

If agencies are unsure about how to select these benefit cutoff values, it is recommended that values be set to closely reflect current maintenance and rehabilitation policies. For example, if an agency typically applies only one preventive maintenance treatment in the life of a pavement, then the benefit cutoff value should be equal to the pavement failure level because a major rehabilitation will most likely be the next pavement-related activity. In contrast, if an agency typically applies a second preventive maintenance treatment after the first application reaches a known condition failure level, the benefit cutoff value can be set equal to the treatment failure level.

Step 3: Computation of Areas Associated with the Do-Nothing Case

The third step in the benefit calculation process involves determining the total do-nothing condition curve areas. The individual condition indicator areas are computed by taking integrals of the specific performance equations that define the do-nothing performance curves. The important benefit-related areas are those below condition indicator curves that decrease over time and above condition indicator curves that increase over time. The final do-nothing condition area for a given condition indicator is determined by applying the following area boundary conditions:

- *Y*-axis limits—in the *y* direction, the pertinent area is bounded by the defined upper and lower benefit cutoff values.
- *X*-axis limits—in the *x* direction, the pertinent area is bounded by zero on the lower end and the age at which the performance curve intersects the benefit cutoff value on the upper end.

The area calculation details differ slightly depending on whether the performance equation is decreasing or increasing. Equations 2 and 3 are used to compute the do-nothing benefit-related areas associated with decreasing and increasing equations, respectively. These equations are functions of the actual do-nothing mathematical equation and the upper and lower benefit cutoff values. Figure 3 illustrates the total
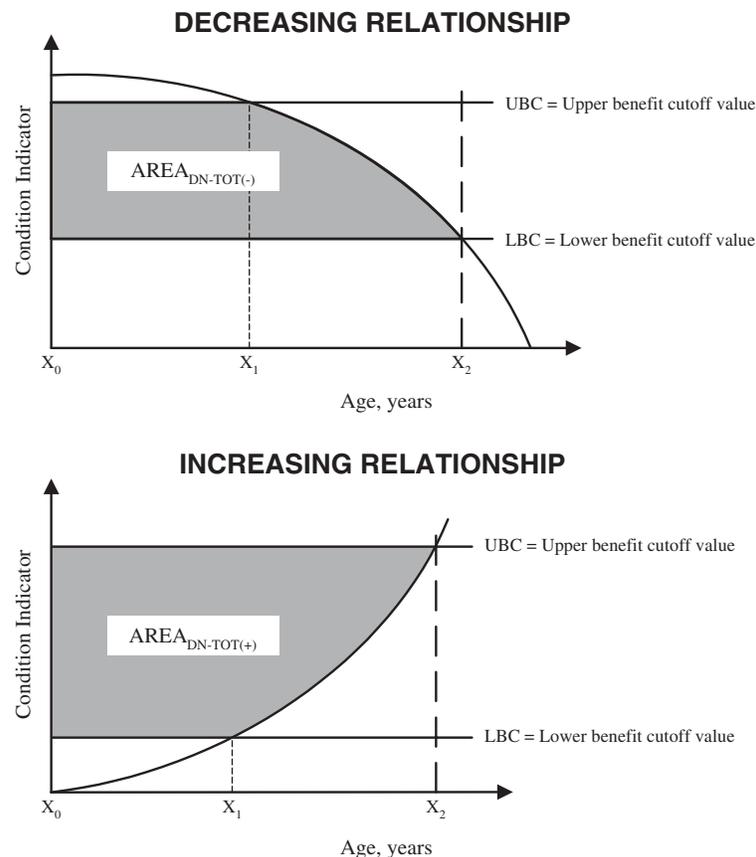
Figure 3.   Total areas associated with decreasing and increasing condition indicators for do-nothing options.

do-nothing areas associated with both decreasing and increasing do-nothing curves and the different intersection points used to define the *x*-axis boundary conditions.

The total do-nothing condition area associated with a decreasing condition indicator relationship [$AREA_{DN-TOT(-)}$] is computed from the following equation:

$$AREA_{DN-TOT(-)} = \int_{X_0}^{X_2} (EQ_{DN} - LBC) \\ - \int_{X_0}^{X_1} (EQ_{DN} - UBC) \qquad (Eq. 2)$$

where:

EQ_{DN} = Equation defining the do-nothing condition indicator relationship.

UBC = Upper benefit cutoff value associated with the condition indicator.

LBC = Lower benefit cutoff value associated with the condition indicator.

X_0 = Lower limit to the age range (set to zero).

X_1 = Age at which the do-nothing curve intersects the upper benefit cutoff value ($X_1 = 0$ if there is no intersection with the UBC).

X_2 = Age at which the do-nothing curve intersects the lower benefit cutoff value ($X_2 = 0$ if there is no intersection with the LBC).

The total do-nothing condition area associated with an increasing condition relationship [$AREA_{DN-TOT(+)}$] is computed from the following equation:

$$AREA_{DN-TOT(+)} = \int_{X_0}^{X_2} (UBC - EQ_{DN}) \\ - \int_{X_0}^{X_1} (LBC - EQ_{DN}) \qquad (Eq. 3)$$

where:

EQ_{DN} = Equation defining the do-nothing condition indicator relationship.

UBC = Upper benefit cutoff value associated with the condition indicator.

LBC = Lower benefit cutoff value associated with the condition indicator.

X_0 = This lower limit to the age range is set to zero.

X_1 = Age at which the do-nothing curve intersects the lower benefit cutoff value ($X_1 = 0$ if there is no intersection with the LBC).

X_2 = Age at which the do-nothing curve intersects the upper benefit cutoff value ($X_2 = 0$ if there is no intersection with the UBC).

Figure 4 illustrates the application of these area boundary conditions and the resulting bounded areas (i.e., $AREA_{DN(FRICTION)}$, $AREA_{DN(RUTTING)}$, and $AREA_{DN(ROUGHNESS)}$) for the previously presented example.

Step 4: Computation of the Overall Expected Service Life of the Do-Nothing Case

While the computed overall expected service life does not influence the do-nothing area or benefit computations, it serves as a baseline for determining the expected extension of life. As the extension of service life is often used as a measure of the success of a preventive maintenance treatment, this computed value is included as part of the analysis output. The expected overall service life for the do-nothing condition is selected as the earliest age at which one of the considered condition indicator do-nothing relationships reaches its benefit cutoff value (i.e., the upper benefit cutoff value for increasing relationships or the lower benefit cutoff value for decreasing relationships). This definition is based on the assumption that, in practice, a second treatment would most likely be applied when the first of the considered condition indicator performance curves reaches its benefit cutoff value as illustrated in the following example. The first assumption in this example is that the benefit from applying preventive maintenance lies in its improvement in friction, rutting, and IRI. Next is that the indicators reach their respective triggering benefit cutoff values at 15, 14, and 17 years. Therefore, the overall do-nothing curve expected service life for the analysis session is 14 years—the earliest age of all of the triggering conditions. Figure 5 illustrates the process for this determination.

Step 5: Computation of Expected Service Life of the Post-Treatment Case

The next step in the benefit calculation process is to plot the post-treatment performance relationships for each condition indicator. The expected service life for the post-treatment case (for a given timing scenario) is then determined as the earliest age at which any of the post-treatment condition indicators reaches its benefit cutoff value. Unlike the do-nothing case where the area computations are unbounded in the *x*-direction, the area computations for the post-treatment case are bounded at this expected post-treatment service life which is also used as the analysis period for the LCC computations.

In the previous example, if a preventive maintenance treatment is applied at a pavement age of 10 years, the performance curves for friction, rutting, and roughness, as shown in Figure 6, reach their triggering benefit cutoff values at 20, 22, and 24 years, respectively. Therefore, the expected service life (and analysis period) for this timing scenario is 20 years—the earliest age of all the triggering conditions. Thus, areas would only be computed for the *x*-range between 0 and 20 years.
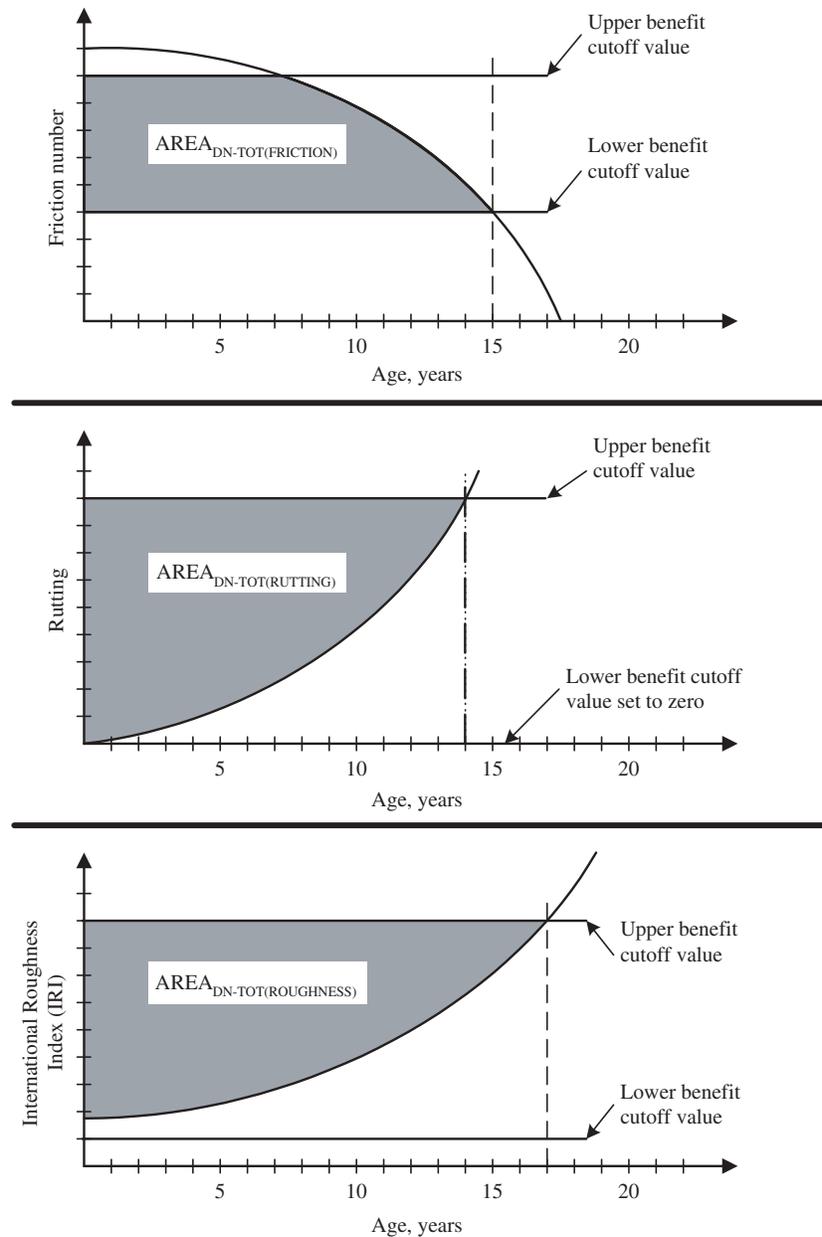
Figure 4. Total areas associated with individual condition indicators for the do-nothing options.

Step 6: Computation of Areas Associated with the Post-Treatment Case

The sixth step in the benefit calculation process is determining the important post-treatment condition curve areas that are used to compute benefit. As with the do-nothing condition area calculations, the individual condition indicator areas are computed by taking the integrals of the specific performance equations that define the post-treatment performance curves. As mentioned previously, the important benefit-related area is the area below condition indicator curves that decrease over time or above condition indicator curves that increase over time (as shown in Figure 7). The final post-treatment condition area for a given condition indicator is only determined after applying the following area boundary conditions:

- *Y*-axis limits—in the *y* direction, the pertinent area is bounded by the defined upper and lower benefit cutoff values.
- *X*-axis limits—in the *x* direction, the pertinent area is bounded by an age of zero on the lower end and the overall determined post-treatment case expected service life (from step 5) on the upper end.
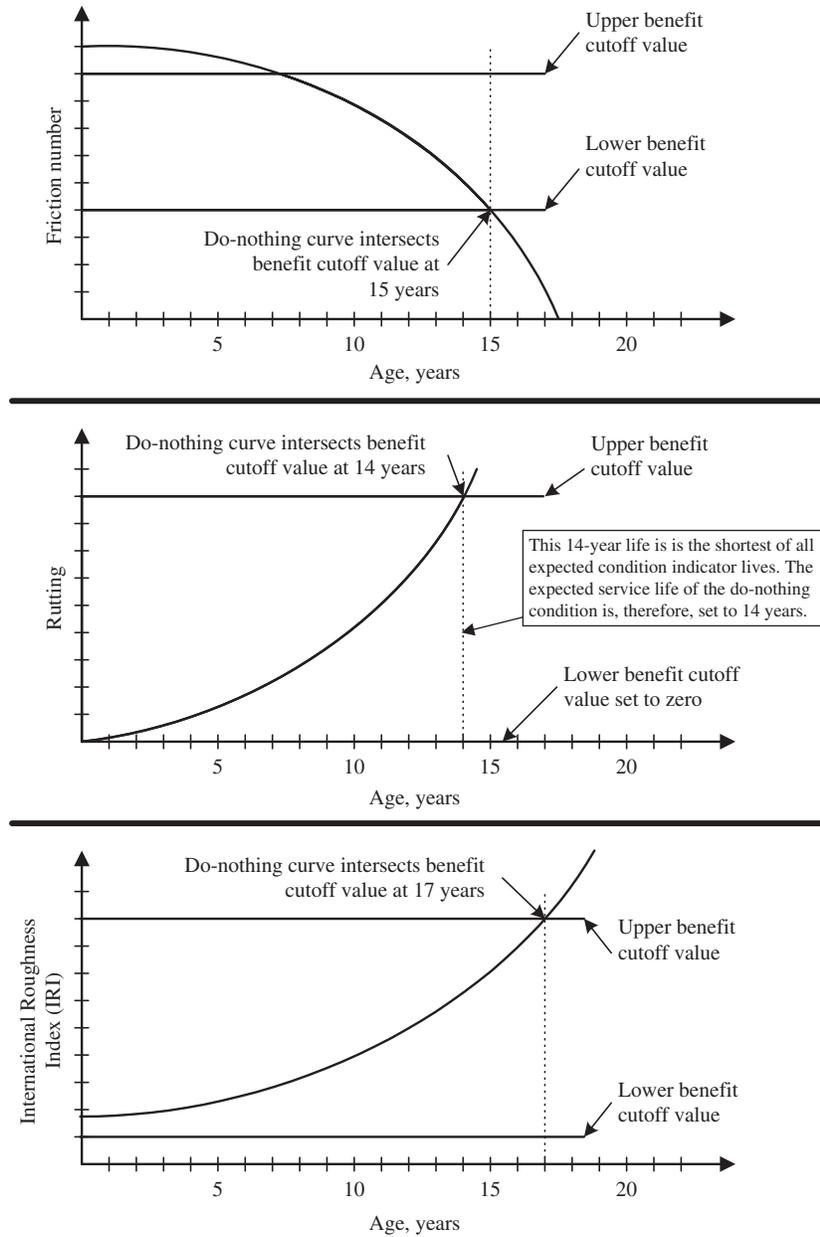
Figure 5.   Determination of the overall do-nothing condition expected service life.

Figure 7 illustrates the total benefit-related areas associated with both decreasing and increasing post-treatment curves. Also illustrated in Figure 7 are the different intersection points used to define the *x*-axis boundary conditions required for the different parts of the area-calculation equations.

The area calculation details are different, depending on whether the post-treatment performance equation is decreasing or increasing. Equations 4 and 5 are used to compute these post-treatment benefit-related areas associated with decreasing and increasing equations, respectively. Both of these equations are functions of the actual post-treatment curve equation and the upper and lower benefit cutoff values. It is important to note that the post-treatment performance equations are expressed in terms of the *treatment* age rather than the *pavement* age. For example, for a linear treatment performance equation such as $y = mx + b$, the x values are *treatment* age values (i.e., time after treatment application) rather than pavement age values (i.e., time since original construction). Therefore, some of the *x*-axis values associated with computing the area after the treatment application age are adjusted to account for this difference in age (e.g., $X_4 - X_A$ and $X_3 - X_A$ in equation 4).
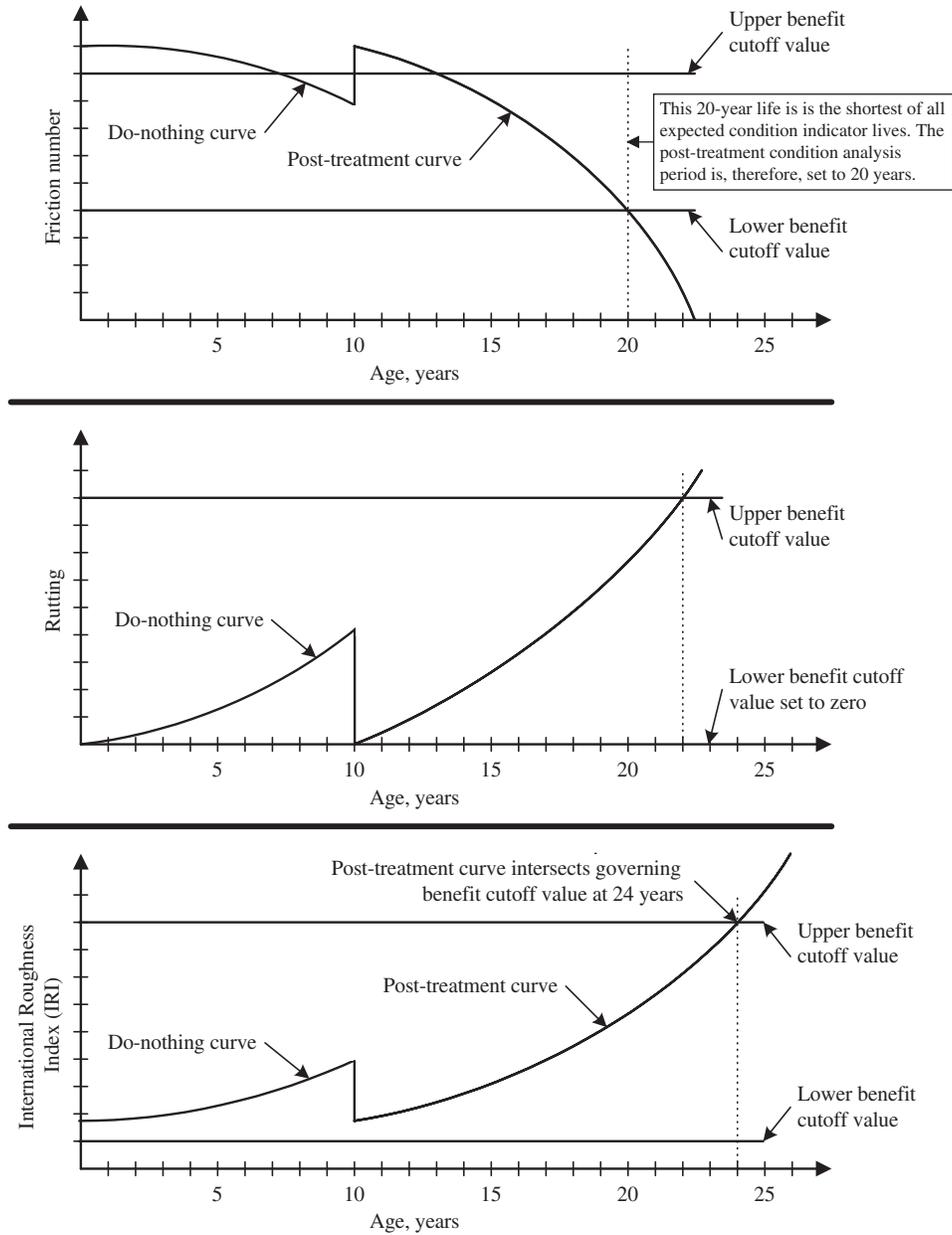
Figure 6. Determination of the overall post-treatment condition expected service life (analysis period).

$$AREA_{PT(-)} = \int_{X_0}^{X_2} (EQ_{DN} - LBC)$$

$$- \int_{X_0}^{X_1} (EQ_{DN} - UBC)$$

$$+ \int_{0}^{(X_4 - X_A)} (EQ_{PT} - LBC)$$

$$- \int_{0}^{(X_3 - X_A)} (EQ_{PT} - UBC)$$

(Eq. 4)

where:

$AREA_{PT(-)}$ = Computed post-treatment area associated with a decreasing condition indicator relationship (i.e., area from time zero to the end of the post-treatment analysis period).

EQ_{DN} = Equation defining the do-nothing condition indicator relationship.

EQ_{PT} = Equation defining the post-treatment condition indicator relationship (i.e., treatment performance curve). Note that the post-treatment equation is a function of the *treatment* age

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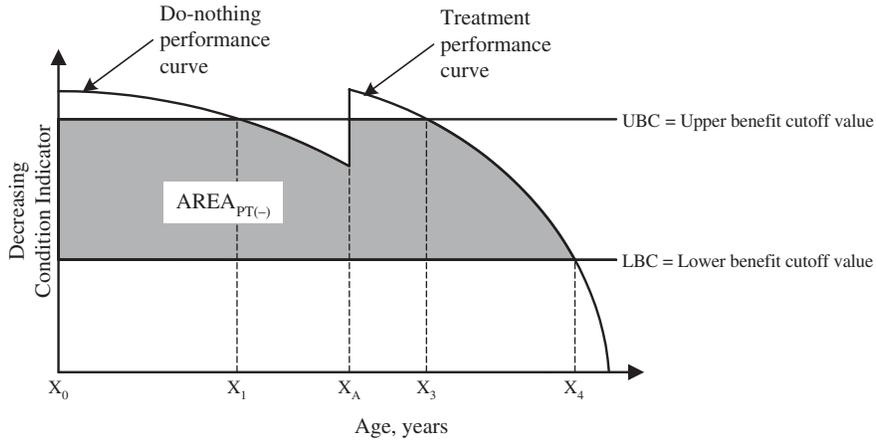
Note: for this case, $X_2 = X_A$ as X_A is less than the projected intersection of the do-nothing curve and the LBC.

INCREASING RELATIONSHIP
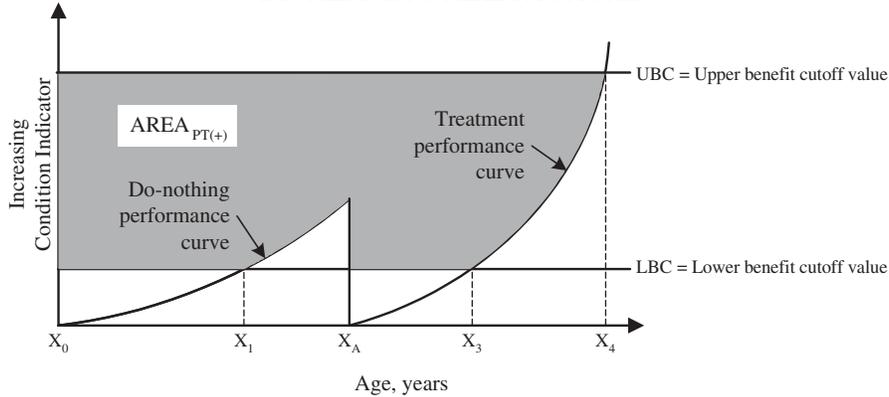
Note: for this case, $X_2 = X_A$ as X_A is less than the projected intersection of the do-nothing curve and the LBC.

Figure 7.   Determination of total areas associated with decreasing and increasing individual condition indicators.

