JOINT TRANSPORTATION
RESEARCH PROGRAM
INDIANA DEPARTMENT OF TRANSPORTATION
AND PURDUE UNIVERSITY

Strategic Scheduling of Infrastructure Repair and Maintenance

Volume 3

Developing Condition-Based Triggers for Pavement Maintenance, Rehabilitation, and Replacement Treatments

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SPR-3827 • Report Number: FHWA/IN/JTRP-2017/14 • DOI: 10.5703/1288284316513

RECOMMENDED CITATION

Qiao, Y., Fricker, J. D., Labi, S., & Sinha, K. C. (2017). *Strategic scheduling of infrastructure repair and maintenance: Volume 3—Developing condition-based triggers for pavement maintenance, rehabilitation, and replacement treatments* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2017/14). West Lafayette, IN: Purdue University. https://doi.org/10.5703/1288284316513

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JOINT TRANSPORTATION RESEARCH PROGRAM

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Published reports of the Joint Transportation Research Program are available at http://docs.lib.purdue.edu/jtrp/.

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Print ISBN: 978-1-62260-487-6

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.
FHWA/IN/JTRP-2017/14

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
Strategic Scheduling of Infrastructure Repair and Maintenance: Volume 3—Developing Condition-Based Triggers for Pavement Maintenance, Rehabilitation, and Replacement

5. Report Date
July 2017

6. Performing Organization Code

7. Author(s)
Yu Qiao, Jon D. Fricker, Samuel Labi, Kumares C. Sinha

8. Performing Organization Report No.
FHWA/IN/JTRP-2017/14

9. Performing Organization Name and Address
Joint Transportation Research Program
Purdue University
550 Stadium Mall Drive
West Lafayette, IN 47907-2051

10. Work Unit No.

11. Contract or Grant No.
SPR-3827

12. Sponsoring Agency Name and Address
Indiana Department of Transportation
State Office Building
100 North Senate Avenue
Indianapolis, IN 46204

13. Type of Report and Period Covered
Final Report

14. Sponsoring Agency Code

15. Supplementary Notes
Prepared in cooperation with the Indiana Department of Transportation and Federal Highway Administration.

16. Abstract

Even for the right treatment, improper timing can have consequences: premature application (treatment is applied too early) could mean wasteful spending even if users enjoy the benefits of higher pavement condition; deferred or delayed application (treatment is applied too late) could result in higher user costs due to poor condition and even reduced asset longevity.

The objectives of this research were to establish the optimal condition or timing for each of the standard M&R treatment types typically used by INDOT; quantify the consequences of departures from such optimal conditions or timings; and to establish the optimal M&R treatment schedule for each asset family. The study focused on three asset types and their treatments:

1. Painting of Steel Bridges. A painting decision tree was developed, to serve as a framework that would enable INDOT to consider other maintenance treatment types, namely spot repair/painting and overcoating.
2. Bridge Deck Maintenance and Rehabilitation. Life-cycle condition-based deck M&R strategies based on different trigger results were proposed and presented.
3. Pavement Maintenance, Rehabilitation, and Replacement. A framework was established to find the optimal scheduling for multiple treatments and recommend appropriate long-term M&R strategies for flexible and rigid pavements on different functional classes.

17. Key Words
asset management, bridges, pavement, steel bridge painting, life-cycle cost

18. Distribution Statement
No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161.

19. Security Classif. (of this report)
Unclassified

20. Security Classif. (of this page)
Unclassified

21. No. of Pages
68

22. Price

Form DOT F 1700.7 (8-69)

EXECUTIVE SUMMARY

STRATEGIC SCHEDULING OF INFRASTRUCTURE REPAIR AND MAINTENANCE: VOLUME 3—DEVELOPING CONDITION-BASED TRIGGERS FOR PAVEMENT MAINTENANCE, REHABILITATION, AND REPLACEMENT TREATMENTS

Introduction

INDOT seeks to apply appropriate treatments for its bridge and pavement assets at the right time. Even for the right treatment, improper timing can have consequences: premature application (treatment is applied too early) could mean wasteful spending even if users enjoy the benefits of higher asset condition; deferred or delayed application (treatment is applied too late) could result in higher user costs due to poor condition, and even reduced asset longevity.