(i.e., time since application age, expressed in years) rather than the overall *pavement* age.

UBC = Upper benefit cutoff value associated with the condition indicator.

LBC = Lower benefit cutoff value associated with the condition indicator.

X_0 = Lower age boundary (equal to zero).

X_1 = One of the following: (1) pavement age (in years) at which the do-nothing curve intersects the UBC, or (2) zero if the do-nothing condition at pavement age zero is less than the UBC, or (3) the pavement age at treatment application (X_A) if the do-nothing condition is greater than the UBC at the treatment application age.

X_2 = Minimum of (1) the pavement age at treatment application and (2) the pavement age at which the do-nothing curve intersects the lower benefit cutoff value.

X_A = Pavement age at treatment application.

X_3 = One of the following: (1) overall *pavement* age at which the treatment performance curve intersects the UBC value, or (2) X_A if the initial treatment condition is less than the UBC, or (3) X_4 if the treatment condition is greater than the UBC at the determined X_4 age.

X_4 = The overall post-treatment analysis period (in terms of pavement age).

$$\text{AREA}_{\text{PT}(+)} = \int_{X_0}^{X_2} (\text{UBC} - \text{EQ}_{\text{DN}})$$

$$- \int_{X_0}^{X_1} (\text{LBC} - \text{EQ}_{\text{DN}})$$

$$+ \int_{0}^{(X_4 - X_A)} (\text{UBC} - \text{EQ}_{\text{PT}})$$

$$- \int_{0}^{(X_3 - X_A)} (\text{LBC} - \text{EQ}_{\text{PT}})$$

(Eq. 5)

where:

$\text{AREA}_{\text{PT}(+)}$ = Computed post-treatment area associated with an increasing condition indicator relationship (i.e., area from time zero to the end of the post-treatment analysis period).

EQ_{DN} = Equation defining the do-nothing condition indicator relationship.

EQ_{PT} = Equation defining the post-treatment condition indicator relationship (i.e., treatment performance curve). Note that the post-treatment equation is a function of *treatment* age (i.e., time since application age) rather than the overall *pavement* age.

UBC = Upper benefit cutoff value associated with the condition indicator.

LBC = Lower benefit cutoff value associated with the condition indicator.

X_0 = Lower age boundary (equal to zero).

X_1 = One of the following: (1) pavement age at which the do-nothing curve intersects the LBC value, or (2) zero if the do-nothing condition at pavement age zero is greater than the LBC, or (3) the pavement age at treatment application (X_A) if the do-nothing condition is less than the LBC at the treatment application age.

X_2 = Minimum of (1) the pavement age at treatment application and (2) the pavement age at which the do-nothing curve intersects the UBC value. Note: X_2 is often equal to X_A.

X_A = Pavement age at treatment application.

X_3 = One of the following: (1) overall *pavement* age at which the treatment performance curve intersects the LBC value, or (2) X_A if the initial treatment condition is greater than the LBC, or (3) X_4 if the treatment condition is less than the LBC at the determined X_4 age.

X_4 = The overall post-treatment analysis period (in terms of pavement age).

Figure 8 illustrates the application of these area boundary conditions and the resulting bounded post-treatment areas (i.e., $\text{AREA}_{\text{PT(FRICTION)}}$, $\text{AREA}_{\text{PT(RUTTING)}}$, and $\text{AREA}_{\text{PT(ROUGHNESS)}}$) for the previously presented example.

Step 7: Computation of Benefit Associated with Each Individual Condition Indicator

When only one condition indicator is included, the individual benefit is determined by comparing the post-treatment area computed in step 6 with the total area computed in step 3 for the do-nothing case. That is, the benefit is quantified as the difference in area between the overall post-treatment area and the associated do-nothing area (see Figure 9). When more than one condition indicator is included in an analysis, the computations are slightly more complex in that all post-treatment and do-nothing benefit areas are truncated at the expected service life of the post-treatment case computed in step 5. By truncating these areas, it is ensured that all computed benefit areas for the included condition indicators use the same analysis period. Figure 10 illustrates the benefit areas associated with friction, rutting, and roughness in the previously presented example.

When multiple condition indicators are analyzed simultaneously, converting individual condition indicator benefit areas into one overall benefit value becomes difficult because different condition indicators are expressed in different units. To solve this problem, each individual benefit area (i.e., the difference between the post-treatment and associated do-nothing areas) is normalized by dividing each computed benefit area by its associated total do-nothing area computed in step 3. The total do-nothing area is used as the basis for this comparison so computed benefit areas may be fairly compared between different timing scenarios. This normalization process results in all individual benefit values being expressed as a percentage. Equation 6 is used for the individual benefit computations.

$$\%\text{BENEFIT}_i = \left(\text{AREA}_{\text{BENEFIT}(i)}\right)/\left(\text{AREA}_{\text{DN-TOT}(i)}\right) \qquad \text{(Eq. 6)}$$

where:

$\%\text{BENEFIT}_i$ = Individual benefit associated with a given condition indicator (benefit area expressed as a percentage of the associated total do-nothing area).

i = One of $i = 1$ to n condition indicators included in the analysis.

$\text{AREA}_{\text{BENEFIT}(i)}$ = Computed benefit area associated with the jth condition indicator in an analysis = $(\text{AREA}_{\text{PT}(i)} - \text{AREA}_{\text{DN}(i)})$

$\text{AREA}_{\text{PT}(i)}$ = Computed post-treatment area between time = 0 and the computed post-treatment analysis period (computed in step 6).

$\text{AREA}_{\text{DN}(i)}$ = Do-nothing area between time = 0 and the computed post-treatment analysis period (computed in step 5). Note: if the analysis period is greater than or equal to the age at which the current condition indicator curve intersects the benefit cutoff value, this area will be the total do-nothing area (i.e., $\text{AREA}_{\text{DN}(i)} = \text{AREA}_{\text{DN-TOT}(i)}$).

$\text{AREA}_{\text{DN-TOT}(i)}$ = Total do-nothing area associated with the jth condition indicator in an analysis (i.e., that computed under step 3).

Step 8: Computation of Overall Benefit

When more than one condition indicator is included in an analysis, individual condition indicator benefit values are combined using defined benefit weighting factors. Continuing with the example, assume that individual benefit values for
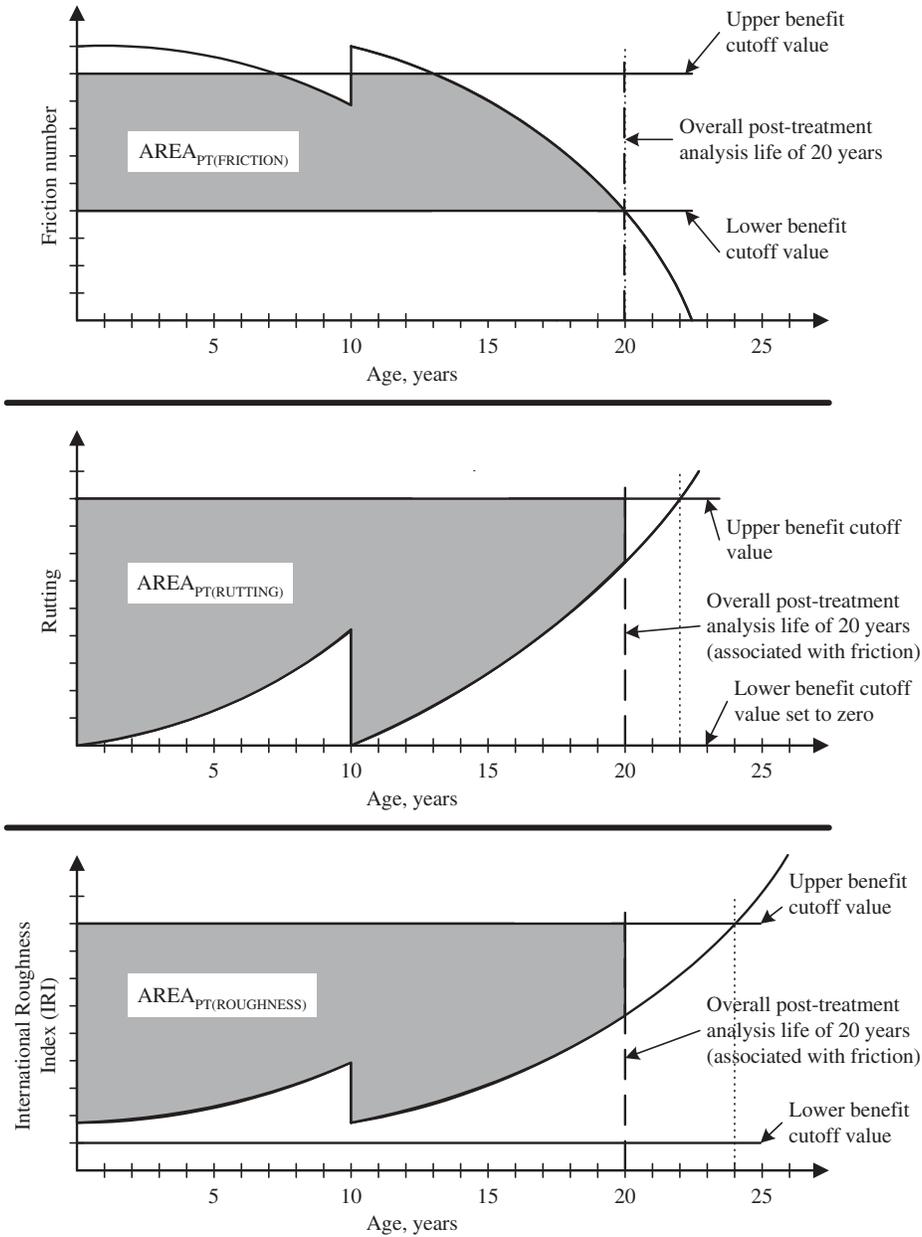
Figure 8.   Illustration of the total areas associated with individual condition indicators.

friction, rutting, and IRI are 10, 16, and 20 percent, respectively (i.e., when compared with the respective areas associated with the do-nothing option, the preventive maintenance treatment application results in increases of 10, 16, and 20 percent in the friction, rutting, and IRI areas, respectively). Further assume benefit weighting factors of 50, 25, and 25 are chosen for friction, rutting, and IRI, respectively (note that these factors add up to 100). The overall benefit contributions are then determined by multiplying the benefit weighting factor percentages by the individual benefit values (e.g., for friction 10 percent $\times$ $^{50}/_{100}$ = 5.0 percent). The total overall benefit contribution is then computed as the sum of the values calcu-

lated for each individual condition indicator. In this example, the total overall benefit contribution is 14.0 percent. While by itself this actual total benefit value is essentially meaningless, total benefit values computed for different timing scenarios can be used to compare the effectiveness of the different timing scenarios. Results of this example are presented in Table 19.

Step 9: Cost Computations

A simple two-step LCCA is conducted to compare the different cost streams associated with each preventive mainte-

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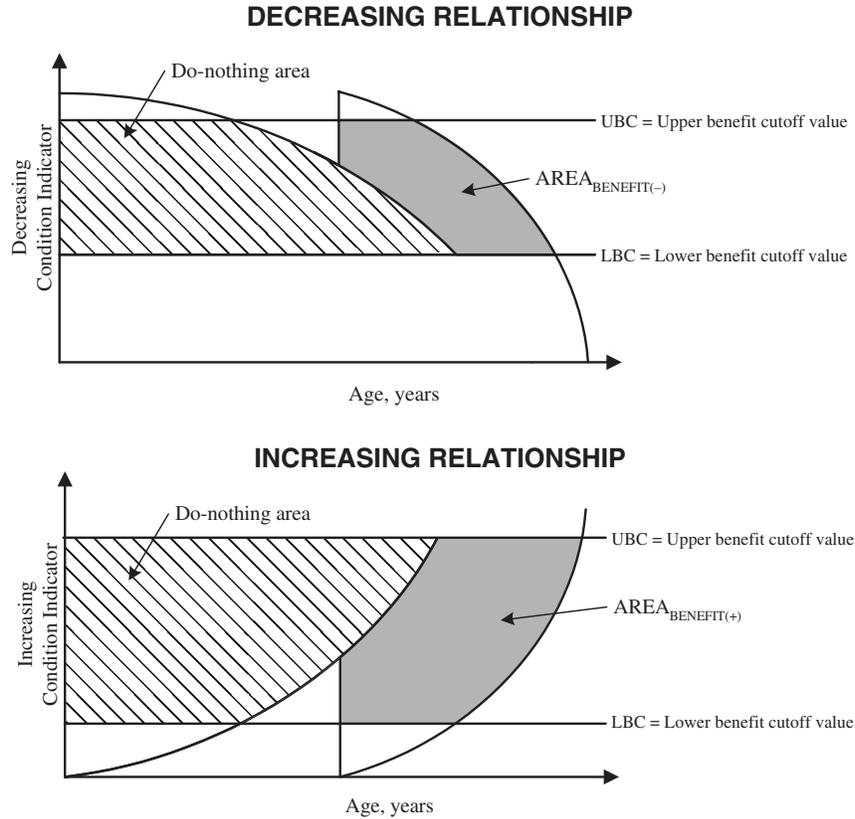
*Figure 9.   Illustration of the benefit area (AREA$_{BENEFIT}$) for a single
decreasing or increasing individual post-treatment condition indicator.*

nance scenario. First, the present worth (at year zero) of each included treatment, rehabilitation, user-delay, or routine maintenance cost is determined using equation 7.

$$\mathrm{PW\$} = \mathrm{C} \times (1+d)^{-n} \qquad \text{(Eq. 7)}$$

where:

   PW\$ = Present worth value of an included cost (in year zero dollars).
   C = Individual maintenance or rehabilitation cost (in actual dollars).
   d = Discount rate expressed as a percentage (e.g., a discount rate of 4 percent translates to $d = 0.04$).
   n = Year (since construction) in which the individual cost is realized.

Second, the computed total present worth cost is converted into an equivalent uniform annual cost (EUAC) using equation 8.

$$\mathrm{EUAC}_i = \sum \mathrm{PW\$}_i \times \left[\frac{d(1+d)^{p_i}}{(1+d)^{p_i} - 1} \right] \qquad \text{(Eq. 8)}$$

where:

EUAC$_i$ = Computed equivalent uniform annual cost associated with the ith timing scenario.
$\sum$PW\$$_i$ = Sum of present worth values of all agency maintenance or rehabilitation costs included in the cost stream associated with the ith timing scenario.
   d = Discount rate expressed as a percentage (e.g., a discount rate of 4 percent translates to $d = 0.04$ in the equation).
   i = Index associated with the current timing scenario.
   p_i = Analysis period associated with the ith timing scenario (time from construction until year at which the first included condition indicator performance curve reaches the benefit cutoff value [from step 5]).

Step 10: Determining the Most Cost-Effective Timing Scenario

The final step of the analysis procedure is to analyze the benefits and costs computed for each application age to determine the timing scenario that provides the largest B/C ratio. To normalize these computed B/C ratios, EIs are computed for each timing scenario by dividing each individual B/C ratio by the largest observed B/C ratio from all the different timing

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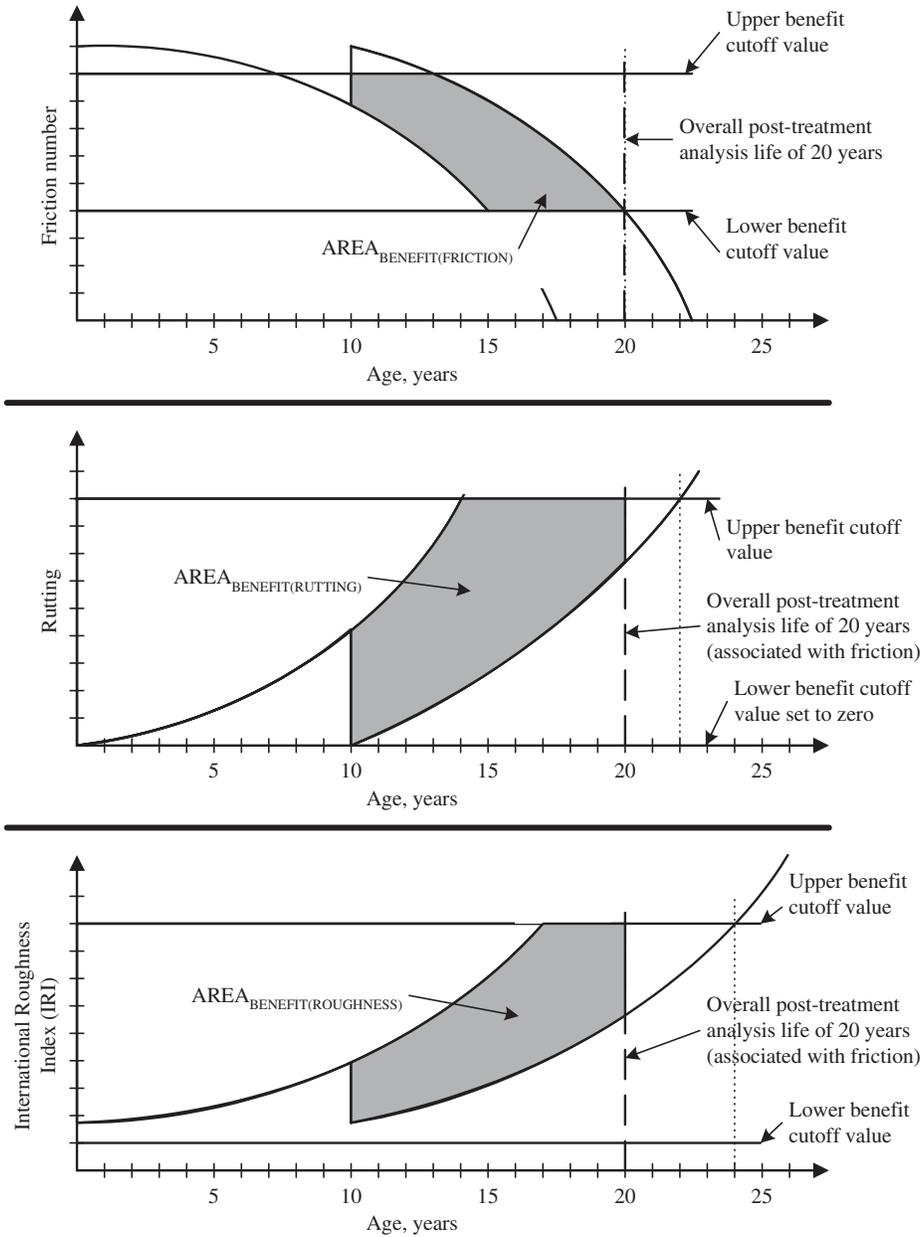
Figure 10. Illustration of benefit areas associated with individual post-treatment condition indicators (applicable for investigating multiple condition indicators).

scenarios investigated. The most cost-effective timing scenario is that with the largest B/C ratio (i.e., that associated with an EI of 100). This process is best illustrated using an example.

For an analysis to investigate six timing scenarios for a treatment applied on an HMA pavement 1, 2, 3, 4, 5, and 6 years after construction, benefit, cost, and B/C ratios are computed for each scenario using the previously outlined procedures. The computed values for this example are presented in Table 20. These values show that timing scenario 4 (i.e., application age at 4 years) provides the largest B/C ratio.

Using equation 1, EIs are computed for each scenario by dividing each individually computed B/C ratio by the largest

observed B/C ratio (i.e., 0.01123 computed for an application age of 4 years after construction). Thus, the EI for application age 1, for example, is 0.00527/0.01123 × 100 = 47). The EI results for this example are illustrated in Figure 11.

These results indicate that the optimal time to apply this preventive maintenance treatment is in year 4, although an application in year 3 produces very similar results. In such cases, other output results such as total benefit, EUAC, or extension of life may help identity the most appropriate timing scenario.

Although the optimal timing methodology is based on comparing B/C ratios, an agency may select treatment based

TABLE 19 Example computation of overall benefit

Condition Indicator	Individual Benefit Values, %	Condition Indicator Benefit Factor	Overall Benefit Contribution, %
Friction	10	0.50	5.0
Rutting	16	0.25	4.0
Roughness (IRI)	20	0.25	5.0
TOTAL	**—**	**1.00**	**14.0**

TABLE 20 Example computation of overall benefit (BENEFIT$_{OVERALL}$)

Year of Application	BENEFIT (B) Overall Benefit, %	COST (C) EUAC, $	BENEFIT-TO-COST RATIO (B/C), %/$	Effectiveness Index (EI)
1	52.7	$10,000	0.00527	47
2	65.5	$9,615	0.00681	61
3	102.4	$9,246	0.01108	99
4	99.8	$8,890	0.01123[*]	100
5	72.5	$8,548	0.00848	76
6	65.4	$8,219	0.00796	71

[*] Largest B/C ratio.

on other criteria. For the previously presented example, if maximizing benefit is the most important overall goal of the agency, an application age of 3 may be chosen because it provides the highest benefit value (i.e., 102.4) in Table 20. If however, adequacy of the performance prediction equations is in question, cost may become the most important decision factor, and an application age of 4 with an EUAC of $8,890 would be favored over an application age of 3 with an EUAC of $9,246.

ANALYSIS TOOL DEVELOPMENT

An important component of this project was the development of a flexible, easy-to-use analytical tool that agencies could use to apply the proposed methodology. The result was OPTime—a macro-driven Microsoft® Excel Visual Basic
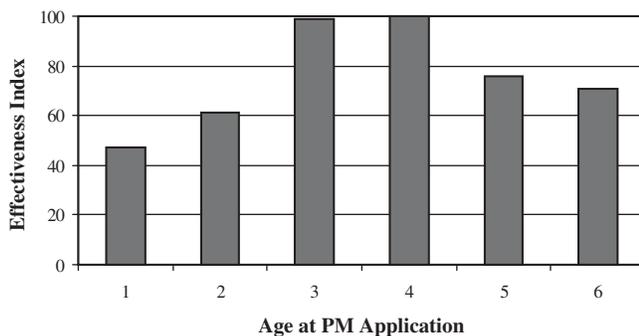
Figure 11. Example of Effectiveness Index versus timing of preventive maintenance application.

Application (VBA)—that can be used to analyze actual data or evaluate hypothetical situations. Details of its development and make up are described.

Built-In Flexibility

Creating a tool that can be readily used by all agencies is difficult due to variations in agency practices, such as condition rating systems, data availability, and data quality. However, flexibility is intentionally built into the analysis tool to facilitate use by different users.

Choice of Detailed or Simple Analysis Types

The primary purpose of the OPTime tool is to allow engineers to analyze actual historical preventive maintenance-related condition data in order to determine the optimal timing of a specific preventive maintenance treatment. However, many agencies are still in the early stages of collecting the performance data needed for such analysis. Therefore, additional flexibility is built into the analysis tool through the inclusion of two distinct analysis methods (referred to as "detailed" and "simple" analysis methods) that may be used to compare preventive maintenance timing scenarios.

The detailed analysis method is used to analyze actual (or estimated) condition versus age data. When actual field data are used for this analysis, expected condition versus age relationships (before and after preventive maintenance treatment applications) must be defined by either selecting an equation type and entering known equation coefficients, or fitting a regression equation using condition versus age data points.

If actual data are not available, or if the user is concerned about the adequacy of specific mathematical relationships (i.e., choosing equation types and coefficients), the simple analysis method is used to compare many "what if" timing scenarios. Performance relationships are more easily defined by choosing a starting condition level, a condition versus age point for the curve to pass through, and the expected extension of life at the benefit cutoff value. Essentially, the condition indicator versus age relationships are defined visually rather than through a specific mathematical relationship.

Flexibility in Defining Pavement Performance

Because there is no universal goal for a preventive maintenance program, potential users of the optimal timing methodology may approach the problem in unique manners. The agency may seek improved friction, reduced roughness, better overall pavement condition, or reduced user delay costs, for example. The analytical tool allows the evaluation of optimal timing in terms of any desired condition or criteria. In addition to the typical condition indicators associated with both HMA and portland cement concrete (PCC) pavements, two user-definable fields are provided to customize the analysis. The units associated with all condition indicators (both standard and user definable) are also completely customizable.

Cost Type Options

Four different cost types may be included in the analysis—treatment costs, work zone user delay costs, rehabilitation costs, and routine maintenance costs; the user decides which of these costs to include in the analysis. This flexibility allows a user to conduct typical, as well as specialized, analysis. A typical analysis primarily consists of determining an optimal timing scenario based only on treatment costs. An example of a specialized analysis is one in which the user wants to choose the optimal timing of a treatment while only considering user costs (i.e., all the other cost types, including the cost of the treatment, are ignored). While such an approach would be considered unconventional, the analysis method permits such investigations.

Analysis Setup

The determination of the optimal timing requires many different inputs during the analysis setup phase. The general steps required to setup an analysis are presented in Figure 12. Brief descriptions of each step are included below.

- **Analysis type selection**—OPTime includes a choice of two distinct analysis types. The detailed analysis is primarily used to analyze actual historical performance data; the simple analysis approach is generally used to
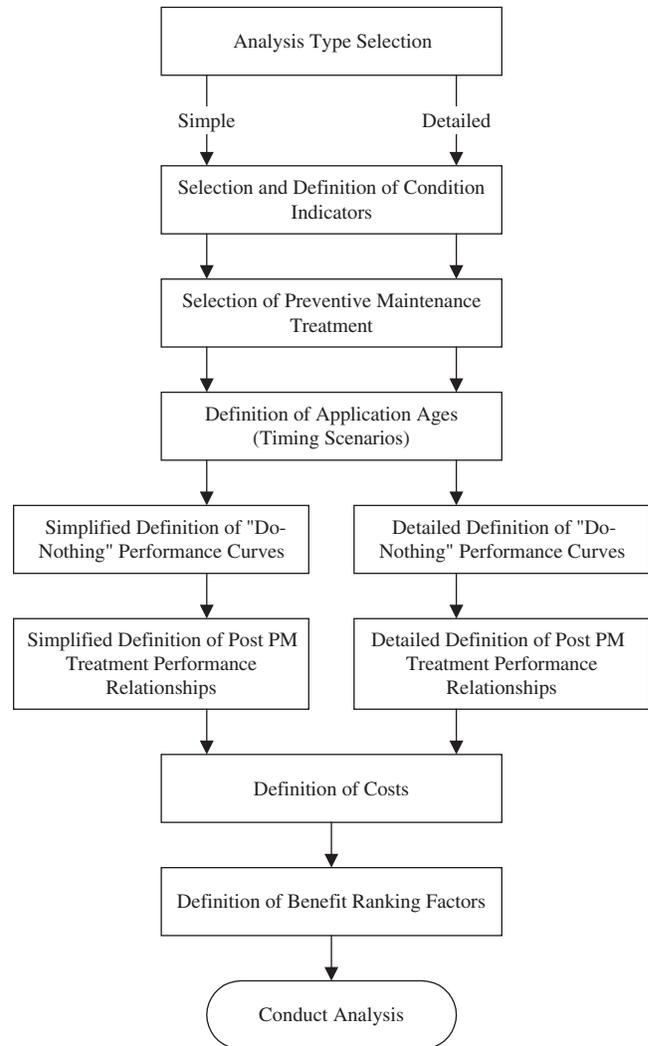
Figure 12. Outline of the data flow through the methodology.

easily conduct hypothetical "what if" scenarios in the absence of actual data.
- **Select condition indicators to be included**—The methodology allows the user to select the one or more condition indicators that will be tracked/predicted over time. The influence of the selected condition indicators' benefit and costs will be estimated to determine optimal preventive maintenance timing.
- **Define the preventive maintenance treatment to be analyzed**—The methodology requires that the user specify a particular preventive maintenance treatment to be analyzed. The methodology only analyzes one treatment at a time (i.e., it does not compare preventive maintenance treatments).
- **Define all timing scenarios that will be investigated**—The methodology evaluates treatment timings that are specified by the user (i.e., all possible treatment timings

are not considered). Therefore, one of the important steps in the analysis setup process is the definition of the specific treatment application ages that will be considered in the analysis. The primary result of the analysis is identifying the most effective treatment application age from among those considered.

- **Define do-nothing curves for each included condition indicator**—The user must define, for the do-nothing option, the expected performance curves for each condition indicator included in the analysis. These relationships represent the expected pavement performance in the absence of any preventive maintenance or rehabilitation activities. The relationships should, however, consider any routine or reactive maintenance that is typical for a given pavement type.
- **Define post-preventive maintenance performance relationships**—In order to compute benefit for a given performance indicator, the user defines how the pavement will perform in the prediction mode (i.e., condition indicator versus time relationships) after a preventive maintenance treatment is applied. Because these performance relationships depend on pavement age (or pavement) condition at treatment application, a separate performance relationship is required for each application age (timing scenario) included within the analysis.
- **Define cost types and values**—The user has the option to include any or all cost types (i.e., preventive maintenance treatment costs, user delay-related costs, rehabilitation costs, and the cost of additional routine or reactive maintenance activities) in the LCCA. Included costs are used to make up the cost streams associated with each individual preventive maintenance timing scenario.
- **Define benefit weighting factors**—Each considered condition indicator is assigned an integer weighting factor between 0 and 100, where all the entered weighting factors must add up to 100. The selected weighting factors are used to combine the individual benefit values into an overall benefit value for each timing scenario.

Data Interpretation

The analysis tool includes a number of summary tables and charts that illustrate the results of the analysis. Specifically, the results summarize the benefit values, EUACs, B/C ratios, and effectiveness indices determined for all timing scenarios. The timing scenario with the largest B/C ratio is identified as the scenario representing optimal timing.

VALIDATION OF THE ANALYSIS METHODOLOGY

An evaluation of the analysis methodology and the analysis tool was undertaken using actual data provided by four state agencies—Arizona, Kansas, Michigan, and North Carolina.

These evaluations are referred to as Case Studies 1 through 4. Also, the LTPP data for the maintenance effectiveness experiments—available on the DataPave 3.0 software—are presented as Case Study 5. This section describes the details of the validation process.

The purpose of the evaluation was not to identify the optimal time to perform preventive maintenance using an agency's data, but to demonstrate the methodology's and the OPTime analytical tool's ability to use actual data. The following case studies indicate how actual data are handled in the analytical approach, the types of assumptions that are made to use the methodology, and how the absence of certain types of information preclude the successful use of the methodology.

Case Study 1—Arizona

Introduction

The Arizona Department of Transportation's (ADOT) data for seal coat treatments on flexible pavements were analyzed. Data summaries and performance models were obtained from a 1999 report (*24, 25*).

Condition Indicators

The effectiveness of seal coats was measured by examining their effect on the following three condition indicators:

- Roughness (IRI)
- Friction (measured with a Mu-meter)
- Cracking (measured in terms of percent area)

An earlier study (*24, 25*) determined that roughness was by far the most useful performance indicator to distinguish between different materials and different circumstances. Table 21 summarizes subjective ratings associated with ranges of each of these condition indicators.

TABLE 21   Condition indicator ranges and their associated subjective ratings

Condition Indicator	Value/Range	Condition Category
Roughness (IRI)	<1.47 m/km (93 in./mi)	Low
	1.47 to 2.26 m/km (93 to 143 in./mi)	Medium
	>2.26 m/km (143 in./mi)	High
Friction (Mu-meter reading)	<35	Low
	35 to 42	Medium
	43 to 99	High
Cracking (percent of area)	<10	Low
	10 to 30	Medium
	>30	High

Do-Nothing Performance Curves

A series of linear do-nothing performance curves are available for the selected roughness, friction, and cracking condition indicators for pavements in all roadway classes, environmental regions, and traffic levels (*24, 25*). Table 22 lists the do-nothing condition indicator versus age relationships selected for this demonstration; these relationships are shown in Figures 13, 14, and 15, respectively.

Benefit Cutoff Values

Benefit cutoff values are determined by analyzing the expected regression equations over the condition indicator ranges listed in Table 21. Details of this analysis are presented as follows:

- **Roughness**—Because IRI increases with time, an upper IRI benefit cutoff value is required. A value of 1.47 m/km (93 in./mi) was chosen because it indicates the transition from a low roughness level to a tolerable roughness level. According to the roughness regression equation, this value is predicted at an age of 27.8 years. The lower benefit cutoff value was set to a value of 0 m/km (0 in./mi).
- **Friction**—As Mu-meter values typically decrease over time, a lower benefit cutoff value is required for the analysis. A comparison of the regression equation to the condition ranges listed in Table 21 finds that friction values of 35 and 43 correlate to ages of 117.1 and 80.7 years, respectively. Because these are extremely high ages, a friction value of 55 was chosen, corresponding to a predicted age of 26.2 years. An upper benefit cutoff value was conservatively set to a value of 100.

Figure 14. Assumed friction do-nothing curve for Case Study 1—Arizona.

- **Cracking**—Since cracking increases with time, an upper cracking benefit cutoff value is required for the analysis. A value of 10% was selected, as it indicates the transition from low to medium cracking. According to the cracking regression equation, this value corresponds to an age of 28.5 years. The lower benefit cutoff value was conservatively set to a value of 0% cracking.

Post-Preventive Maintenance Performance Relationships

A series of linear post-treatment performance curves for the selected roughness, friction, and cracking condition indicators are available (*24, 25*); these relationships are listed in Table 23 and plotted for roughness, friction, and cracking in Figures 16, 17, and 18, respectively. However, these relationships are presented as functions of the treatment age (T_{AGE}), not as functions of the pavement's age when the treatment was applied.

TABLE 22   Do-nothing performance equations

Condition Indicator	Regression Equation
Roughness (IRI), m/km[*]	IRI = 0.0207 × AGE + 0.89
Friction (Mu-meter results)	Friction = –0.22 × AGE + 60.76
Cracking (% of 1,000 sf area at each milepost), %	Cracking = 0.33 × AGE + 0.6

[*]1 m/km = 63.4 in./mi.
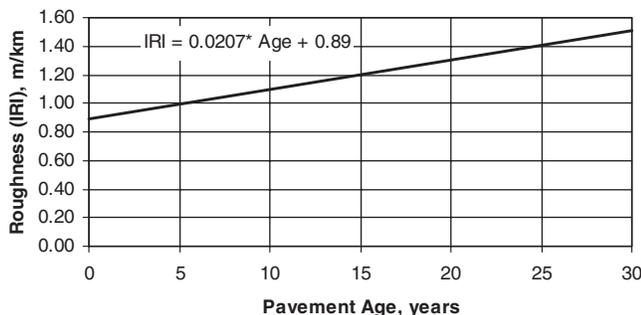
Figure 13. Assumed roughness do-nothing curve for Case Study 1—Arizona.

Figure 15. Assumed cracking do-nothing curve for Case Study 1—Arizona.

TABLE 23   Post-treatment performance equations associated with a seal coat treatment

Condition Indicator	Regression Equation
Roughness (IRI), m/km	IRI = 0.0273 × T_{AGE} + 1.52
Friction (Mu-meter results)	Friction = –0.54 × T_{AGE} + 69.2
Cracking (% of 1000 sf area at each milepost), %	Cracking = 0.7 × T_{AGE} + 3.2
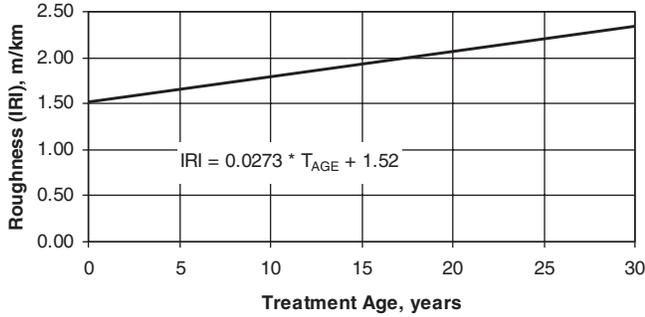
Figure 16. Assumed post-treatment seal coat roughness relationship for Case Study 1—Arizona.
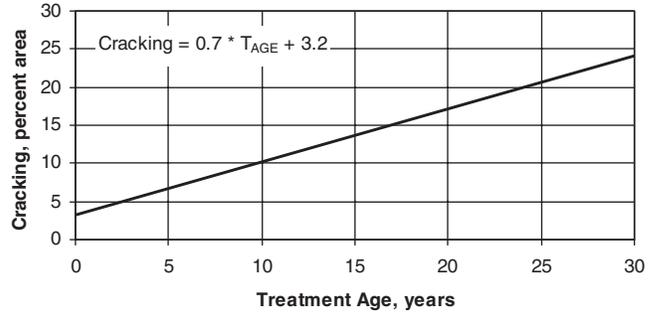
Figure 18. Assumed post-treatment seal coat cracking relationship for Case Study 1—Arizona.
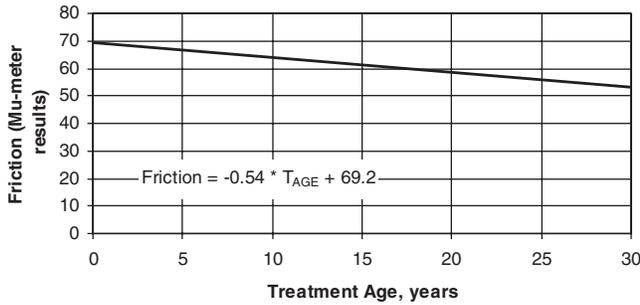
Figure 17. Assumed post-treatment seal coat friction relationship for Case Study 1—Arizona.

Analysis Setup

The analysis tool is used to analyze the interpreted performance data. Specifically, the following inputs define the analysis session for this case study:

- **Analysis Type**—A detailed analysis type is selected because actual data are being analyzed.
- **Condition Indicators**—Three condition indicators are used in this analysis: roughness, friction, and cracking.
- **Preventive Maintenance Treatment Selection**—A seal coat applied at 1, 4, 7, 10, and 13 years is investigated. No routine/reactive maintenance costs are included.

TABLE 24   Analysis results for Case Study 1—Arizona

Output Data

Pavement Surface Type:	HMA
Treatment Type:	Seal Coat
Application Years:	1, 4, 7, 10, 13
Expected Do-Nothing Service Life (yrs):	26.2

Benefit Summary

	Individual Benefit Summary		
Benefit Ranking Factors =>	25	15	60
Application Age, yrs	Total Benefit	Nonload-Related Cracking	Roughness/ Smoothness	Friction
1	0.04	-0.68	-0.84	0.57
4	0.23	-0.49	-0.75	0.77
7	0.39	-0.32	-0.67	0.95
10	0.53	-0.17	-0.59	1.11
13	0.65	-0.05	-0.52	1.24

Cost Summary

Application Age, yrs	Treatment Cost, PW $	User Cost, PW $	Other Maintenance Cost, PW $	Rehab. Cost, PW $	Total Present Worth, $	EUAC, $
1	$24,423	n/a	n/a	n/a	$24,423	$2,847
4	$21,712	n/a	n/a	n/a	$21,712	$2,088
7	$19,302	n/a	n/a	n/a	$19,302	$1,606
10	$17,159	n/a	n/a	n/a	$17,159	$1,275
13	$15,255	n/a	n/a	n/a	$15,255	$1,035

Effectiveness Summary

Application Age, yrs	Effectiveness Index	Total Benefit	EUAC, $	Expected Life, yrs	Expected Extension of Life, yrs
1	2.38	0.04	$2,847	10.7	-15.5
4	17.32	0.23	$2,088	13.7	-12.5
7	38.66	0.39	$1,606	16.7	-9.5
10	66.30	0.53	$1,275	19.7	-6.5
13	100.00	0.65	$1,035	22.7	-3.5

Effectiveness Index vs. Application Timing

Extension of Life vs. Application Timing

EUAC ($) vs. Application Timing
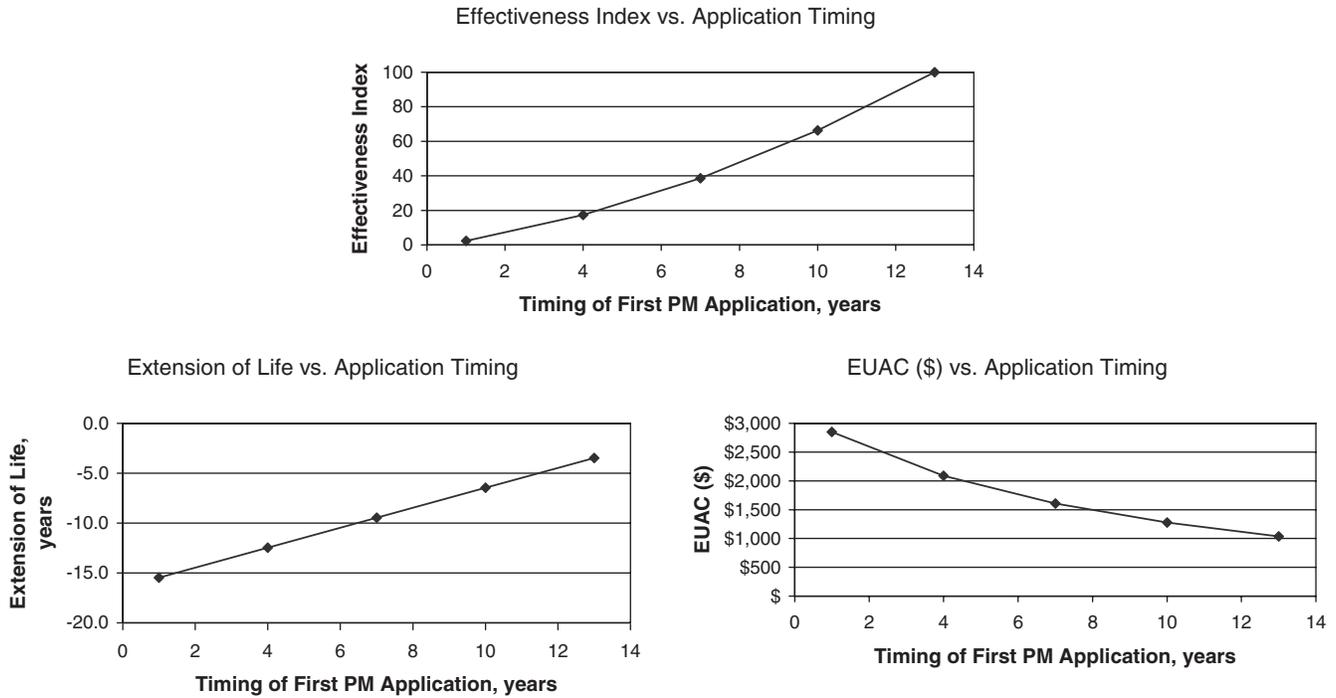
Figure 19.   Results of the analysis for Case Study 1—Arizona.

- **Performance Relationships**—Models are already provided. The do-nothing performance relationships are defined in Table 22 and the post-treatment performance relationships are defined in Table 23.
- **Project Definition**—The project size is defined as 16,723 m² (20,000 yd²).
- **Cost Data**—Only treatment costs are included in the cost analysis (i.e., rehabilitation, user, and routine maintenance costs are excluded). The in-place unit cost of a seal coat application is $1.52/m² ($1.27/yd²) as reported by ADOT

(i.e., for the entire treatment application. A discount rate of 4.0 percent is used in the analysis.
- **Benefit Weighting Factors**—Benefit weighting factors are needed for three condition indicators; they were arbitrarily chosen as 15, 60, and 25 percent for roughness, friction, and cracking, respectively.

Analysis Results

The output results are summarized in Table 24 and Figure 19. These results show that of the five investigated appli-
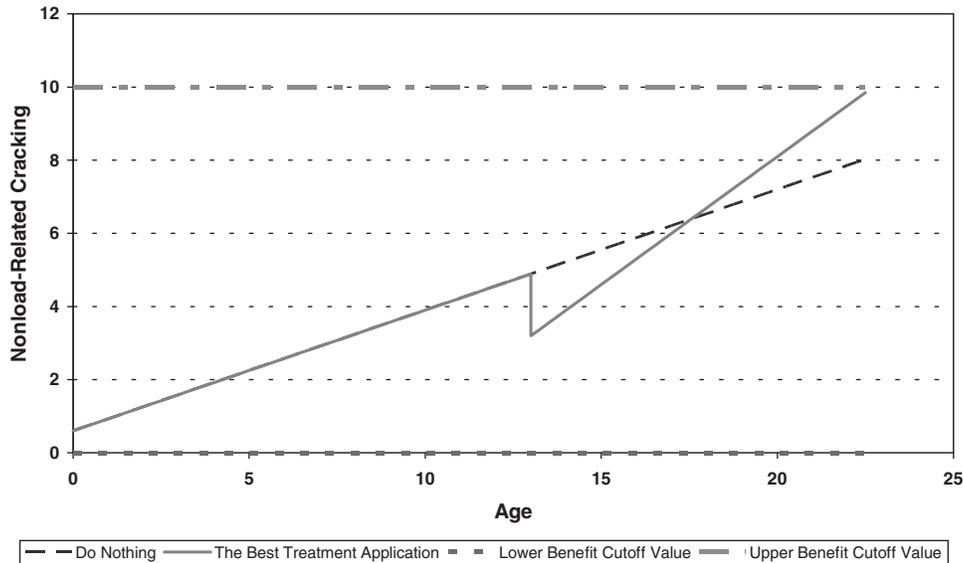
Figure 20.   Cracking versus age for the most appropriate application age of 13 years for Case Study 1—Arizona.
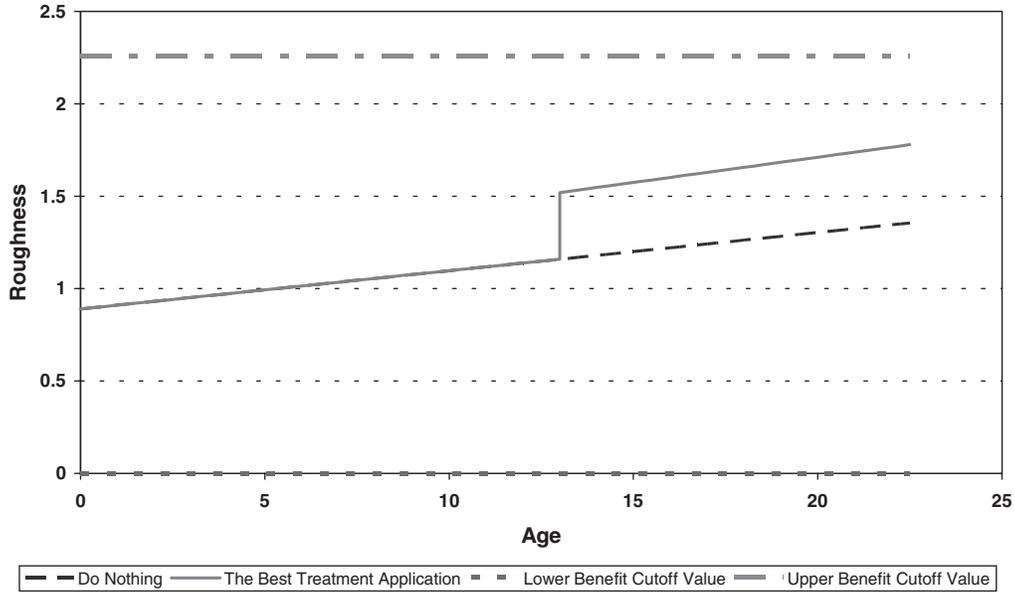
Figure 21. Roughness versus age for the most appropriate application age of 13 years for Case Study 1—Arizona.

cation ages, the most cost-effective option is applying the treatment at age 13 (indicated by an EI of 100). Because the same equation is used for all application ages, it is not unexpected that the largest benefit is associated with the latest application. This is because the benefit increases and treatment cost decreases with application age. The actual condition versus age plots for the three included condition indicators are illustrated in as Figures 20, 21, and 22.