The objectives of this research were to establish the optimal condition or timing for each of the standard maintenance and rehabilitation (M&R) treatment types typically used by INDOT; quantify the consequences of departures from such optimal conditions or timings; and establish the optimal M&R treatment schedule for each asset family. The study focused on:

1. Painting of steel bridges
2. Bridge deck maintenance and rehabilitation
3. Pavement maintenance, rehabilitation, and replacement

Findings

1. The study established a cost-effective way of timing the painting of steel highway bridges.

    a. Deterioration models were developed for painted steel superstructures of highway bridges on routes of various functional classes.
    b. A painting cost model was developed using INDOT's painting contract records. Scenario analyses were conducted by varying the relative weights of agency and user costs.
    c. A painting decision tree was developed to serve as a framework that would enable INDOT to consider other paint maintenance treatment types—namely, spot repair/painting and overcoating. Based on the results, it would be appropriate for INDOT to continue applying complete recoating at trigger value 4, or to include spot repair and overcoating for its highway bridge steel superstructures.

2. The study established appropriate performance thresholds for triggering bridge deck M&R activities.

    a. Statistical models were developed to describe bridge deck and wearing surface deterioration, and performance jump (condition improvement) due to deck overlays. The agency cost models for latex-modified concrete (LMC) and polymeric overlays took into account the pre-treatment deck condition and the impact of scale economies. Two types of bridge user costs were considered: travel time costs due to work zone delays and the incremental vehicle operating costs (VOCs) during normal operations due to the increased roughness of the bridge deck surface.
    b. A life-cycle cost analysis optimization framework was proposed. The analysis used data for bridges on the state-owned routes in Indiana. Various weights were assigned to the agency and user costs for sensitivity analysis purposes. The results indicated that different weighting would have an impact on the optimal trigger or the threshold associated with the lowest equivalent uniform annual cost. In addition, the life-cycle condition-based deck M&R strategies based on different triggers were presented.
    c. Some modifications are recommended to be made to the original decision tree (DTREE) used in the Indiana Bridge Management System (IBMS) in order to incorporate the triggers for specific deck overlay treatments in the DTREE flow paths.

3. The study established a framework for determining the appropriate (condition-based) performance triggers for pavement maintenance, rehabilitation, and replacement activities.

    a. Fourteen types of treatments were considered. Statistical models were developed in terms of performance jump due to each maintenance and rehabilitation (M&R) treatment. Models were also developed for post-treatment performance, agency costs, and user costs.
    b. An optimization approach was proposed to determine the optimal International Roughness Index (IRI) trigger for each type of treatment on different families of assets that maximize the cost-effectiveness. The life-cycle cost analysis incorporates both agency cost (AC) and user cost (UC). Sensitivity analysis indicates that changing the relative weights of agency and user costs has a significant impact on the optimal trigger. The results of sensitivity analysis in terms of other important variables (e.g., AC:UC ratio, traffic load, discount rate, IRI upper bound, and pre-treatment performance) are also provided. The results show how the change in these factors can influence the optimal condition trigger results. This provides asset managers with greater flexibility in making M&R decisions.
    c. The study established a framework to determine the optimal schedules for multiple treatments and recommended appropriate long-term M&R strategies for flexible and rigid pavements on different road functional classes.

Implementation

The methodologies used in this study can help INDOT and other agencies enhance their M&R decisions in terms of the performance threshold of individual assets, as well as long-term M&R scheduling. The findings for each of the three parts of this study provide INDOT asset managers with an enhanced basis for making programming decisions and estimating the consequences of premature or delayed treatments. Possible limitations are:

1. The optimal triggers for pavements are given for surface roughness (IRI). Other important performance indicators such as rutting and cracking are not considered in this study due to the lack of data availability.
2. The lack of quality data limited this study to finding only general relationships between the variables. As more accurate and reliable data become available, the models can be refined, creating a stronger basis for optimal triggers and long-term M&R strategies.

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1. INTRODUCTION

1.1 Background and Problem Statement

In the US, as in many countries, highway infrastructure is among the most valuable of taxpayer-owned assets (Dojutrek, Volovski, & Labi, 2014). Such infrastructure plays an essential role in economic growth. In order to meet continuously increasing travel demands and user expectations regarding overall system levels of service (travel time, ride quality, road safety, and so on), highway agencies are seeking more rational preservation strategies for their highway assets.

Among the various highway asset improvement activities, pavement rehabilitation and maintenance are associated with the highest spending levels. Federal regulations have continually stressed the importance of keeping pavement assets in good condition through regular and timely rehabilitation and maintenance (FHWA, 1998). According to the 1991 Intermodal Surface Transportation Efficiency Act, 35% of federal highway funds were allocated to activities geared towards pavement improvement (FHWA, 1998). Over the years, pavement asset managers have been investing significantly into identifying and implementing cost-effective rehabilitation and maintenance strategies. There is therefore a great need for a reliable and comprehensive Pavement Management System (PMS), which can help pavement managers make rational decisions and invest money appropriately to preserve their infrastructure assets.