Note that all of the individual benefits associated with cracking and roughness are computed as negative values. As illustrated in Figure 20, the post-treatment cracking curve crosses the do-nothing curve and the areas above the do-nothing and post-treatment curves bound by the upper benefit cutoff value of 10 percent appear to be similar. However, the results provided in Table 24 show an individual benefit value of −0.05 (for an application age of 13 years) that indicates a slightly greater benefit area for the do-nothing case than for the post-treatment case. The negative benefit values associated with roughness occurred because, according to the IRI equations, the application of the treatment resulted in an increased pavement roughness as shown in Figure 21.
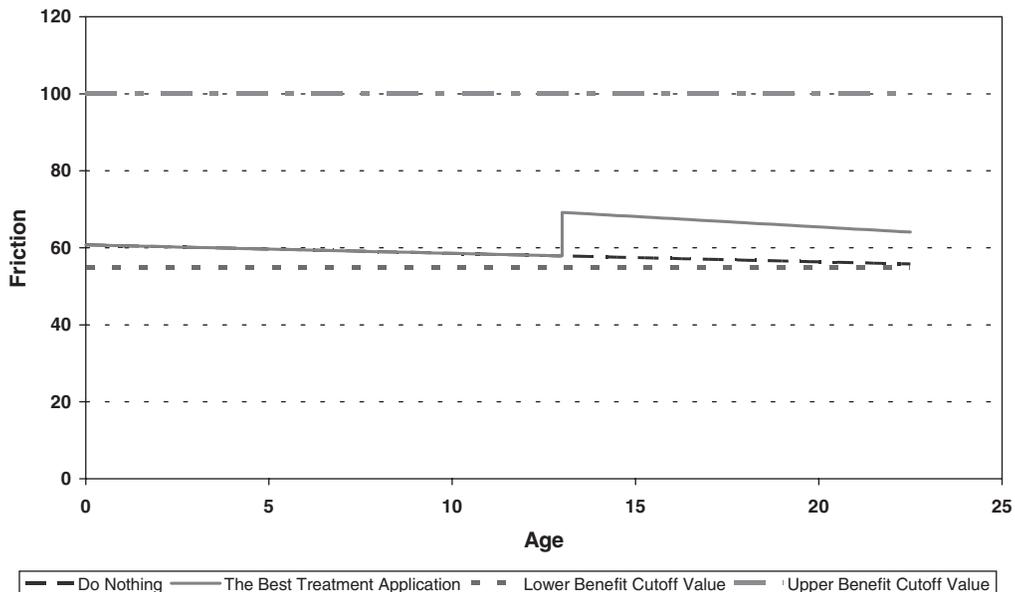
Figure 22. Friction versus age for the most appropriate application age of 13 years for Case Study 1—Arizona.

Although these results appear to contradict engineering judgment, they reflect the accuracy of the provided condition prediction models. This case study points out the importance of not only obtaining representative datasets, but also focusing on compiling separate datasets for different treatment application ages.

Case Study 2—Kansas

Introduction

As part of an ongoing study, the Kansas Department of Transportation (KDOT) is developing condition indicator prediction models based on the historical condition data available in their pavement management database for nearly 11,000 pavement segments. For this case study, only the transverse cracking models developed by KDOT were used to demonstrate the analysis approach. This subsection introduces the modeling approach used by KDOT and demonstrates how such agency-developed models may be used within the analysis approach developed under this project.

KDOT Modeling Procedure

Modeling the performance of a given construction, rehabilitation, or maintenance activity is a four-step process.

Estimate Equivalent Asphalt Thickness (EqThick). In an effort to estimate the expected pavement performance impact associated with a specific paving activity, KDOT has estimated the equivalent asphalt thicknesses associated with different non-structural, light-structural, and heavy-structural paving actions used in Kansas. Examples of selected equivalent thickness values are listed in Table 25.

Compute Expected Design Lives. The second step of the KDOT modeling procedure is to compute an expected design life of a selected paving action. Based on the results of a multiple linear regression process, the following equation is used to compute the expected design life for a given paving activity on a flexible pavement:

$$
\begin{aligned}
\text{DL\_Flex} = {} & 8.836 + 1.610 \times \text{FDBit} \\
& + 1.201 \times \text{EqThick} \\
& - 3.725 \times \text{Ln}(\text{EqTCR} + 1) \\
& - 0.957 \times \text{Ln}\left(\frac{\text{D\_ADL\_t}}{\text{EqThick}}\right)
\end{aligned} \quad \text{(Eq. 9)}
$$

where:

DL_Flex = Flexible pavement design life, years.

FDBit = Full-depth bituminous index (value of 1.0 if the pavement is a full-depth section).

EqThick = Equivalent thickness of current paving action (construction, rehabilitation, or maintenance activity), in.

EqTCR = Equivalent number of transverse cracks at time of current paving action. Note: EqTCR is the equivalent number of "code 3" (rough or very wide) cracks expected per 30-m (100-ft) segment.

D_ADL_t = Design lane average daily 80 kN (18 kip) loads.

In the KDOT study, the limits shown in Table 26 are used to "cap" the computed design life if necessary.

Compute the Condition Indicator Value for the First Survey Year After a Paving Action. The third step of the KDOT modeling procedure is to compute the condition indicator

TABLE 25 Examples of equivalent thickness values associated with various construction actions in Kansas

Action Type	Paving Action Description	Equivalent Thickness, mm (in).
Non-Structural	Do nothing	0 (0.00)
	Modified slurry seal	6 (0.25)
	Rout and crack seal on flexible pavement	13 (0.50)
	25-mm (1.0-in.) asphalt overlay	25 (1.00)
Light-Structural	38-mm (1.5-in.) asphalt overlay	38 (1.50)
	Extensive patching, 38-mm (1.5-in.) asphalt overlay	44 (1.75)
	50-mm (2.0-in.) asphalt overlay	50 (2.00)
Heavy-Structural	63-mm (2.5-in.) asphalt overlay	63 (2.50)
	Cold recycle 100-mm (4-in.), 38-mm (1.5-in.) asphalt overlay	100 (4.00)
	New HMA construction 50, 100, 150, or 200 mm (2, 4, 6, or 8 in.) depending on chosen design	50, 100, 150, or 200 (2, 4, 6, or 8 in.) depending on chosen design

TABLE 26 Flexible pavement design life limits for equivalent thickness values

Equivalent Thickness of Last Paving Action	Design Life Projection Limit, yrs
< 38 mm (1.50 in.)	10
39 to 75 mm (1.51 to 3.00 in.)	10
76 to 100 mm (3.01 to 4.00 in.)	15
> 100 mm (> 4.01 in.)	20

values expected at the first survey year after a paving action. Different prediction equations are developed for KDOT's structural and non-structural paving actions. The following equations are used to compute the EqTCR value at the first year after a structural or non-structural paving action, respectively.

Structural Action

$$EqTCR_{post} = 0.0973 + 0.0845 \times EqTCR_{prior} + 0.000394 \times D\_ADL \quad (Eq. 10)$$

where:

EqTCR$_{post}$ = Equivalent number of transverse cracks at year 1 after a structural paving action. Note: EqTCR is the equivalent number of "code 3" (rough or very wide) cracks expected per 30-m (100-ft) segment.
EqTCR$_{prior}$ = Equivalent number of transverse cracks immediately before the paving action.
D_ADL = Design lane average daily 80 kN (18 kip) loads at the year of the last structural action.

Non-Structural Action

$$EqTCR_{post} = 0.376 + 0.239 \times EqTCR_{prior} - 0.351 \times EqThick + 0.0943 \times FDBit - 0.0190 \times DL\_Flex \quad (Eq. 11)$$

where:

EqTCR$_{post}$ = Equivalent number of transverse cracks at year 1 after a non-structural paving action.
EqTCR$_{prior}$ = Equivalent number of transverse cracks immediately before the paving action.
EqThick = Equivalent thickness of current paving action (construction, rehabilitation, or maintenance activity), in.
FDBit = Full-depth bituminous index (value of 1.0 if the pavement is a full-depth section).
DL_Flex = Flexible pavement design life (years) based on the design life regression model of the last structural action.

Note: the equivalent transverse cracking value is assumed to drop to zero immediately after a rehabilitation action (i.e., EqTCR = 0 at the year of the paving action).

Compute the Condition Indicator Values for Subsequent Years. The last step of the KDOT modeling procedure is to compute the condition indicator values for all other years after the first survey year. In this case study, the following equation is used to compute the EqTCR at these subsequent years regardless of the type of the most recent paving action:

$$EqTCR_{t+1} = 0.182 + 1.10 \times EqTCR_t + 0.282 \times CTCR_t - 0.0218 \times FDBit - 0.0113 \times DL\_Flex \quad (Eq. 12)$$

where:

EqTCR$_{t+1}$ = Equivalent number of transverse cracks in any year after the first survey year. Note: EqTCR$_{t+1}$ is the maximum of the predicted value from the regression or EqTCR$_t$ + 0.05.
EqTCR$_t$ = Equivalent number of transverse cracks in the previous year.
CTCR$_t$ = Change in EqTCR in the previous year (i.e., CTCR$_t$ = EqTCR$_t$ − EqTCR$_{t-1}$).
FDBit = Full-depth bituminous index (value of 1.0 if the pavement is a full-depth section).
DL_Flex = Flexible pavement design life (years) based on the design life regression model of the last structural action.

The following subsections describe an example of how the KDOT modeling equations are used within the analytical tool.

Treatment Selection

For this case study, routing and sealing cracks on a flexible pavement is chosen as the preventive maintenance treatment. "Rout and Crack Seal" is assigned an effective HMA thickness of 13 mm (0.5 in.).

Treatment Costs

The assumed average crack sealing cost is $1,865 per km ($3,000 per mi). A discount rate of 2.0 percent is used for the analysis (the discount rate typically used by KDOT).

Condition Indicators

The equivalent number of "code 3" (rough or very wide) cracks expected per 30-m (100-ft) segment (EqTCR) is the sole condition indicator for this treatment. Note that at the time of initial construction, or the time at which all cracks are routed and sealed, this EqTCR condition indicator is set or

reset to a value of zero. Also, because the number of developing cracks increases over time, the general trend of this condition indicator is increasing.

Benefit Cutoff Values

Based on recommendations from KDOT personnel, a distress threshold value for EqTCR is identified as 0.62. Because EqTCR is expected to increase over time, 0.62 is set as an upper benefit cutoff; the practical lower limit of EqTCR of zero is used as the lower benefit cutoff value in the analysis.

Do-Nothing Performance Curve

In this example, the do-nothing performance curve is defined as the EqTCR versus time relationship associated with the initial pavement construction. An equivalent asphalt pavement thickness of 200 mm (8.0 in.) represents the do-nothing condition. The following steps are used to determine the do-nothing performance curve for the equivalent transverse cracking condition indicator.

Step 1—Compute the Expected Design Life Associated with the Initial Construction Action. The first step in determining the representative EqTCR do-nothing curve is to compute the expected service life for the assumed 200-mm (8.0-in.) equivalent asphalt thickness. The following inputs are used in equation 9 to compute the design life associated for the initial construction.

- FDBit = 1.0 for a full-depth bituminous pavement.
- EqThick = 200 mm (8.0 in.) for an equivalent asphalt thickness of 200 mm (8.0 in.) associated with new construction paving.
- EqTCR = 0 for pavement with no equivalent number of transverse cracks at time zero (initial construction).
- D_ADL_t = 250 for assumed 250 average daily 80kN (18 kip) loads (average daily ESALs) in the design lane at time of initial construction. (This is reported by KDOT to be a typical traffic level for a 2-lane highway in Kansas.)

Inserting these values into equation 9 results in the following:

$$\begin{aligned} \text{DL\_Flex} &= 8.836 + 1.610 \times (1.0) + 1.201 \times (8.0) \\ &\quad - 3.725 \times \text{Ln}(0 + 1) - 0.957 \times \text{Ln}(250/8.0) \\ &= 16.8 \text{ years (design life associated with initial} \\ &\qquad \text{construction)} \end{aligned}$$

Step 2—Compute the EqTCR Value for the First Survey Year (Year 1) After Initial Construction. The next step is to determine the expected EqTCR value for year 1 (i.e., the first survey year after initial construction). Since the initial construction activity is a structural action, the EqTCR value at year 1 is computed using equation 10. The specific inputs used in that equation are the following:

- $\text{EqTCR}_{prior} = 0$ at the previous year (initial construction).
- D_ADL = 250 for the number of average daily 80kN (18 kip) loads (average daily ESALs) at the time of initial construction (assumed to be 250).

Inserting these input values into equation 10 results in the following:

$$\begin{aligned} \text{EqTCR}_{post} &= 0.0973 + 0.0845 \times (0) + 0.000394 \times (250) \\ &= 0.196 \text{ (EqTCR at first year after initial} \\ &\qquad \text{construction)} \end{aligned}$$

Step 3—Compute Subsequent Year EqTCR Values Used to Define the Performance After Initial Construction (Do-Nothing Curve). The final step is to determine the expected EqTCR values for years other than years 0 and 1. EqTCR values for subsequent years are computed using equation 12. The following inputs illustrate the case for computing the EqTCR value at year 2:

- $\text{EqTCR}_1 = 0.196$ as computed in step 2.
- $\text{CTCR}_1 = 0.196$ is the computed change in EqTCR in the previous year. (For this example, $\text{CTCR}_1 = \text{EqTCR}_1 - \text{EqTCR}_0 = 0.196 - 0 = 0.196$.)
- FDBit = 1.0 for full-depth bituminous pavement section.
- DL_Flex = 16.8 years is the expected initial construction design life as computed in step 1.

Inserting these values into equation 12 results in the following:

$$\begin{aligned} \text{EqTCR}_2 &= 0.182 + 1.10 \times (0.196) + 0.282 \times (0.196) \\ &\quad - 0.0218 \times (1.0) - 0.0113 \times (16.8) \\ &= 0.241 \end{aligned}$$

As explained in equation 12, the EqTCR_2 value is the higher of this computed value (i.e., 0.241) or $\text{EqTCR}_1 + 0.05$ (i.e., $0.196 + 0.05 = 0.246$). Therefore, EqTCR_2 is redefined as 0.246.

Completing this iterative process for subsequent years (up to year 20) results in the expected EqTCR values presented in Table 27. Figure 23 illustrates the plotted EqTCR data and the following second-order polynomial equation that represents the do-nothing condition:

$$\text{EqTCR} = 0.0015 \times \text{Age}^2 + 0.0348 \times \text{Age} + 0.1415 \quad \text{(Eq. 13)}$$

Post-Preventive Maintenance Performance Relationships

In order to test the sensitivity of the timing of routing and sealing cracks, a wide range of application ages (1, 3, 5, 7, 9,

TABLE 27 Computed yearly EqTCR values used to define the do-nothing curve

Pavement Age	Computed Equivalent Number of Rough or Very Wide Transverse Cracks per 30 m (100 ft) (EqTCR)
0	0.000
1	0.196
2	0.246
3	0.296
4	0.346
5	0.396
6	0.446
7	0.496
8	0.546
9	0.596
10	0.646
11	0.696
12	0.750
13	0.812
14	0.881
15	0.959
16	1.048
17	1.149
18	1.263
19	1.392
20	1.538

indicated previously, the expected treatment design life is a function of four different variables:

- $EqTCR_{prior}$—the computed values given in Table 27.
- EqThick—the equivalent asphalt thickness of 13 mm (0.5 in.) associated with the rout and crack seal preventive maintenance treatment.
- FDBit = 1.0—for full-depth bituminous section.
- DL_Flex—the expected design life of the last structural treatment application. Since the last structural application is initial construction, this value is held constant in the analysis at the calculated 16.8 years.

Table 28 lists all the required inputs and the resulting expected first survey year $EqTCR_{post}$ values (computed using equation 11) for each application age. The following example illustrates the computation of the $EqTCR_{post}$ value for the application age of 3 years using equation 11.

$$
\begin{aligned}
EqTCR_{post} &= 0.376 + 0.239 \times (0.239) - 0.351 \times (0.5) \\
&\quad + 0.0943 \times (1.0) - 0.0190 \times (16.8) \\
&= 0.047 \text{ (equivalent number of cracks at the first} \\
&\quad \text{survey year after routing and sealing cracks at} \\
&\quad \text{a pavement age of 3 years)}
\end{aligned}
$$

Compute Subsequent Year EqTCR Values Used to Define the Performance After Applying the Rout and Crack Seal Treatment. The second step involves defining the post-treatment performance curves for each application age by computing EqTCR values for subsequent years (i.e., all years after the first survey year after treatment application) using equation 12. Table 29 lists all the computed EqTCR values that define the post-treatment performance for the different application ages. Table 30 lists the EqTCR versus age second-order polynomial regression equations that are fit through the data for each application age. Also shown in Table 30 are the computed times at which each regression equation crosses the previously determined upper benefit

11, and 13 years) were considered. The following two-step process is used to determine post-treatment performance curves for each application age.

Compute the EqTCR Value for the First Survey Year After a Treatment Application (for All Application Ages). The first step in determining the representative post-treatment performance relationships is to estimate the expected EqTCR value for the first survey year after each treatment application. Since the rout and seal activity is a non-structural action, these year 1 EqTCR values are computed using equation 11. As

$$EqTCR = 0.0015x^2 + 0.0348x + 0.1415$$
$$R^2 = 0.9857$$

Figure 23.   Estimated do-nothing curve for Case Study 2—Kansas.

TABLE 28   Required inputs and computed equivalent cracking values at the first survey year after a treatment application (at different chosen application ages)

| Application Age | Inputs | | | | Equivalent No. of Cracks at First Year After Paving Action (EqTCR$_{post}$) [1] |
	FDBit Index (FDBit)	Equivalent Asphalt Thickness (EqThick)	Equivalent No. of Cracks Before Paving Action (EqTCR$_{prior}$)	Expected Design Life, years	
1	1.0	13 mm (0.5 in.)	0.196	16.8 (the DL_Flex value is held constant for all application ages)	0.023
3	(the FDBit variable is held constant for all application ages)	(the EqThick variable is held constant for all application ages)	0.296		0.047
5			0.396		0.071
7			0.496		0.095
9			0.596		0.119
11			0.696		0.143
13			0.812		0.170

[1] Equivalent number of cracks at year 1 after paving action (EqTCR$_{post}$) are computed using equation 11.

TABLE 29   Computed post-treatment EqTCR values associated with the different chosen application ages

| Treatment Age, years | Application Age, years | | | | | | |
	1	3	5	7	9	11	13
0	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1	0.023	0.047	0.071	0.095	0.119	0.143	0.170
2	0.073	0.097	0.121	0.145	0.169	0.193	0.220
3	0.123	0.147	0.171	0.195	0.219	0.243	0.270
4	0.173	0.197	0.221	0.245	0.269	0.293	0.320
5	0.223	0.247	0.271	0.295	0.319	0.343	0.370
6	0.273	0.297	0.321	0.345	0.369	0.393	0.420
7	0.323	0.347	0.371	0.395	0.419	0.443	0.470
8	0.373	0.397	0.421	0.445	0.469	0.493	0.520
9	0.423	0.447	0.471	0.495	0.519	0.543	0.570
10	0.473	0.497	0.521	0.545	0.569	0.593	0.620

TABLE 30   Determined post-preventive maintenance performance relationships for Case Study 2—Kansas

Application Age	Regression Equation	Computed Life Until Equation Reaches Upper Benefit Cutoff Level (EqTCR = 0.62)
1	EqTCR = 0.0492 * AGE - 0.0199	13.0
3	EqTCR = 0.0499 * AGE - 0.0022	12.5
5	EqTCR = 0.0506 * AGE + 0.0156	11.9
7	EqTCR = 0.0515 * AGE + 0.0325	11.4
9	EqTCR = 0.0523 * AGE + 0.0499	10.9
11	EqTCR = 0.0536 * AGE + 0.0653	10.3
13	EqTCR = 0.0555 * AGE + 0.0820	9.7

Regression Trends Through Selected Post-Treatment Data
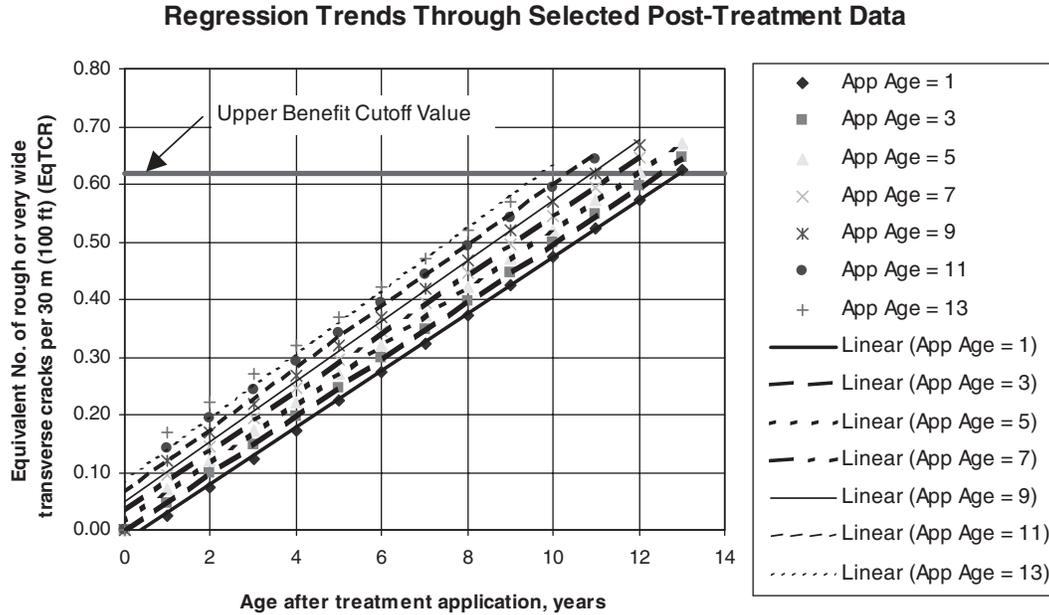
Figure 24.   Illustration of post-treatment performance relationships based on KDOT models.

cutoff value of EqTCR = 0.62. These computed times represent the expected ages at treatment failure. Finally, the determined post-treatment performance curves associated with different application ages are plotted in Figure 24.

Analysis Setup

The analysis tool is used to evaluate the estimated performance data described. The following inputs are used for analyzing the data obtained for this project:

- **Analysis Type**—A detailed analysis type is selected because actual data are being analyzed.
- **Condition Indicators**—A custom condition indicator for equivalent transverse cracking is defined and labeled as EqTCR.
- **Preventive Maintenance Treatment Selection**—A custom treatment, Rout and Seal Cracks, is used. Application ages of 1, 3, 5, 7, 9, 11, and 13 years are investigated.
- **Performance Relationships**—The do-nothing performance curve from Figure 23 and the post-treatment performance relationships defined in Table 30 are entered directly.
- **Project Definition**—The sample project is assumed to be a 1.6-km (1-mi) segment of a 2-lane (7.3-m [24-ft] wide) rural highway. Therefore, for this particular condition indicator, the project is defined by setting the project length to 1.6 km (1 mi).

- **Cost Data**—Only the cost of routing and sealing cracks is included in the analysis (i.e., rehabilitation, user, and routine maintenance costs are excluded). The assumed average crack sealing cost is $1,865 per km ($3,000 per mi). A discount rate of 2.0 percent is also chosen for the analysis based on KDOT's typical practice.
- **Benefit Weighting Factors**—Since only one condition indicator is used in the analysis session, the benefit weighting factor associated with the equivalent cracking value (EqTCR) is set to 100 percent.

Analysis Results

The results obtained from this analysis are summarized in Table 31. These results indicate that out of the seven investigated application ages, application of the treatment at age 11 is the most cost-effective option as indicated by an EI of 100. Also, the application treatment at this age is expected to extend pavement life by 11.6 years (i.e., 11.6 more years than the expected do-nothing service life of 9.7 years) and an EUAC of $140. To help illustrate the results of this analysis, plots of EI, total benefit, extension of life, and EUAC versus treatment application age are shown in Figure 25.

It is interesting to note that the highest EI is obtained for an application age of 11 years while an application age of 7 years provides the largest total benefit. Therefore, if an agency regards the differences in EUAC as insignificant, the most appropriate option would be the application age of 7 years.

TABLE 31   Analysis results for Case Study 2—Kansas

Output Data

Pavement Surface Type: HMA
Treatment Type: Rout and Seal Cracks
Application Years: 1, 3, 5, 7, 9, 11, 13
Expected Do-Nothing Service Life (yrs):   9.7

Benefit Summary

		Individual Benefit Summary
Benefit Ranking Factors =>		100
Application Age, yrs	**Total Benefit**	**EqTCR**
1	0.81	0.81
3	1.01	1.01
5	1.15	1.15
7	1.22	1.22
9	1.21	1.21
11	1.12	1.12
13	1.02	1.02

Cost Summary

Application Age, yrs	Treatment Cost, PW $	User Cost, PW $	Other Maintenance Cost, PW $	Rehab. Cost, PW $	Total Present Worth, $	EUAC, $
1	$2,941	n/a	n/a	n/a	$2,941	$243
3	$2,827	n/a	n/a	n/a	$2,827	$214
5	$2,717	n/a	n/a	n/a	$2,717	$191
7	$2,612	n/a	n/a	n/a	$2,612	$171
9	$2,510	n/a	n/a	n/a	$2,510	$154
11	$2,413	n/a	n/a	n/a	$2,413	$140
13	$2,319	n/a	n/a	n/a	$2,319	$128

Effectiveness Summary

Application Age, yrs	Effectiveness Index	Total Benefit	EUAC, $	Expected Life, yrs	Expected Extension of Life, yrs
1	41.38	0.81	$243	14.0	4.3
3	58.89	1.01	$214	15.5	5.7
5	75.45	1.15	$191	16.9	7.2
7	89.09	1.22	$171	18.4	8.7
9	97.77	1.21	$154	19.9	10.2
11	100.00	1.12	$140	21.3	11.6
13	99.24	1.02	$128	22.7	13.0
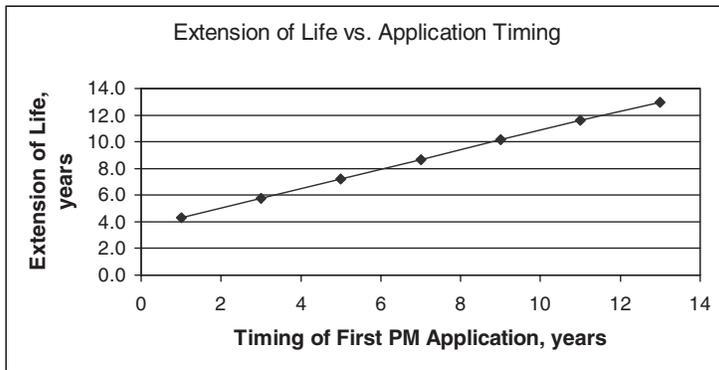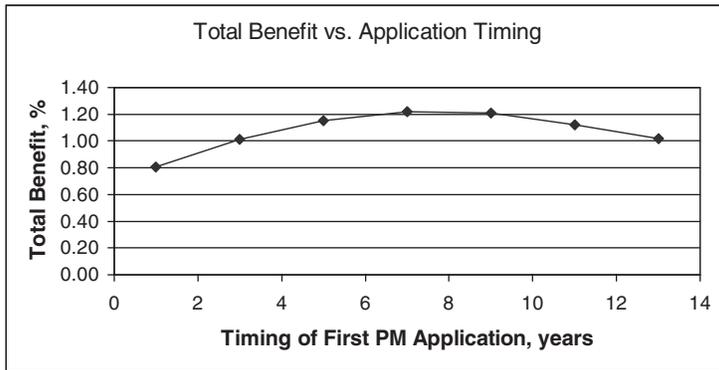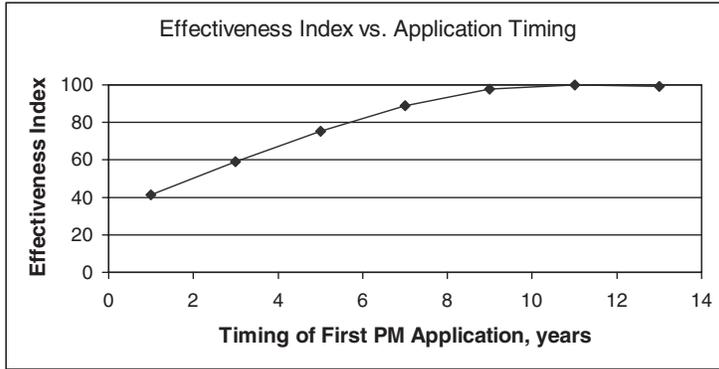
Figure 25.   Summary charts for Case Study 2—Kansas.

Case Study 3—Michigan

Introduction

Michigan DOT has a well-documented preventive maintenance program with many years of experience. Much of MDOT's preventive maintenance is applied through a capital preventive maintenance (CPM) program aimed at protecting the pavement structure, slowing the rate of pavement deterioration, and correcting pavement surface deficiencies, mostly through the use of surface tr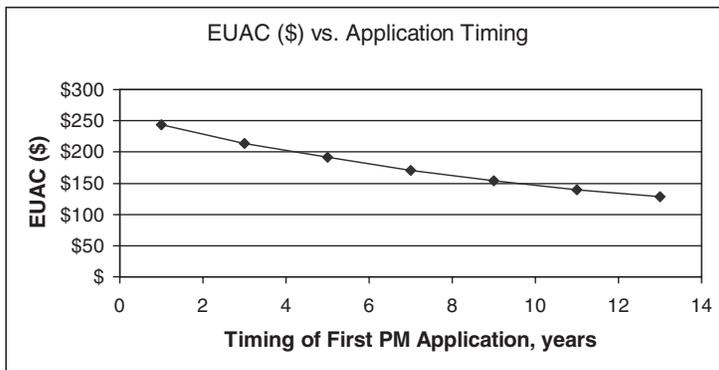eatments. The CPM guidelines indicate that preventive maintenance projects should be relatively simple and should focus on pavement structures with more than 2 years of remaining service life. Severely distressed pavement structures or pavements with a severely distorted cross section are generally not candidate projects for the CPM program (*11*).

MDOT provided data for 56 preventive maintenance projects of HMA pavements. Much of the data were from a report documenting a 3-year evaluation of MDOT's Capital Preventive Maintenance Projects (*26*). Table 32 presents evaluation details of four treatment types that were initially considered for use in this project.

Specific types of data available for each project consist of the following:

- Project location data (route number, project number, MDOT region, beginning and ending mileposts, project length),
- Construction history (pavement type, initial construction type and year, rehabilitation and treatment history),
- Traffic information (1993/1994 and 1997 ADT),
- Distress data, and
- Computed remaining service life (RSL).

Conventional chip seal and crack sealing data were selected for evaluation. Descriptions of these two activities (as presented in MDOT's CPM Manual) are included below (*11*).

Conventional (Single) Chip Seals. A single chip seal is defined as an application of a polymer modified asphalt emulsion with a cover aggregate. The purpose of a chip seal is to

- Seal and retard the oxidation of an existing pavement surface,
- Improve skid resistance,
- Seal fine surface cracks in the pavement, thus reducing the intrusion of water into the pavement structure, and
- Retard the raveling of aggregate from a weathered pavement surface.

The existing pavement should exhibit a good cross section and a good base. The visible distress may include (1) slight raveling and surface wear, (2) longitudinal and transverse cracks with a minor amount of secondary cracking and a slight raveling along the crack face, (3) first signs of block cracking, or (4) slight to moderate flushing or polishing and/or an occasional patch in good condition. MDOT reports an expected life extension of 3 to 6 years from a chip seal application on a flexible pavement.

Crack Sealing of Bituminous Surfaces. MDOT specifies a "cut and seal" technique to seal cracks on bituminous pavements. This method consists of cutting the desired reservoir shape at the working crack in the existing bituminous surface, cleaning the cut surfaces, and placing the specified sealant into the cavity to prevent the intrusion of water and incompressible material.

The existing bituminous surface should be a relatively newly placed surface on a good base with a good cross section. On a flexible base, the bituminous surface should be 2 to 4 years old, and 1 to 2 years old on a composite pavement. The visible surface distress may include fairly straight, open longitudinal and transverse cracks with slight secondary cracking and slight raveling at the crack face, and no patching or very few patches in excellent condition. MDOT reports an expected life extension of up to 3 years on a flexible pavement as a result of crack sealing. However, it is noted that in order to remain effective, this treatment should be followed by routine maintenance crack sealing operations when additional cracks develop.

Treatment Costs

Average cost data for the two chosen treatment types are listed in Table 33 (*26*).

TABLE 32 Summary of projects (for selected treatment types) included in a recent evaluation of MDOT's Capital Preventive Maintenance Program

Treatment	Year of Evaluation	Number of Projects Evaluated	Construction Years of Selected Projects
Conventional (single) chip seals	1999	17	1994 to 1995
Crack sealing of HMA surfaces	1999	12	1994 to 1995
Non-structural HMA overlays without milling	2000	13	1995 to 1997
Double chip seals	2001	14	1995 to 2000

51

TABLE 33 Average treatment cost data

Treatment Type	Average Cost, $/lane-km ($/lane-mi)	Year of Cost Data
Conventional (single) chip seals	$7,603 ($12,240)	1998
Crack sealing of bituminous surfaces (bituminous crack treatment)	$4,288 ($6,900)	1998

Condition Indicators

MDOT performance data are expressed in terms of a distress index (DI) and ride quality index (RQI). DI is a measure of the extent of surface distress and is expressed on a 0 to 100 scale, where a value of 0 represents a pavement with no distress. MDOT uses DI to determine the RSL of a pavement, that is, the number of years left to reach a threshold DI value of 50 (*27*).

RQI is an objective measure of ride quality computed from the power spectral density (PSD) of the road surface profile. Table 34 summarizes Michigan's RQI ranges and associated subjective ride quality rating.

For the projects included in this analysis, 1999 RSL values are provided for the conventional chip seal and crack sealing projects and 2000 RSL values are provided for the non-structural overlay projects. RSL values are not available for the double chip seals, making it very difficult to determine meaningful performance relationships without additional monitoring data.

The RSL data are used to complete estimated linear performance trends by defining the pavement age at which the pavement is expected to reach a terminal DI value of 50. Because RSL is only a function of DI, RQI could not be used as a condition indicator. RSL data were not available for some sections.

MDOT has also investigated the practice of sealing cracks prior to the placement of conventional chip seals on bituminous surfaced pavements; the database includes sections both with and without presealing. Because of the limited number of sections for which data are available, the current conventional chip seal data groups all projects together regardless of whether they received presealing.

Benefit Cutoff Values

To remain consistent with the DI threshold used for RSL, an upper benefit cutoff value of 50 is chosen for use in the analysis. However, the benefit calculations are not limited on the lower end (i.e., a lower benefit cutoff value of 0 is used for the analysis).

Do-Nothing Performance Curves

A linear do-nothing curve is assumed for this analysis because no data were available to support the use of an alternative. This relationship is defined by the line that passes through DI = 0 at an age of zero, and DI = 50 (terminal DI value) at an assumed age of 13 years (see Figure 26). Thus, the linear equation representing the do-nothing DI versus age relationship is as follows:

$$DI = 3.8462 \times Age \qquad (Eq.\ 14)$$

Post-Preventive Maintenance Performance Relationships

Available data are listed in Table 35. These data are used to determine performance equations for all observed application ages for conventional chip seals and crack sealing. Based on general observations of the time series performance data, engineering judgment is used to choose linear regression equations to fit the monitoring data associated with each application age. Since the initial DI rating is always zero, the linear model equation will take the form $DI = m \times (T_{AGE})$, where m is the slope of the line and T_{AGE} is the age of the treatment (i.e., years since placement). The determined regression equations are listed in Table 36. Charts showing the post–treatment performance trends for

TABLE 34 RQI ranges and their subjective ride quality ratings

RQI Range	Subjective Ride Quality
0 to 30	Excellent
31 to 54	Good
55 to 70	Fair
> 70	Poor

Figure 26. Assumed distress index do-nothing curve for Case Study 3—Michigan.

TABLE 35   Construction history analysis for the preventive maintenance sections

Treatment Type	No. of Sections with Meaningful RSL Values	Construction Years of Selected Projects	Application Ages of Data
Conventional (single) chip seals	17	1994 to 1995	10, 11, 12
Crack sealing of bituminous surfaces	12	1994 to 1995	3, 4, 5, 7, 8

TABLE 36   Treatment performance relationships

Treatment Type	Application Age or Age Range	Regression Equation	Computed Treatment Life Until Equation Reaches Upper Benefit Cutoff Level (DI = 50), years
Conventional (single) chip seals	10	$DI = 10.05 \times T_{AGE}$	5.0
	11	$DI = 7.4447 \times T_{AGE}$	6.7
	12	$DI = 8.26685 \times T_{AGE}$	6.0
Crack sealing of bituminous surfaces	3	$DI = 4.825 \times T_{AGE}$	10.4
	4	$DI = 3.3814 \times T_{AGE}$	14.8
	5	$DI = 3.2394 \times T_{AGE}$	15.4
	7	$DI = 6.6536 \times T_{AGE}$	7.5
	8	$DI = 5.0327 \times T_{AGE}$	9.9

conventional chip seals and bituminous crack sealing are shown in Figures 27 and 28, respectively.

Analysis Setup

Because two different treatments are considered, two separate analyses are conducted. Specifically, the analyses are performed using the following inputs and assumptions:

- **Analysis Type**—A detailed analysis type is selected for both analyses since actual data are being analyzed.
- **Condition Indicators**—A custom condition indicator is defined and labeled Distress Index for both analysis sessions.
- **Preventive Maintenance Treatment Selection**—The treatments defined for the two different analyses are Chip Seals and Crack Sealing, respectively.
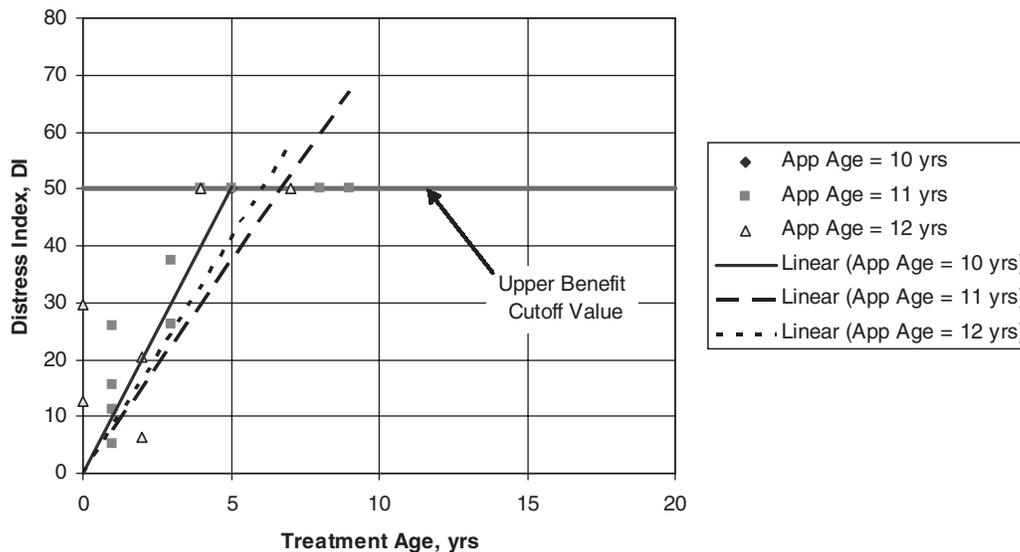
Figure 27.   Post-treatment performance trends for chip seals applied at different ages.
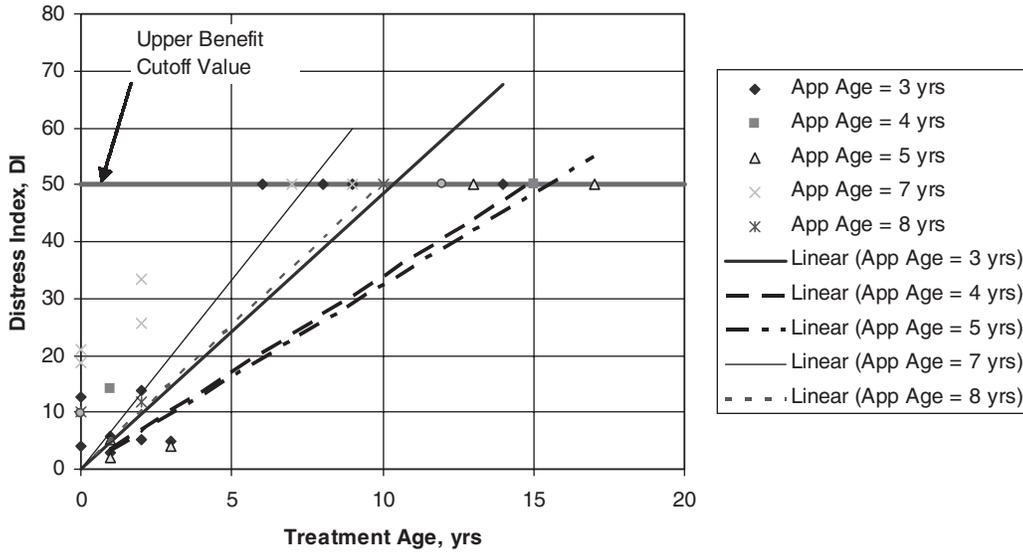
Figure 28.   Post-treatment performance trends for bituminous crack sealing applied at different ages.

TABLE 37   **Analysis results of chip seal for Case Study 3—Michigan**

Output Data

Pavement Surface Type: HMA
Treatment Type: Chip seal
Application Years: 10, 11, 12
Expected Do-Nothing Service Life (yrs):   13.00

Benefit Summary

	Individual Benefit Summary
Benefit Ranking Factors =>	100
Application Age, yrs	Total Benefit	Distress Index (DI)
10	0.33	0.33
11	0.49	0.49
12	0.46	0.46

Cost Summary

Application Age, yrs	Treatment Cost, PW $	User Cost, PW $	Other Maintenance Cost, PW $	Rehab. Cost, PW $	Total Present Worth, $	EUAC, $
10	$8,268.91	n/a	n/a	n/a	$8,268.91	$744.62
11	$7,950.87	n/a	n/a	n/a	$7,950.87	$634.99
12	$7,645.07	n/a	n/a	n/a	$7,645.07	$602.80

Effectiveness Summary

Application Age, yrs	Effectiveness Index	Total Benefit	EUAC, $	Expected Life, yrs	Expected Extension of Life, yrs
10	56.99	0.33	$744.62	15.0	2.0
11	100.00	0.49	$634.99	17.7	4.7
12	98.16	0.46	$602.80	18.0	5.0

- **Performance Relationships**—For both analyses, the do-nothing performance relationship shown in Figure 26 and the respective post-treatment performance relationships defined in Table 36 are used.
- **Project Definition**—A typical project size is defined as 1.6 km (1 mi) long.
- **Cost Data**—Only treatment costs are included in the cost analysis (i.e., rehabilitation, user, and routine maintenance costs are excluded). The unit costs per mile are listed in Table 33; a discount rate of 4.0 percent is used.
- **Benefit Weighting Factors**—Since only one condition indicator is used in each analysis session, the benefit weighting factor associated with the DI is set to 100 percent.

Analysis Results

The analysis results for the chip seal and crack sealing treatments are presented separately.

Chip Seal Example. The results of the chip seal analysis are listed in Table 37. These results indicate that of the three investigated application ages, applying the treatment at age 11 is the most cost-effective option as indicated by an EI of 100, although the application age of 12 produced a greater life extension (5.0 years) and a smaller EUAC ($603) than the year 11 timing option. Note that the EI for the year 12 timing scenario is 98.16, which is very close to 100. Therefore, for all practical purposes, a chip seal applied at year 12 is likely to be as effective as a chip seal applied at year 11.

Crack Sealing Example. The results of the crack sealing analysis are listed in Table 38. These results indicate that of the five investigated application ages, applying the treatment at age 5 is the most cost-effective option as indicated by an EI of 100. This timing scenario not only produces the largest total benefit value (0.81) and the largest extension of life (7.4 years), it also has the second lowest EUAC at $2,427. The second most effective timing scenario is the year 8 application with an EI of 78.55. The large difference between the first and second timing

TABLE 38   Analysis results of crack sealing for Case Study 3—Michigan

Output Data

Pavement Surface Type:	HMA
Treatment Type:	Crack sealing
Application Years:	3, 4, 5, 7, 8
Expected Do-Nothing Service Life (yrs):	13.00

Benefit Summary

		Individual Benefit Summary
Benefit Ranking Factors =>		100
Application Age, yrs	Total Benefit	Composite Index
3	0.21	0.21
4	0.66	0.66
5	0.81	0.81
7	0.37	0.37
8	0.62	0.62

Cost Summary

Application Age, yrs	Treatment Cost, PW $	User Cost, PW $	Other Maintenance Cost, PW $	Rehab. Cost, PW $	Total Present Worth, $	EUAC, $
3	$6,134.08	n/a	n/a	n/a	$6,134.08	$601.51
4	$5,898.15	n/a	n/a	n/a	$5,898.15	$452.51
5	$5,671.30	n/a	n/a	n/a	$5,671.30	$411.46
7	$5,243.43	n/a	n/a	n/a	$5,243.43	$483.19
8	$5,041.76	n/a	n/a	n/a	$5,041.76	$399.26

Effectiveness Summary

Application Age, yrs	Effectiveness Index	Total Benefit	EUAC, $	Expected Life, yrs	Expected Extension of Life, yrs
3	17.38	0.21	$601.51	13.4	0.4
4	74.01	0.66	$452.51	18.8	5.8
5	100.00	0.81	$411.46	20.4	7.4
7	38.44	0.37	$483.19	14.5	1.5
8	78.55	0.62	$399.26	17.9	4.9

scenario choices suggests that the year 5 application is the far more cost-effective choice for applying crack sealing. Figure 29 shows plots of EI, extension of life, and EUAC versus treatment application age for this analysis.

While an age of 5 years is the suggested application age based on the default analysis approach (i.e., analyzing benefit and cost simultaneously), this may not represent the philosophy of all agencies. For example, if the benefit differences in the crack sealing example were considered insignificant, an application age of 8 years would become most appropriate as it provides the lowest EUAC value. Therefore, it is always important for an agency to consider the analysis results in conjunction with other established goals.
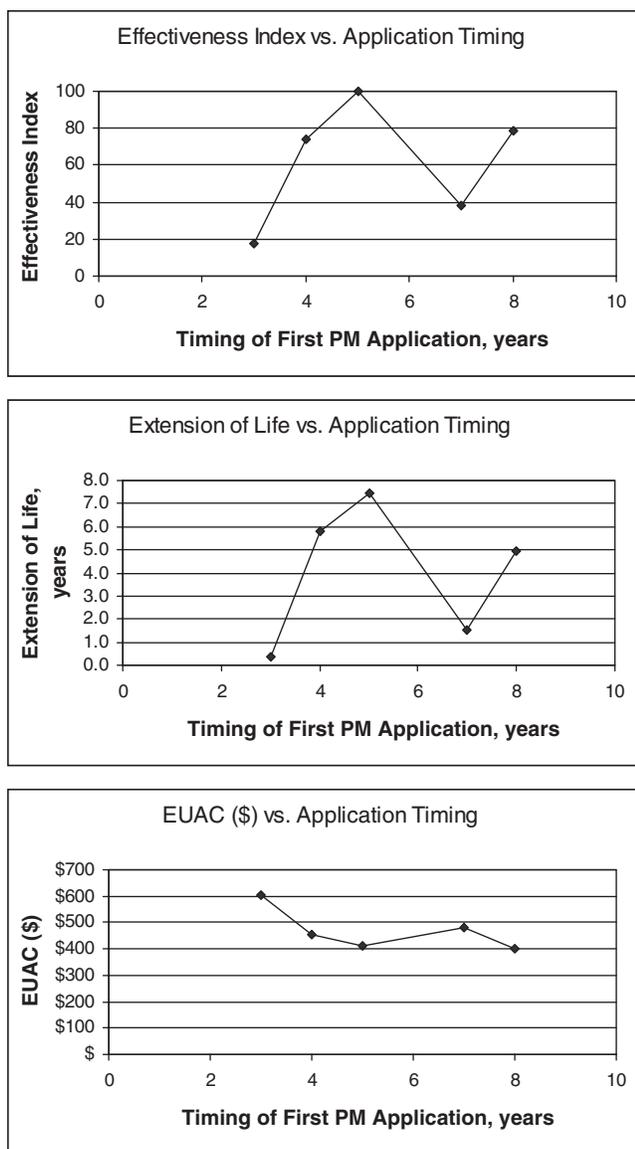
Figure 29. Summary charts of crack sealing for Case Study 3—Michigan.

Case Study 4—North Carolina

Introduction

North Carolina Department of Transportation (NCDOT) provided project data for 10 HMA sections, including pavement condition rating (PCR) history, treatment type, year of treatment application, the (estimated) year of the previous maintenance treatment, and pavement structure (from coring) for 5 of the 10 sections. Treatments organized by type and DOT division were obtained from NCDOT's "2001 Road Oil Summary (28)." Cost information was obtained from NCDOT pavement management unit staff.

Treatment Selection

Two different asphalt seal coats (Triple Seal and Split Seal) were used on the 10 projects as preventive maintenance treatments. Split Seal treatment was used on 8 projects and Triple Seal treatment was used on 2 projects. Construction details described in Section 660 of North Carolina's State Construction Handbook (29) are summarized.

Split Seal. A split seal consists of two applications of asphalt binder and aggregate. Total binder and aggregate application rates are approximately 2.04 to 2.26 L/m^2 (0.45 to 0.50 gal/yd^2) and 16 to 19 kg/m^2 (30 to 35 lb/yd^2), respectively. In the first application, approximately 0.91 to 1.13 L/m^2 (0.20 to 0.25 gal/yd^2) of asphalt material is applied to the existing surface, followed immediately by the application of approximately 11 to 12 kg/m^2 (20 to 22 lb/yd^2) of seal coat aggregate spread uniformly over the treated surface. Immediately after the first application of seal aggregate has been made uniform, the remainder of the required amount of asphalt material and seal coat aggregate are applied and the seal coat is rolled; specific rolling instructions are provided in Section 660 of the handbook (28).

Triple Seal. To construct a triple seal, approximately 0.91 to 1.13 L/m^2 (0.20 to 0.25 gal/yd^2) of liquid asphalt is applied to the existing surface followed immediately by the application of approximately 8 to 9 kg/m^2 (15 to 17 lb/yd^2) of seal coat aggregate spread uniformly over the treated surface. The operation is performed three times; aggregate applied in the final application is then rolled as described in the handbook (29).

Treatment Costs

Treatment costs are summarized in NCDOT's "2001 Road Oil Summary (28)." Relevant details are provided in Table 39 for both treatment types.

TABLE 39   Summary of 2001 treatment cost data

Treatment Type	No. of Divisions with Data	Length of Preservation Projects, km	Area of Preservation Projects, m²	Total Cost of Preservation Projects, $	Average Unit Cost for Data from All Divisions, $/m²	Range of Average Unit Costs Determined for Each Division, $/m²
Split Seal	12	1,166	6,154,018	$2,346,429	$0.84	$0.75 to 1.05
Triple Seal	9	88	475,022	$643,093	$1.24	$0.97 to 1.65

Note: 1 mi = 1.61 km; 1 yd² = 0.84 m²

Condition Indicator

Time series PCR data are provided for the 10 sections. The pavement condition rating is a composite index that reflects the extent of surface distress, expressed on a 0 to 100 scale (a value of 100 represents a pavement with no distress).

Benefit Cutoff Values

Based on the pavement condition time-series data, a lower benefit cutoff value of 70 is selected, suggesting that when the condition falls below 70, a second asphalt seal coat is triggered. The benefit calculations are not subjected to any limit on the upper end (i.e., an upper benefit cutoff value of 100 is used for the analysis).

Do-Nothing Performance Curves

All analyzed preventive asphalt seal coats were placed on pavements that already had a Mat and Seal treatment applied. To simplify the analysis, the performance of the existing Mat and Seal layers is defined as the do-nothing performance. Thus the do-nothing performance curve is defined by the time series performance data from the Mat and Seal layer application year (defined as year 0) to the application year of the first preventive asphalt seal coat. A representative do-nothing curve is then assumed for the analysis by fitting a linear equation

through this time series data (through a value of 100 at time zero) as shown in Figure 30. To check the reasonableness of this approach, the age at which the resulting regression equation ($PCR = -1.6506 \times Age + 100$) crosses the assumed condition trigger level of 70 is determined. The expected age at this trigger value is 18.2 years, which is reasonable.

Post-Preventive Maintenance Performance Relationships

Construction and maintenance history of the 10 sections is summarized in Table 40. It appears there is a definitive relationship between the timing of the first and second preventive maintenance treatments (see Figure 31). The trend indicates that the life of the first preventive maintenance treatment is longer when applied sooner rather than later after initial construction.

As shown in Table 40, monitoring data associated with first treatment application ages of 4, 5, 8, 9, 11, 13, and 14 years are available (two sections with *unknown* construction history were ignored). Three additional sections were eliminated from the analysis. One of these sections with an application age of 8 years was eliminated because the monitoring data for the section did not appear to be representative; treatment condition deteriorated at a much more rapid rate than any other sections. Two other sections with application ages of 11 years were eliminated because the data showed com-
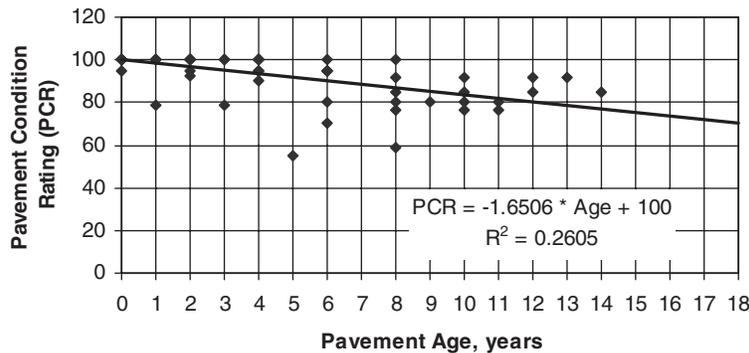
Figure 30.   Assumed representative do-nothing curve for the North Carolina projects.

TABLE 40   Construction history analysis for the 10 asphalt seal coat sections

State Route	Assumed Original Construction Year	First Preventive Maintenance Treatment Year	Last Preventive Maintenance Treatment Year	Age at Timing of First Preventive Maintenance Treatment, yrs	Time from First Treatment Application to Last Treatment Application, yrs
SR 1125	1984	1992	1999	8	7
SR 1226	1982	1986	2000	4	14
SR 2249	1980	1991	2000	11	9
SR 2018	1982	1993	2000	11	7
SR 2028	1980	1989	2000	9	11
SR 1828	1982	1996	2002	14	6
SR 1722	Unknown				
SR 1721	1983	1988	2002	5	14
SR 2245	1982	1995	2002	13	7
SR 1719	Unknown				
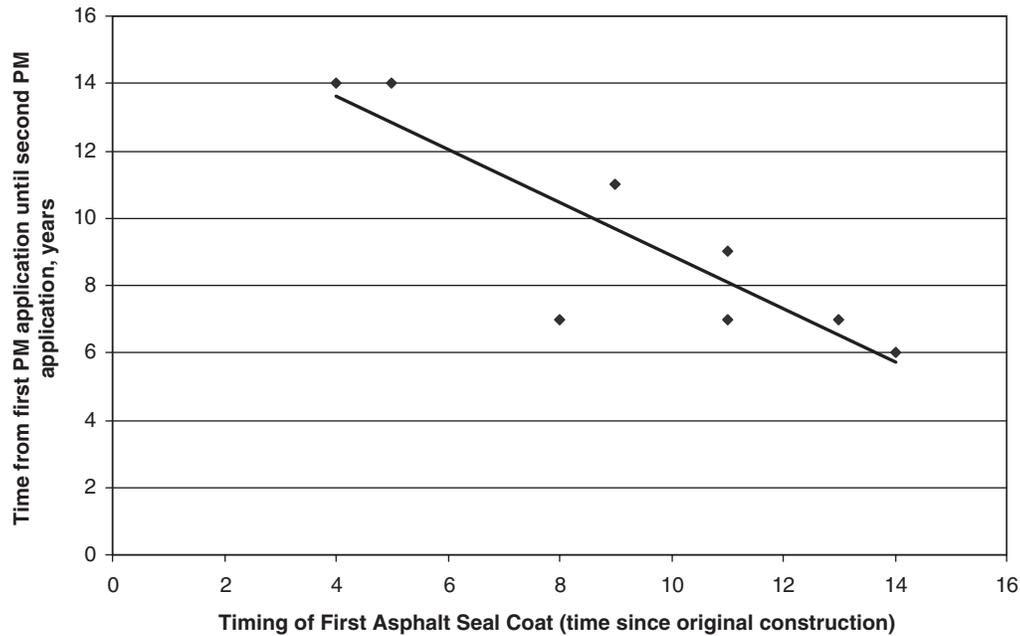
Figure 31.   General trend between the life of the first preventive maintenance treatment and its application timing (time after initial construction).

TABLE 41   Post-treatment performance relationships for Case Study 4—North Carolina

Application Age	Regression Equation	Computed Life Until Equation Reaches Lower Benefit Cutoff Level (PCR = 70)
4	$PCR = 100 - 0.007535 * AGE^{2.747556}$	20.4
5	$PCR = 100 - 0.333097 * AGE^{1.511787}$	19.6
9	$PCR = 100 - 5.618E\text{-}12 * AGE^{11.474446}$	12.9
13	$PCR = 100 - 0.000138 * AGE^{6.191617}$	7.3
14	$PCR = 100 - 0.020379 * AGE^{3.969362}$	6.3
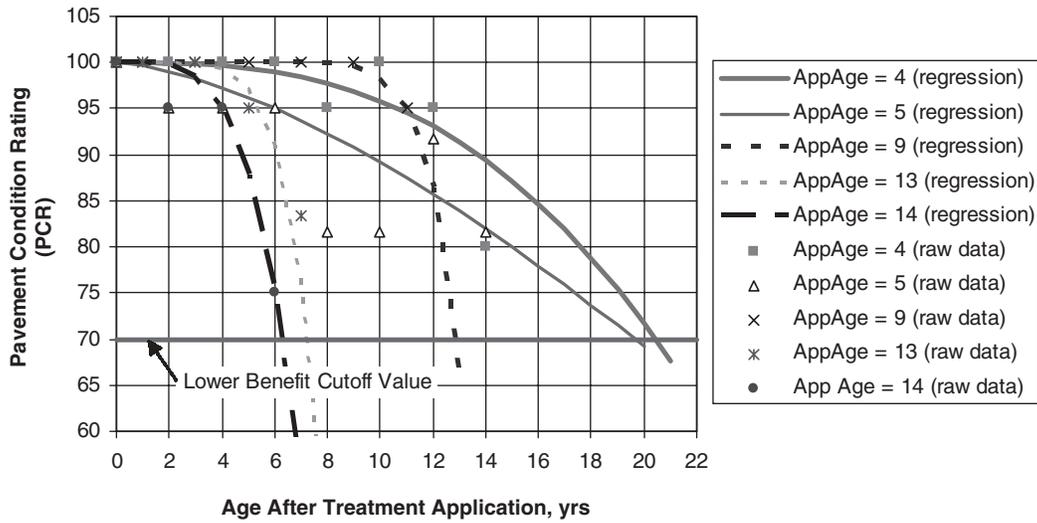
Figure 32.   Determined post-treatment performance relationships for Case Study 4—North Carolina.

TABLE 42   Analysis results for Case Study 4—North Carolina

Output Data

Pavement Surface Type:	HMA
Treatment Type:	Asphalt Seal Coat
Application Years:	4, 5, 9, 13, 14
Expected Do-Nothing Service Life (yrs):	18.18

Benefit Summary

		Individual Benefit Summary
Benefit Ranking Factors =>		100
Application Age, yrs	Total Benefit	Pavement Condition Rating
4	1.04	1.04
5	0.77	0.77
9	1.05	1.05
13	0.61	0.61
14	0.50	0.50

Cost Summary

Application Age, yrs	Treatment Cost, PW $	User Cost, PW $	Other Maintenance Cost, PW $	Rehab. Cost, PW $	Total Present Worth, $	EUAC, $
4	$14,531.67	n/a	n/a	n/a	$14,531.67	$943.00
5	$13,972.76	n/a	n/a	n/a	$13,972.76	$902.39
9	$11,943.97	n/a	n/a	n/a	$11,943.97	$829.87
13	$10,209.76	n/a	n/a	n/a	$10,209.76	$744.37
14	$9,817.08	n/a	n/a	n/a	$9,817.08	$715.75

Results

Application Age, yrs	Effectiveness Index	Total Benefit	EUAC, $	Expected Life, yrs	Expected Extension of Life, yrs
4	87.43	1.04	$943.00	24.4	6.3
5	68.04	0.77	$902.39	24.6	6.5
9	100.00	1.05	$829.87	21.9	3.7
13	64.84	0.61	$744.37	20.3	2.1
14	55.32	0.50	$715.75	20.3	2.1

pletely different rates of deterioration, without clarification. The analysis compares the expected post-preventive maintenance trends associated with assumed application ages of 4, 5, 9, 13, and 14 years after initial construction.

Based on general observations of the time series performance data, engineering judgment was used to select an exponential regression equation to fit the monitoring data for each of the application ages. The exponential model type is a good choice for a decreasing trend that has a known starting condition value. In this case, the initial PCR is always 100; therefore, each of the individual post-preventive maintenance relationships must yield a value of 100 at an age of zero. The equation form $PCR = C - m \times (Age)^P$ was selected; the specific regression equations are listed in Table 41 and plotted (along with the reported data) in Figure 32.

Analysis Setup

The following inputs are used in the analysis:

- **Analysis Type**—A detailed analysis type is selected since actual data are being analyzed.
- **Condition Indicators**—A custom condition indicator is defined and labeled Pavement Condition Rating.
- **Preventive Maintenance Treatment Selection**—A custom treatment named Asphalt Seal Coat applied at ages of 4, 5, 9, 13, and 14 years is investigated.
- **Performance Relationships**—The do-nothing performance curve shown in Figure 30 and the post-preventive maintenance performance relationships defined in Table 41 are used.
- **Project Definition**—A typical project size is defined to be 15,290 m² (20,000 yd²).
- **Cost Data**—Only treatment costs are included in the cost analysis (i.e., rehabilitation, user, and routine maintenance costs are excluded). Because data for three split seal and two triple seal projects are used, a treatment unit cost of $1.02/m² ($0.85/yd²) is chosen for this analysis, because it is within the observed cost ranges for both treatment types. The selected project size and unit cost would yield a total cost of $17,000 for each treatment application; a discount rate of 4.0 percent was also chosen for the analysis.
- **Benefit Weighting Factors**—Because only one condition indicator is used in the analysis session, the benefit weighting factor associated with the PCR is set to 100 percent.

Analysis Results

Results of the analysis are summarized in Table 42. These results indicate that out of the five investigated application
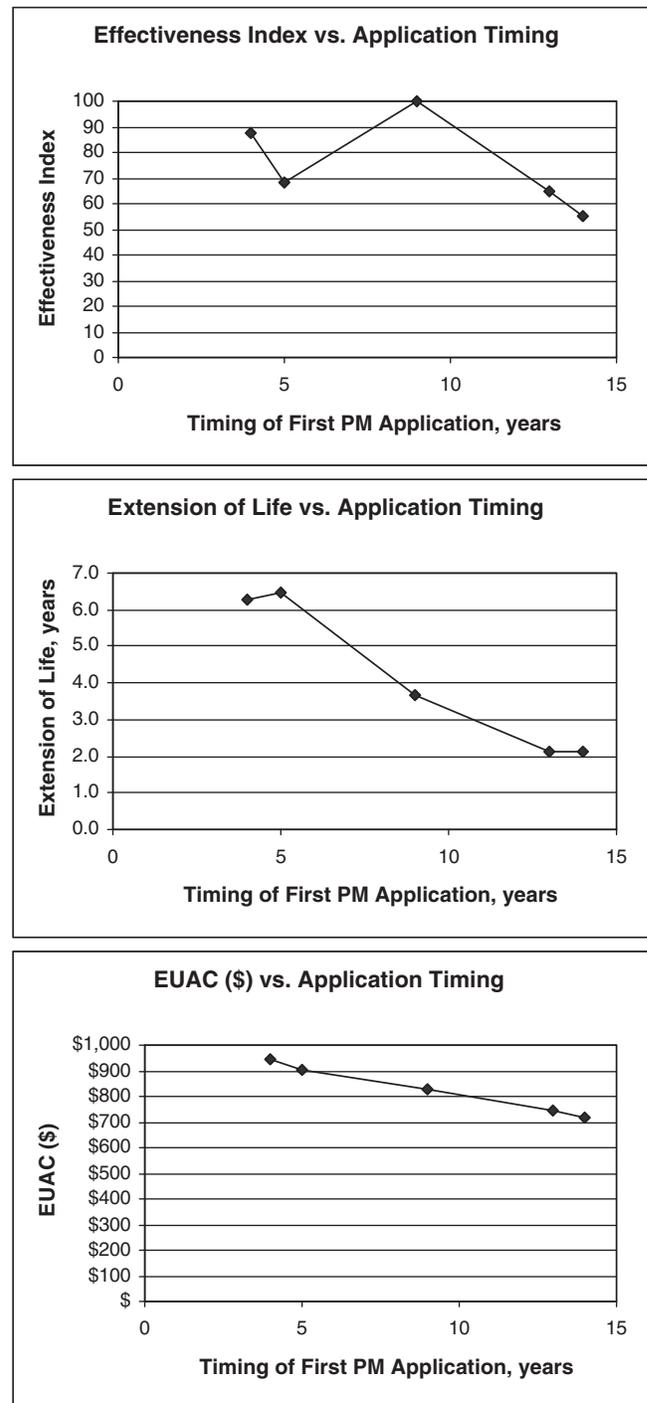
Figure 33. *Summary charts for Case Study 4—North Carolina.*

ages, applying the treatment at age 9 is the most cost-effective choice as indicated by an EI of 100. At this application age 9, a life extension of 3.7 years is expected (i.e., the pavement will last 3.7 more years than the 18.2 years expected if no treatment is applied), with an EUAC of approximately $830. The largest expected extension of life (6.5 years) is with a treatment applied at age 5 that provides the second highest EUAC and the

third highest EI at 68.04; the second largest effectiveness (87.43) is with an application age of 4 years. The results of this analysis session, shown in Figure 33, illustrate EI, extension of life, and EUAC versus treatment application age relationships.

Case Study 5—LTPP Data

This example involves the use of data from the LTPP SPS-3 and SPS-4 experiments. In these experiments, maintenance treatments were applied to both HMA and PCC pavements and performance of these pavements and nearby control sections was monitored over time. Using the LTPP DataPave 3.0 software program, LTPP data were examined to identify maintenance effectiveness test sections meeting the following requirements:

- Have "adequate" time series data—in order to establish accurate condition indicator trends over time, only sections with three or more time series data points were included.
- Be applied on pavements in "Good" condition—since preventive maintenance treatments are applied to pavement in "Good" condition, only sections with treatment applied to a pavement in "good" condition were included.
- Have condition data before first preventive maintenance treatment application—in order to determine the initial impact of a preventive maintenance treatment on condition, sections that had condition information in the year immediately prior to the preventive maintenance treatment applications were included.
- Use of control section—in order to assess the impact of preventive maintenance on pavement performance its expected service life, all sections suitable for this evaluation must have data associated with a "control" section to define the do-nothing performance trend.

For flexible pavements, the initial search of the database identified the following SPS-3 sections as meeting these criteria:

- 80 sections with chip seal coats
- 80 sections with slurry seal coats
- 69 sections with crack sealing
- 79 sections with (thin) overlays

The following types of condition indicator data are available for each of these sections:

- Nonload-related and load-related cracking
- Average rut depth
- IRI
- Friction

- Oxidation—viscosity and penetration of asphalt from recovered cores (available for a very limited number of sections)

For rigid pavements, 43 SPS-4 sections were found to have data for crack and joint sealing treatments. However, these maintenance activities were combined in these sections, making it difficult to isolate the separate effect of each treatment. For these sections, the following types of condition indicator data are available:

- Cracking
- Joint spalling
- Faulting
- IRI
- Friction

An initial review of the collected data was conducted to determine their usefulness in evaluating the optimal timing methodology. Specifically, it was considered essential to have data available on the performance of the pavement after application of a specific preventive maintenance treatment to compare with the performance of a control section that did not receive the treatment (i.e., the do-nothing trends). This review concluded that the LTPP data could not be used to conduct a meaningful analysis for several reasons. The performance trends for a large number of sections revealed counterintuitive trends (e.g., untreated control sections performing better than adjacent sections that received a preventive maintenance treatment [see Figure 34]). Because these sections did not show an improvement in performance as a result of treatment application, they were not studied further. Also, sections that were not in good condition when treatment was applied were excluded because they do not meet the definition of preventive maintenance. With this, there were not enough remaining sections with treatments applied at different ages that exhibited the expected trends to support a meaningful analysis.

SUMMARY

A product of this research was the development of a methodology that can be used to determine the optimal time to apply preventive maintenance treatments. The methodology is based on an understanding of how pavements perform over time and how preventive maintenance affects its performance. By analyzing appropriate performance data from pavements treated at a variety of times, it is possible to identify the "right" time to apply preventive maintenance. That "right" time, identified through the optimal timing methodology, is defined as the time when the treatment's application provides the greatest ratio of improvement in condition (benefit) to cost (i.e., that time with the largest associated B/C ratio).
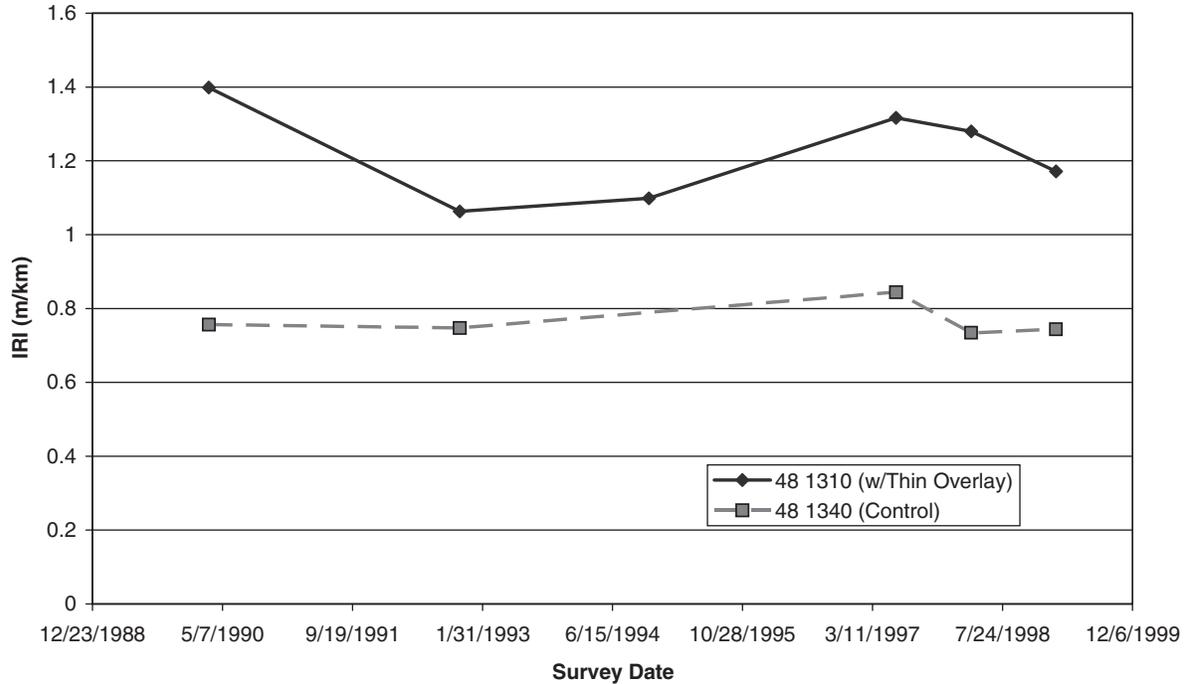
Figure 34.   Example of LTPP data exhibiting a counterintuitive trend for a thin overlay application.

To assist in the implementation of the methodology, OPTime, a Microsoft® Excel-based analysis tool capable of analyzing actual preventive maintenance-related performance data, was developed. The analysis tool greatly facilitates the application of the methodology through a logical, step-by-step, input sequence. Further explanation of the optimal timing approach and a detailed user's guide is provided in Appendix C, which is available to users by accessing the NCHRP website (http://trb.org/news/blurb_detail.asp?id=4306).

Data were collected from four SHAs and from the LTPP SPS-3 and SPS-4 experiments for possible use in an analysis to validate the optimal timing approach and to demonstrate the use of the OPTime tool. These data were analyzed using OPTime although the results of the analyses did not always match expectations. Data from the LTPP experiments were not analyzed because the data did not support the premise that the maintenance treatments improved performance compared with the do-nothing case. A holistic approach to identifying the optimal time of preventive maintenance application is needed. Such an approach should address project selection, treatment selection, pavement performance monitoring, and data analysis and reporting. These observations are further described in Chapter 4 as part of Suggested Research.

CHAPTER **4**

CONCLUSIONS AND SUGGESTED RESEARCH

Reported highway agency experience and observations of practice show that there is a clear need for guidance on the selection, timing, and measurement of effectiveness of pavement preventive maintenance treatments. In many cases, such guidance can be developed from an agency's available data if preventive maintenance treatments have been used. Otherwise, a significant investment of time and resources will be needed to collect the required data. For agencies interested in implementing or improving preventive maintenance practices, perhaps the single most significant change would come from using preventive treatments at the optimal time.

In this project, "optimal timing," as it relates to preventive maintenance is defined as the time at which the greatest improvement in performance (over doing nothing) is realized at the lowest cost. As suggested by the highway agency examples in Chapter 3, identifying optimal timing requires a systematic approach to preventive maintenance that includes the following actions:

- Identify specific objectives of the preventive maintenance program.
- Select preventive maintenance treatments and define guidelines on their appropriate use.
- Define the typical performance of pavements when no treatment is applied (the do-nothing option) as well as the expected performance for different treatments.
- Identify and track appropriate measures of performance for different treatments.
- Analyze data and calculate the optimal timing for specific preventive maintenance treatments.

Each of these actions is discussed in more detail as follows.

PREVENTIVE MAINTENANCE PROGRAM OBJECTIVES

Program objectives identify what the agency expects to accomplish with a preventive maintenance program and how to impact specific measures of performance. Potential objectives could address, for example, deteriorating pavement conditions, unsafe surface conditions, and frequent user complaints. Appropriate performance measures would include pavement distresses, friction, and roughness or ride.

TREATMENT SELECTION

Identifying preventive maintenance treatments that can help to accomplish the established objectives is an important step. The characteristics of available treatments should be considered and compared with identified needs or objectives. Information about preventive maintenance treatments provided in Chapter 2 could serve as a starting point. Research, materials, construction, and maintenance staff of SHAs, industry representatives, and local contractors can contribute to developing lists of appropriate preventive maintenance treatments. Because each treatment provides unique benefits or can be placed subject to different constraints, it is good practice to develop meaningful guidelines on the local or regional use of these treatments, including information on project selection, construction, quality control/quality assurance, and troubleshooting.

TREATMENT PERFORMANCE AND DO-NOTHING PAVEMENT PERFORMANCE

The performance of a preventive maintenance treatment is measured as the change in pavement performance over the do-nothing condition as measured by performance measures of interest. This performance is predominantly influenced by the condition of the pavement on which the treatment is being applied. To accurately estimate the most cost-effective treatment application time, both the current condition of the pavement and how that condition changes with the application of preventive maintenance must be known. This knowledge is acquired either by analyzing existing data or by constructing and monitoring test sections. A methodology to perform this analysis that considers both changes in performance and the associated costs is described in Chapter 3. To measure the improvement in performance, a do-nothing performance trend is used to represent how the pavement behaves without any treatment. Do-nothing trends are actually required for each measure of performance that is considered. To estimate the optimal timing, performance and cost data that reflect the effects of applying the treatment at different times are analyzed.

An agency may already have access to such data, but the literature search and visits to agencies actively using preventive maintenance treatments suggest that only a few agencies either

applied preventive maintenance treatments or monitored subsequent performance in a manner that generated the needed data. In the absence of such data and if the implementation of an optimal timing approach is desired, test sections must be constructed and monitored over time. Guidelines for constructing and monitoring test sections are presented in Appendix D.

APPROPRIATE MEASURES OF PERFORMANCE

The process of identifying and tracking appropriate measures of performance is a key component of the optimal timing analysis. An appropriate measure is one that reflects the benefit of using the treatment; preferably it relates to the identified program objectives (e.g., if customer satisfaction is a preventive maintenance program objective, then pavement roughness could be used as a performance measure). In monitoring treatment performance, it is also important to recognize that a treatment can "last" much longer than it provides a benefit. Ultimately treatment performance (or true treatment "life") is determined by the time at which the treated pavement's performance reverts to the do-nothing condition, or when it reaches a defined threshold.

DATA ANALYSIS AND SELECTION OF OPTIMAL TIMING

Whether preventive maintenance treatment performance data come from existing databases or test sections, the proper analysis of the data identifies the optimal time to apply such treatments. The optimal timing methodology described in Chapter 3 and Appendix C is incorporated in OPTime. (Appendix C is available to users by accessing the NCHRP website: http://trb.org/news/blurb_detail.asp?id=4306). The output of the analyses is presented in tables and charts to help to understand the findings and identify the sensitivity of the treatment's performance to different treatment application timings.

SUGGESTIONS FOR ADDITIONAL RESEARCH

For agencies that intend to implement or improve their preventive maintenance practices, there is a need for research efforts to develop guidance on issues related to optimal timing, including the following:

- Relating measured material properties to pavement performance—While many agencies focus on conventional distress indicators to identify the optimal time to apply preventive maintenance, other meaningful performance measures that reflect the benefits of applying preventive maintenance might be used. Examples of these measures are asphalt viscosity, surface texture, and pavement moisture content or infiltration.
- Planning and monitoring test sections—Agencies are strongly encouraged to construct preventive maintenance test sections using treatments of local interest placed at different times to generate optimal timing data; monitoring the performance over a long enough time is necessary to generate differences in performance.
- Enhancing the optimal timing methodology—When more time-series performance data for pavements receiving preventive maintenance treatments at different times become available either from agency databases or from experimental sections, the optimal timing methodology should be further evaluated and enhanced.
- Developing a guide on optimal timing—When sufficient results are available from agencies across the country, a guide could be developed to assist agencies which have neither the performance experience nor the means to construct and monitor test sections to identify optimal timing based on the experiences of others.
- Programming a more robust, stand-alone software tool—The tool could expand on the methodology developed in this project to facilitate more comprehensive analyses by including the following:
  - Ability to analyze preventive maintenance strategies (i.e., more than one preventive maintenance treatment application) rather than the application of one treatment,
  - Use of a true optimization method in which all possible treatment strategy timings are analyzed, and
  - Ability to include multiple treatment types to help estimate the most effective treatment type and its associated optimal timing.
- Conducting training workshops—Training on the application of the methodology and the use of the analysis tool will facilitate its use. Such training could be offered on a regional basis or to individual highway agencies. In the latter option, an agency's pavement performance data could be used to demonstrate the applicability of these data to the optimal timing methodology or the need for other types of data.

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APPENDIXES A THROUGH E

UNPUBLISHED CONTRACTOR'S MATERIAL

Appendixes A, B, C, and E submitted by the research agency are not published herein. Titles of available appendixes are as follows:

APPENDIX A   Summary of Agency Experiences
APPENDIX B   Historical Optimization-Based Approaches Used for Transportation-Related Problems
APPENDIX C   User's Guide for the Optimal Preventive Maintenance Timing Analytical Tool (OPTime)
APPENDIX D   Plan for Constructing and Monitoring Preventive Maintenance Test Sections
APPENDIX E   Example Illustrating the Inclusion of Different Cost Types

Appendixes C and E are accessible on the web at http://trb.org/news/blurb_detail.asp?id=4306. The OPTime software in Appendix C can be copied on a CD-ROM for use. For a limited time, copies of Appendixes A and B will be available on a loan basis from the NCHRP. Appendix D is provided on the following pages.

APPENDIX D

PLAN FOR CONSTRUCTING AND MONITORING PREVENTIVE MAINTENANCE TEST SECTIONS

INTRODUCTION

The underlying premise of preventive maintenance is that the application of treatments to a pavement in "good" condition will provide some benefit above and beyond the performance of the untreated pavement. It is further assumed that the benefit will vary, depending on the type of treatment, when it is applied, and the condition of the pavement at the time of application. However, because only a few agencies have had long-term experience with preventive maintenance practices, there is little evidence of these benefits. Attempts to track these benefits after the fact—by examining historical pavement performance data, for example—are problematic because of the absence of critical data, such as the condition of the pavement at the time of treatment application, the quality of construction, and periodic observations of performance.

Contributing to the difficulties in documenting the benefits of preventive maintenance is the lack of a strong connection between the commonly used methods of monitoring pavement performance and the types of benefits provided by preventive maintenance treatments. Preventive maintenance is often aimed at maintaining or improving functional performance while most condition surveys focus on a pavement's structural performance.

Perhaps the best way to evaluate preventive maintenance effectiveness—and show when it is most effective—is through monitoring specially constructed test sections. Properly designed, constructed, and monitored test sections would generate data appropriate for the pavement types, traffic loadings, environmental conditions, and maintenance treatments that are typical of an agency's practices and conditions.

This appendix outlines the steps involved in creating a plan for establishing preventive maintenance test sections that can be used to generate the information needed to implement a successful preventive maintenance program. Results from the experiment would be used to determine the benefits (or effectiveness) of specific preventive maintenance treatments based on the age and condition of the pavement. An analysis using the methodology described in Chapter 3 can then be made to identify the optimal time to perform preventive maintenance. The steps in developing the plan include the following:

- Identify objectives
- Complete experiment design
- Construct experiment
- Monitor performance
- Analyze results

OBJECTIVES

The first step in developing an experiment is to identify the objectives or goals of the preventive maintenance program to help establish a link between the treatments selected for study, the measures used to monitor performance, and the agency's expectations. Goals might address pavement smoothness, noise mitigation, accident reduction, and pavement life extension, for example. While the overall objective of the experiment is to identify the best time to apply preventive maintenance, the objective is inextricably linked to preventive maintenance performance objectives.

The types of treatments of asphalt and concrete pavements that might be evaluated to achieve specific objectives are listed in Table D-1. While almost any treatment could extend pavement life, certain performance objectives would best be achieved with the application of specific treatments.

EXPERIMENT DESIGN

Perhaps the most important part of the plan is the design of the experiment. An effective design ensures that the objectives of the experiment are fully met. Test section sites are selected to meet the immediate and long-term needs of the experiment. While concerns about constructibility and the availability of local support for placing the test sections are recognized. Long-term needs include monitoring and data collection, and subsequent analyses of data. An underlying consideration in locating a test section is to avoid possible confounding factors, such as variability in the pavement condition that could impact the interpretation of the results.

Some of the key items in the design are discussed in the following sections.

Site Selection

There are two major issues to consider in site selection: (1) limiting or avoiding confounding factors and (2) ensuring that applicable and useful results are obtained from the site. Confounding factors refers to variations in site conditions that might later complicate the analysis of the data. Among such factors are non-uniform traffic volumes, cross sections, and support conditions. The key to site selection is to consider the analyses that will be performed and control as many of the factors that will affect them as possible. Understanding how the findings will eventually be used is another factor in obtaining useful results. For example, if the agency

TABLE D-1   Relationship between performance objectives and preventive maintenance treatments

Preventive Maintenance Objective	Pavement Surface Type		Performance Measure
	Bituminous	**PCC**	
Improve Ride (Reduce roughness)	Slurry Seal Microsurfacing Ultrathin Friction Course Thin Overlay	Diamond Grinding	IRI PSI
Noise Control	Ultrathin Friction Course Slurry Seal Microsurfacing	Diamond Grinding	dB
Increase Surface Friction	Chip Seal Slurry Seal Ultrathin Friction Course Thin Overlay	Diamond Grinding	Skid Number Mean Texture Depth IFI

Extend Pavement Life	Crack Sealing
	Fog Seal
	Scrub Seal
	Chip Seal
	Slurry Seal
	Microsurfacing
	Thin Overlay
	Ultrathin Friction Course
		Joint and Crack Sealing	Condition:
			  Cracking
			  Patching
			  Rutting
			  Raveling
			  Faulting
			  Pumping
			  Spalling
			  Potholes
			  Patching

Reduce Moisture Infiltration	Crack Sealing
	Scrub Seal
	Chip Seal
	Slurry Seal
	Microsurfacing
	Thin Overlay
	Ultrathin Friction Course
		Joint and Crack Sealing	Condition:
			  Cracking
			  Patching
			  Rutting
			  Raveling
			  Faulting
			  Pumping
			  Spalling
			  Potholes
			  Patching

IRI = International Roughness Index; IFI = International Friction Index; dB = decibel

maintains pavements in different environments, then producing broadly acceptable results from sites constructed in one type of environment should be carefully considered. Similar consideration should be given to other relevant aspects of the site, such as pavement type, design, condition and age, and traffic level.

Pavement Type

Hot-mix asphalt (HMA), portland cement concrete (PCC), and other bituminous-surfaced pavements are all candidates for inclusion in a preventive maintenance experiment. Test sections should be constructed on the types of pavement for which preventive maintenance treatment applications will be evaluated.

It is recommended that initial efforts be kept fairly simple by limiting pavement type to bituminous-surfaced or PCC pavements that have not been rehabilitated or received any other blanket maintenance treatment. While it could be argued that an overlaid pavement will provide similar results for some of the objectives (such as noise mitigation or improved surface friction), the contribution of the original pavement to

the performance of the overlay, and to that of the maintenance treatment, cannot be fully isolated.

Pavement Design

The pavement should be of a uniform design over the length of the project. This means that all structural features (i.e., paving layers, materials, and thicknesses) and geometric features (i.e., number of lanes) should be the same over the length of the project. The subgrade should also be fairly uniform over the project and free of swelling or frost susceptible soils.

Pavement Condition and Age

Because pavement age is an indirect indicator of the pavement condition, a pavement that is fairly young (e.g., less than 5 years old) and still in good condition should be selected. It should not exhibit any signs of significant structural deterioration (such as rutting or fatigue cracking), and only small amounts of other types of distress (such as linear cracking or

weathering/raveling) should be present. As with other factors, it is also desirable that the condition of the pavement be fairly uniform over the length of the project and that any significantly deteriorated areas not be included as part of the experiment.

Traffic Levels

The traffic levels should be uniform over the project to eliminate the effect of traffic variability on treatment performance. Low to moderate traffic volumes (e.g., 1,000 to 5,000 vehicles per day) may be most appropriate for the experiment because they cover the conditions for which many treatments are used. While lower traffic volumes make it easier to monitor the performance, roadways with higher traffic volumes provide a more severe test for the treatments. Higher traffic volumes also make it harder to monitor performance and may cause problems when the treatments fail and some form of rehabilitation is required. Also, it is important that adequate construction and performance records be kept not only to fully document the design of the project, but also to help assess the effects of the various treatments on key performance measures.

Treatment Selection

The selection of preventive maintenance treatments for evaluation in the project should be based on the specific goals of the agency's preventive maintenance program. The agency must recognize that including different treatments will require a larger test site and will involve the collection of a large amount of data and the conduct of extensive data analysis. For each treatment included in the experiment, additional sections are needed for replicating, and multiple sections are needed for treatment applications at different times in the future.

Ultimately, the selected treatments should match the agency's preventive maintenance objectives. For example, if an agency's objective is to maintain high levels of surface friction, then treatments that enhance surface friction should be evaluated in the experiment. Table D-2 summarizes some of the primary benefits provided by the different preventive maintenance treatments; this information would help in selecting treatments to support specific preventive maintenance objectives. Of course, several different treatments intended for different purposes cannot be studied in the same project.

As part of the experiment, agencies may also include new materials or techniques or treatments with which they have little or no previous experience.

Treatment Timing

In the experiment, the timing of the treatment application will be varied so that the effect of treatment timing on performance (or effectiveness) can be evaluated. In this regard, two critical issues must be considered: determining when the first treatment should be applied and determining how often subsequent treatments should be applied. On a new pavement, a preventive maintenance treatment might be applied before the pavement is opened to traffic (e.g., a fog seal application to bituminous surfaces) or shortly after construction (e.g., 1 to 3 years). To evaluate timing issues, a number of untreated sections must initially be kept within the experiment so that treatments can be applied at different times in the life of the pavement. For example, if a chip seal is applied 2 years after construction, sufficient untreated test sections must be available to allow chip seal application later (e.g., 3, 4, 5, or 6 years). Applying the treatment at 1 year should also be considered to determine if more benefit is obtained from such an early application.

TABLE D-2   Primary benefits of different maintenance treatments

Treatment	Roughness	Friction	Noise	Life Extension	Moisture Reduction
Bituminous-Surfaced Pavements					
Crack Sealing				X	✓
Fog Seals				X	✓
Scrub Seals				✓	✓
Slurry Seals	✓	✓	✓	✓	X
Microsurfacing	✓	✓	✓	✓	X
Chip Seals	✓	✓		✓	X
Ultrathin Friction Course	✓	✓	✓	✓	✓
Thin Overlays	✓	✓	✓	✓	✓
PCC Pavements					
Joint and Crack Sealing				X	✓
Diamond Grinding	✓	✓	✓	✓	

✓ = Major effect
x = Minor effect

The actual timing of the treatments depends on the type and purpose of the treatment. More substantial maintenance treatments (such as thin overlays) would require greater timing cycles than a lesser treatment (such as a fog seal). Also, the timing cycles are influenced by other factors such as climate and quality of construction; some general guidelines are provided for various preventive maintenance treatments in Table D-3.

Site Layout

One of the most important aspects of the site layout is its length, it must be long enough to accommodate all the treatments under consideration, including control (do-nothing) and replicate sections. The site must be long enough to allow adding treatments to bare sections in subsequent years in order to address the timing issue. Specific items relevant to the site layout are described in the following subsections.

Project Length

The project must be long enough to accommodate all test sections. As a general rule, the required length of the project can be computed as follows:

$$TPL = \left[TSL \times ((N \times TC) + 1)\right] \times R \qquad \text{(Eq. D-1)}$$

where:

TPL = Total project length, m (or ft).
TSL = Total section length, m (or ft) (457 m [1,500 ft] recommended).

N = Number of treatments to be evaluated.
TC = Number of timing cycles per treatment.
R = Number of sections incorporating each treatment.

For example, if four treatments are to be evaluated at three timing cycles (3, 6, and 9 years), and there are to be two sections per treatment (1 set of replicates), then the required project length is $[457 \times ((4 \times 3) + 1)] \times 2$, or 11,882 m (38,980 ft). Some additional length may be needed for transitions between sections or to exclude certain areas (such as intersections or bridges) within a project.

It can be seen from the example that a test site can become quite long rather quickly, so it is important that agencies carefully select the number of treatments to evaluate. Of course, the replicate treatments could be placed in the opposing direction which would help shorten the required project length (but potentially add a confounding factor because of different traffic levels).

Section Length

Each individual test section should be long enough not only to facilitate construction but also to provide a statistically valid sampling of performance. With many of the treatments using equipment that requires some start-up calibration, shorter sections could have areas at their beginning and/or end that are not uniform in performance. At the same time, the section should be short enough to help contain the physical size and costs of the experiment. A minimum section length of 457 m (1,500 ft) appears to be reasonable, although longer sections may be warranted in some instances. However, the evaluation length does not need to be as long as the section length; a section evaluation length of 150 m (500 ft) is appropriate.

Replicate Sections

The use of replicate sections as part of the design is strongly recommended. Replicates are identical sections that are constructed to improve the statistical validity of the analysis and also to create "back-ups" if the original sections are taken out of service. On the other hand, while more replication improves the reliability of the results it also increases the cost of constructing, monitoring, and analyzing the results. Although several replicates makes it easier to break out anomalous behavior and improve the statistical validity of the results, only one set of replicates is recommended (that is, a total of two sections for each treatment/timing combination) to reduce cost.

It is also recommended that replicate sections be constructed on the same roadway, end to end in the same lane, if possible, but placed randomly within the project. If site constraints do not allow this layout, the replicates can be built in the opposing traffic lanes and placed randomly within the project. For multi-lane roadways, replicates can either be con-

TABLE D-3 Suggested treatment timing cycles

	Treatment	Recommended Year of Initial Treatment	Treatment Timing Cycle
Bituminous-surfaced	Crack Sealing	1 to 3	Annually
	Fog Seals	0 to 3	Annually
	Scrub Seals	2 to 6	Annually
	Slurry Seals	2 to 6	Annually
	Microsurfacing	3 to 7	2 years
	Chip Seals	2 to 5	Annually to 2 years
	Ultrathin Friction Course	2 to 6	2 years
	Thin Overlays	5 to 8	2 years
PCC-surfaced	Joint and Crack Sealing[1]	4 to 10[2]	2 years
	Diamond Grinding	5 to 10	3 years

[1] Refers to joint resealing and crack sealing. It is assumed that if optimal timing of joint resealing is being evaluated, any cracks will be kept sealed.
[2] Timing is somewhat dependent on the occurrence of cracking and/or the need for resealing the joints.

structed at the end of the project or in the opposing lanes. For example, if chip seals, slurry seals, and thin overlays are constructed as three separate sections in the northbound lanes of a roadway, replicate sections of the same three treatment types can be constructed in the southbound lanes of the same roadway. While it is possible to apply a treatment to both lanes in one direction of a multi-lane facility and use the second lane as a replicate, the different traffic level in the replicate lane will introduce a confounding factor in the analysis.

Factorial Design

Factorial designs are typically developed for such experiments. These designs are often presented in a tabular form to show what is being evaluated in the experiment in an easy-to-understand manner. A hypothetical example of a factorial design for a project that has been designed to last "n" years is shown in Table D-4. Factorial design tables are an effective way for agencies to lay out their experiment and quickly get an indication of how sizeable it can become.

Layout

The order and layout of the test sections over the length of a project should be done as randomly as possible. However, given that different treatments will be constructed at different times, it is logical to construct all the treatments for a given timing cycle at one end of the project, and then proceed from that point for future construction of treatments at subsequent timings. An example layout of test sections on a multi-lane facility is shown in Figure D-1. For a two-lane facility, test sections will have to be placed end-to-end.

Duration of Experiment

The required period of time for monitoring treatments varies depending on the type of treatments. Less substantial preventive maintenance treatments (such as fog seals or crack sealing) will require shorter evaluation periods then those required for treatments such as microsurfacings or thin overlays. For most bituminous-surfaced sections, the monitoring period is expected to range between 6 and 15 years.

The duration of the experiment can be shortened, however, based on regular analysis of the test results. For example, new treatments do not need to be applied and maybe performance does not need to be further monitored if it is clear that the performance trend is declining.

CONSTRUCTION

The most important construction concern is ensuring that test sections are properly constructed. This is best accomplished by following best practice, project specifications, and the material supplier's recommendations. While this might seem like unnecessary guidance, there are any number of research efforts that have been compromised by construction problems. The following subsections describe specific areas where attention is needed to minimize or eliminate construction problems.

Time of Year

Several of the bituminous-surfaced pavement treatments are affected by ambient conditions at the time of placement. In particular, the cold-applied thin surfacings do not perform well when placed at low air or pavement temperatures, and chip seals should never be placed on wet pavement when rainfall is expected. Also, joint and crack sealants cannot be placed on damp surfaces. While in practice, preventive maintenance treatments are not always placed during optimal environmental conditions, it makes sense to try to construct the test sections under favorable conditions. This is likely to mean a time of the year when daytime temperatures are 16 °C (60 °F) and rising, freezing is not expected within 24 hours, and rainfall can be avoided. Crack sealants and joint resealing materials are usually placed on a dry pavement when temperatures are moderate, such as during late spring or late fall.

Quality Control/Quality Assurance

The placement of a preventive maintenance treatment should not be approached any differently than other construction undertaken by the agency. However, every effort should be made to ensure that treatments are properly constructed,

TABLE D-4 Example factorial design table

	Timing of Application							
	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	...	Year n
Crack Sealing		2 sections	2 sections	2 sections	2 sections	2 sections	2 sections	2 sections
Chip Seal				2 sections		2 sections		2 sections
Fog Seal	2 sections	2 sections	2 sections	2 sections	2 sections	2 sections	2 sections	2 sections
No Treatment (Control)	2 sections							

Two-Lane Roadways

	Section 1	Section 2	Section 3	Section 4	Section 5	Section 6	Section 7
← WB	Treatment B Timing X	Control	Treatment C Timing X	Treatment A Timing X	Treatment C Timing Y	Treatment A Timing Y	Treatment B Timing Y
EB →	Treatment C Timing Y	Section	Treatment A Timing Y	Treatment B Timing Y	Treatment B Timing X	Treatment C Timing X	Treatment A Timing X

← Min 457 m →

← Total Project Length Depending on Number of Treatment/Timing Combinations →

Four-Lane Roadways

	Section 14	Section 13	Section 12	Section 11	Section 10	Section 9	Section 8
← WB	Treatment A	Treatment C	Treatment B	Control	Treatment A	Treatment B	Treatment C
← WB	Timing X	Timing X	Timing X	Section	Timing Y	Timing Y	Timing Y

	Section 1	Section 2	Section 3	Section 4	Section 5	Section 6	Section 7
EB →	Treatment B	Control	Treatment C	Treatment A	Treatment C	Treatment A	Treatment B
EB →	Timing X	Section	Timing X	Timing X	Timing Y	Timing Y	Timing Y

← Min 457 m →

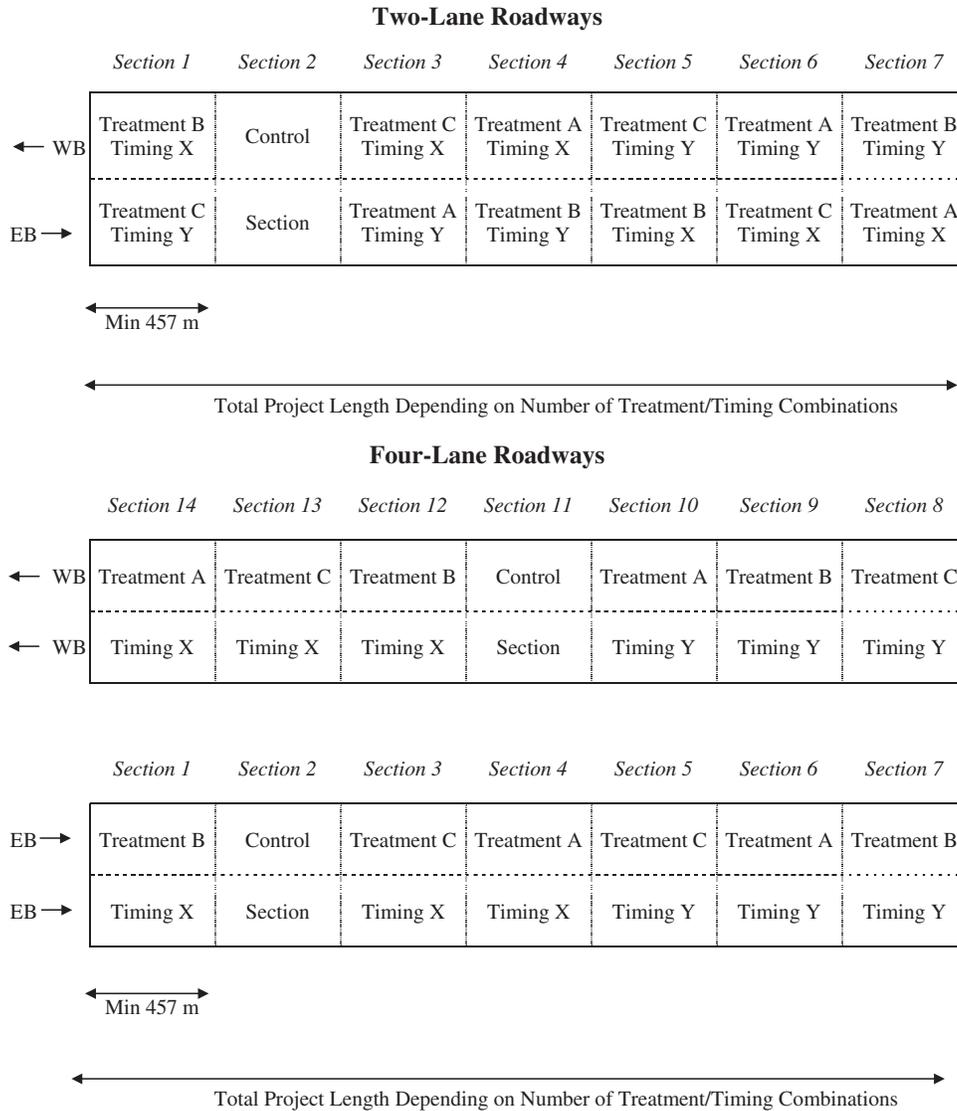← Total Project Length Depending on Number of Treatment/Timing Combinations →

Figure D-1.   Example test section layouts for 2-lane and 4-lane roadways.

and that subsequent performance is related to the treatment's capabilities and not to construction defects.

It is recommended that the construction of all preventive maintenance treatments follow the agency's standard specifications. In the absence of a standard specification, such as when an experimental material is being evaluated, the supplier's or contractor's specifications should be followed.

The agency should provide inspection services during construction to monitor the placement of the test sections. The inspector should be familiar with the project specifications and note the aspects of the project that affect performance, including the following:

- Surface preparation
  - Defects
  - Overall surface condition
  - Treatments
  - Cleanliness
- Materials
  - Constituents
  - Mix design
  - Properties
- Environmental conditions
  - Temperature
  - Humidity
  - Rainfall
- Equipment calibration and performance
- Treatment application rates

A standard form may be adapted to local conditions and used to record the results of the construction inspection. While the specifications may be fairly detailed, most preventive

maintenance treatments are not complex, and required plans can typically be covered in a single 8½ × 11 sheet of paper.

Contractor Versus Agency Forces

Some treatments are applied solely by specialty contractors and equipment (such as microsurfacing, diamond grinding, and ultrathin surface treatments), while others may be applied by agency forces or contractors (e.g., fog seals and chip seals). There is no compelling reason to use contractors; perhaps the best practice to follow is to apply the treatments in the same manner that the agency would normally follow.

Voiding Sections

Sections that are improperly placed should be voided and removed from the experiment (i.e., not be further monitored). Signs of improper placement include failure of the treatment to "stick," improper application rates, placement outside of the recommended environmental conditions (temperature and moisture, for example), and failures within the first year.

Section Marking

It is extremely important to be able to locate the various pavement sections for many years after construction in order to (1) place the treatments in the right locations in subsequent years and (2) perform the necessary performance evaluations. The use of permanent markers, such as surveying nails driven into the pavement, is preferred over paint, which can wear off over time and under traffic. Often test sections are marked and remarked on the shoulder, but this may not be possible with certain surface treated or granular shoulders. If the shoulders cannot be permanently marked with the test section limits, delineators should be placed adjacent to section limits at a safe distance to the side of the pavement.

A map to the experimental section should also be developed. The map should show the locations of permanent landmarks (e.g. culverts, intersections, etc.) and offsets to the various test sections. The map should be updated whenever new sections are constructed.

MONITORING ACTIVITIES

Regular monitoring of the experimental pavement sections is needed to assess the effects of the treatment and timing combinations. There are a wide variety of monitoring activities that can be carried out; data collection efforts should focus on collecting information that will facilitate the evaluation of the treatment objectives (see Table D-1). The types of information that could be monitored are described in the following subsections.

Manual Condition Surveys

It is recommended that manual condition surveys be conducted on all experimental sections within a project on at least an annual basis. This can be done using an agency's distress manual or any similar manual that provides uniform definitions of distress type and severity (such as the LTPP distress manual). Recommended distress types that should be collected are listed in Table D-5, but highway agencies may include additional distresses as appropriate. A 150-m (500-ft) segment located within the central part of each section and away from the transition areas at either end should be selected as the monitoring sample unit.

Roughness

Roughness should be measured on all experimental sections within a project on an annual basis. The use of profiling equipment is recommended, and the results should be expressed in terms of an International Roughness Index (IRI). ASTM E1926, Standard Practice for Computing International Roughness Index of Roads from Longitudinal Profile Measurements, and AASHTO PP 37-00, Standard Practice for Quantifying Roughness of Pavements, provide details on these measurements.

Surface Friction

If improving surface friction is a goal of placing the preventive maintenance treatments, then surface friction should be monitored on an annual basis. Surface friction is generally measured using a locked-wheel skid trailer with either a ribbed or smooth tire; however, the smooth tire correlates better with surface texture and wet-weather accidents. The output of the surface friction is expressed as either a skid number (SN) or in terms of the International Friction Index (IFI). Applicable specifications include ASTM E1960 and ASTM E274.

TABLE D-5 Recommended distress types to be collected

HMA and Bituminous Pavements	PCC Pavements
Block Cracking	Corner Breaks
Fatigue Cracking	Linear Cracking
Linear Cracking	Joint Seal Damage
Rutting	Joint Spalling
Bleeding	Joint Faulting
Raveling	Pumping
Weathering (Oxidation)	Blowups
Polished Aggregate	Patching
Potholes	
Patching	

Surface Texture

Closely related to surface friction is surface texture, which refers to the variations in a pavement surface that contribute to wet-weather friction, tire-pavement noise, splash and spray, rolling resistance, and tire wear. If determined to be appropriate for a project, it is recommended that surface texture be measured on an annual basis using either the sand patch test or an outflow meter; alternatively, the use of high-speed, laser-based profiling devices could be used if available. The preferred method of reporting surface texture is the mean texture depth (MTD); if automated equipment is used the output is an estimate of MTD, which is also acceptable. ASTM E965 is the relevant specification.

Noise

Noise produced by the tire-pavement interaction of vehicles may be a concern in urban areas. If controlling noise levels is one of the goals of an agency's preventive maintenance treatments, it should be monitored for consideration in the analysis.

Photo and Video Documentation

As a final part of the data collection activities, it is recommended that each test section be photographed and perhaps videotaped during each annual inspection to provide a permanent record of the treatment condition over time.

These items are perceived to be the primary performance indicators to be collected for the experimental pavement sections. There may be additional indicators that highway agencies may wish to include for specific treatments or to ensure compatibility with other performance monitoring that they may be conducting.

Treating Failure

Eventually, the test sections will fail. If all goes well, failure will occur at the end of the life of the treatment. However, as part of the design, the agency must be prepared to address sections that fail either due to a construction problem or due to failure of the pavement. The following guidance may be used to formulate a response to various failures. It is based on the premise that it is treatment timing that is being investigated in this experiment and not treatment performance. Therefore, certain treatment failures may be repaired to allow the section to stay in service.

- Alligator cracking or other localized structural failures—Fix pavement failures and continue to monitor the treatment if possible.

- Bleeding—If localized, the section can continue to be monitored. If widespread, remove the section from the experiment.
- Rutting—It is unlikely that rutting is related to the performance of a preventive maintenance treatment; the cause and extent of rutting should be evaluated. Rutting that is prevalent throughout the project indicates that the section may not have been a good candidate for preventive maintenance, but rutting that is isolated to different sections may indicate a performance difference. As sections fail due to rutting they should be removed from the experiment, but localized areas may be left in service.
- Raveling/Delamination—The cause of these distresses should be further investigated. If they occur in localized areas, then it may be possible to keep the section in service. Thin bituminous surfacings may be repaired if the problem is localized and repaired soon after it occurs. If the problem is widespread or it is likely that the treatment has failed, the section should be taken out of the experiment.
- Faulting/Pumping—These are likely signs that the pavement was not a good candidate for a preventive maintenance experiment; the cause and extent of faulting or pumping should be evaluated. Faulting and rutting that are prevalent throughout the project indicate that the section was probably not a good candidate for preventive maintenance, but faulting and rutting that are isolated to different sections may indicate a performance difference. As sections fail due to faulting or pumping they should be removed from the experiment, but localized areas may be left in service.
- Spalling—This should be further investigated to determine whether the spalling is due to a materials/construction problem or to failure of the sealant system.
- Joint or Crack Sealant Failure—If the sealant can be fixed shortly after failure, it should be fixed and the section monitoring continued. If the sealant has failed and cannot be repaired rapidly, the section should be taken out of the experiment.

Ongoing Maintenance

Once all treatments are constructed and the pavement is opened to traffic, the issue of what maintenance is allowed needs to be addressed; the agency's approach should be determined ahead of time. It is recommended that the agency maintain the serviceability of the experimental section by maintaining the project with the same level of crack sealing and patching that would normally apply to the pavement.

DATA ANALYSIS

After sufficient performance monitoring data is collected, the optimal timing of a given preventive maintenance treat-

ment can be estimated using the spreadsheet-based analysis tool. The analysis tool allows the calculation of the optimal time to apply a specific treatment by analyzing different treatment application ages (timing scenarios) through the computation of a benefit-cost (B/C) ratio associated with each selected timing scenario. The timing scenario with the largest computed B/C ratio identifies the optimal timing of those application ages investigated.

The primary reason for implementing a plan is to collect performance data that can be used to compute benefit values associated with different timing scenarios for a specific preventive maintenance treatment. Benefit is defined as any observed influence (mostly positive, but it could also be negative) on any one or more condition indicators resulting from the application of a preventive maintenance treatment. Using this definition, there could be many different types of benefit associated with a given application of the treatment (e.g., applying a chip seal could result in benefits in the form of improved friction, retarded oxidation, or reduced rutting).

Benefit for a given condition indicator is determined by comparing the area associated with the condition indicator curve without the application of preventive maintenance (i.e., the do-nothing curve) with the area associated with the condition indicator curve that is altered by the application of the preventive maintenance treatment. For condition indicators that decrease over time (e.g., serviceability, friction, or a typical composite index), it is the area under the curve that defines benefit. For condition indicators that increase over time (e.g., roughness, cracking, rutting, faulting, and spalling), it is the area above the curve that defines benefit. Figure D-2 illustrates the resulting benefit area (AREA$_{BENEFIT}$) for a chosen condition indicator (e.g., serviceability [roughness]) when a treatment is applied at a pavement age of 12 years.

The treatment performance data collected as part of the plan is directly used to define these post-preventive maintenance relationships associated with each unique combination of condition indicator and treatment application timing.

Database Development

To effectively use the provided analysis tool, it is recommended that a database be built to store the performance and cost data that will be collected as part of the plan. The primary data types required by the analysis tool are the following:

- **Do-nothing expected condition indicator (performance)**—Before the influence of a preventive maintenance application can be analyzed, the analysis requires a baseline performance curve (or curves). The baseline performance curve of interest for a particular condition indicator is that performance curve (condition indicator versus time) that the agency would expect if only routine maintenance were conducted on the pavement (such curves are referred to as do-nothing performance curves). The current methodology requires that the user define a do-nothing performance curve for each of the condition indicators that are included in the analysis. The best source for this information is existing pavement management systems, although users without access to such curves can easily be walked through a process of approximation. Within the analysis tool, each do-nothing performance relationship may be defined as (1) a known equation (i.e., defined by an equation type and associated coefficients) or (2) a series of performance versus age points through which a regression equation is fit.
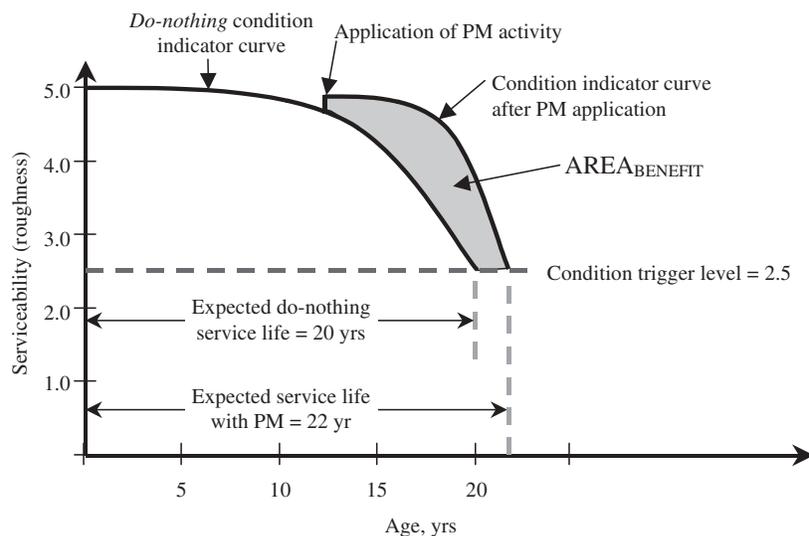

Figure D-2.   Illustration of benefit associated with the application of a preventive maintenance treatment.

- **Treatment performance relationships**—In order to compute the benefit associated with a given performance indicator, the performance monitoring data collected under the plan is used to define the pavement's performance after a preventive maintenance treatment is applied. These relationships are used to compute the benefit associated with each unique combination of condition indicator and application age. As with the do-nothing curves, each post-preventive maintenance relationship may be defined by either defining a known equation or by entering a series of performance versus age data.
- **Treatment cost data**—As part of implementing the plan, detailed cost-related records should be kept during treatment construction to document the treatment-related costs incurred by the agency.

Refining Data for Analysis

Upon collecting and organizing all relative performance and cost data, the user must refine the data to facilitate use in the analysis tool. The goal is to get one performance-versus-time relationship for each unique combination of condition indicator and treatment application timing. Therefore, data from replicate experimental sections must be combined into one representative performance relationship. This may be accomplished by using engineering judgment or mathematical techniques such as averaging expected condition values at each treatment age. Replicate cost data should be analyzed using similar methods. While statistical analyses such as *t*-tests are most appropriate for analyzing whether replicate data are representative of the mean values, it is unlikely that there will be enough replicates to apply such tests.

Conducting the Analysis

In addition to defining the many performance relationships (do-nothing and treatment-related) required by the analysis tool, many other project specific data elements must also be defined prior to conducting the analysis. The following are the primary steps involved in the analysis:

- Condition indicator selection—Specification of one or more condition indicators used to define pavement performance.
- Preventive maintenance treatment selection—Selection of one preventive maintenance treatment to be analyzed.
- Selection of treatment application ages—Definition of more than one treatment application age that will be compared in the analysis (the analysis will identify the most cost-effective application age from among those ages included in the analysis).
- Definition of do-nothing performance curves—Do-nothing condition indicator relationships are entered (as defined equations or as data for regression analysis) to define the baseline pavement performance without preventive maintenance.
- Definition of post-preventive maintenance performance curves—Performance data/relationships collected as part of the plan are entered directly into the analysis tool.
- Definition of costs—Inclusion of one of three costs types: (1) treatment construction costs, (2) work zone-related user delay costs, and (3) rehabilitation costs (applied at the end of a pavement's expected service life).
- Benefit ranking factors—If multiple condition indicators are selected, an individual benefit is calculated for each and ranking factors are assigned as a means for differentially weighting the individual benefits associated with the different condition indicators.

The analysis will provide detailed information associated with each application age. For each considered application age, the output data include a detailed benefit summary (both individual benefit values as well as a total combined benefit), a detailed cost summary, the computed B/C ratio, and the computed Effectiveness Index (EI). The timing scenario with the largest computed B/C ratio (i.e., EI = 100) is the most cost-effective application age.

SUMMARY

The recommended plan describes an approach to help highway agencies collect the necessary data for determining the optimal time to apply preventive maintenance treatments. Successful implementation of this plan requires identification of the objectives of the preventive maintenance program and then selection of treatments and monitoring methods that match these objectives.

Recommendations are provided for site selection, site layout, construction, and monitoring. The approach for analyzing the collected data is described in this report; analysis can be facilitated through the use of OPTime, the software tool developed in this project. It should be emphasized that this plan is intended to identify the optimal time to perform a specific preventive maintenance treatment, not to identify the best preventive maintenance treatment.