The PMS decision rules for pavement maintenance and rehabilitation are often based on the opinions of experts in the field of pavement rehabilitation, or derived from the practices and strategies that have been applied in the past. Decisions based on the opinions of pavement experts are inherently subjective, and those based on historical data are subject to inconsistency due to non-engineering judgments made by agencies on the maintenance and rehabilitation (M&R) activities in the past (Khurshid, Irfan, & Labi, 2010; Labi, 2014; Labi, Pasupathy, & Sinha, 2004; Lamptey, 2004; Pasupathy, Labi, & Sinha, 2007). Therefore, the current methods used by most agencies to establish asset M&R thresholds are subjective, are vulnerable to serious bias and subsequently lacking a systematic and logical basis, and are not always defensible.

A more scientific way to make maintenance and rehabilitation decisions is to carefully investigate the existing data, and find the most cost-effective solutions based on analytical methods through statistical modeling, optimization techniques, and simulation. As state and local highway agencies continue to grapple with ongoing and emerging challenges (including aging infrastructure, inadequate funding for reconstruction and preservation, increased demand and loading, and higher user expectations), the need for data-driven highway asset management is now more apparent than ever before.

In order to plan, program, and budget for long-term pavement preservation programs, pavement management and maintenance practitioners have expended great effort in seeking data-driven approaches to evaluate the cost-effectiveness of different rehabilitation and maintenance treatments. In the existing research studies, explicit optimization of pavement M&R over the life cycle continues to be an important technique for analyzing the cost-effectiveness of various treatments used to improve pavement condition and to help asset agencies determine optimal maintenance solutions.

During past years, in realization of the importance of managing pavement assets efficiently and effectively, the Indiana Department of Transportation (INDOT) has been undertaking numerous projects to monitor and predict pavement performance, evaluate the cost-effectiveness of pavement maintenance and rehabilitation, and develop strategies to better implement pavement M&R management systems. (Colucci-Rios & Sinha, 1985; Feighan, Sinha, & White, 1986; Fwa, Chan, & Hoque, 2000; Sinha & Fwa, 1989; Irfan, 2010; Khurshid, 2010; Lamptey et al., 2005; Mouaket et al., 1991; Sinha et al., 1989; Sinha, Labi, Rodriguez, Tine, & Dutta, 2005). The framework and analysis tools established by past studies also help INDOT better manage its pavement assets in the long-term (over a pavement life cycle) and at a network level. Although these have no doubt improved INDOT's capabilities to manage pavements, there are still some gaps in the existing research. Calibration and updates of current pavement performance models and cost models may be necessary, the number of different type pavement treatments considered and analyzed in past studies is limited, and finally, a systematic framework is needed to integrate these ideas and tools for better asset preservation.

1.2 Study Objectives

The primary objective of this research is to develop a methodology for determining the optimal condition-based timing for applying various M&R treatments to rigid and flexible pavements. This study seeks to develop a methodology flexible enough to apply to a variety of pavement treatments and families of assets. Another goal is to establish the appropriate long-term M&R treatments schedule for each pavement asset family over the pavement life cycle.

1.3 Scope of the Study

This study focuses on the cost-effectiveness of applying various pavement treatments under different conditions for different families of assets in the state of Indiana. The study identifies the optimal conditions resulting from the application of different types of individual treatments for each family of assets, obtains the optimal solution for M&R schedules given a sequence of treatments, and recommends long-term M&R strategies to the highway agency.

In this study, fourteen M&R treatments were considered for analysis as commonly used treatments in the state of Indiana. The treatments examined are:

- HMA preventative maintenance (PM) overlay,
- HMA minor structural overlay,
- HMA major structural overlay,

- PCCP cleaning and sealing joints,
- Crack sealing
- Diamond grinding
- Rubblize PCCP & HMA overlay,
- Repair PCCP & HMA overlay,
- Crack and seat composite pavement & HMA overlay,
- Rubblize composite & HMA overlay and
- Pavement replacement.

The pavement performance indicator used is the International Roughness Index (IRI). The framework established in this study is applicable to all pavement families (rigid, flexible, and composite) and to all three main functional classes of the state highway system (Interstates, National Highway Systems or NHS Non-Interstates, and Non–NHS).

With regard to the measures of treatment effectiveness, this study uses the non-monetized benefits (area bounded by the performance threshold line and the post-treatment performance curve). The cost categories considered are the agency costs and user costs. Agency costs are comprised of the initial construction costs and the rest-of-life costs of rehabilitation and maintenance. The user costs considered in the current study are the "incremental" vehicle operating costs (VOC) caused by increased wearing due to surface roughness and the extra user cost incurred because of travel time delay during work zones for pavement M&R treatments.

1.4 Study Organization

This chapter began with the study background and problem statement. A description of the study objectives and study scope followed, above. Chapter 2 presents a review of the state of the practice and the state

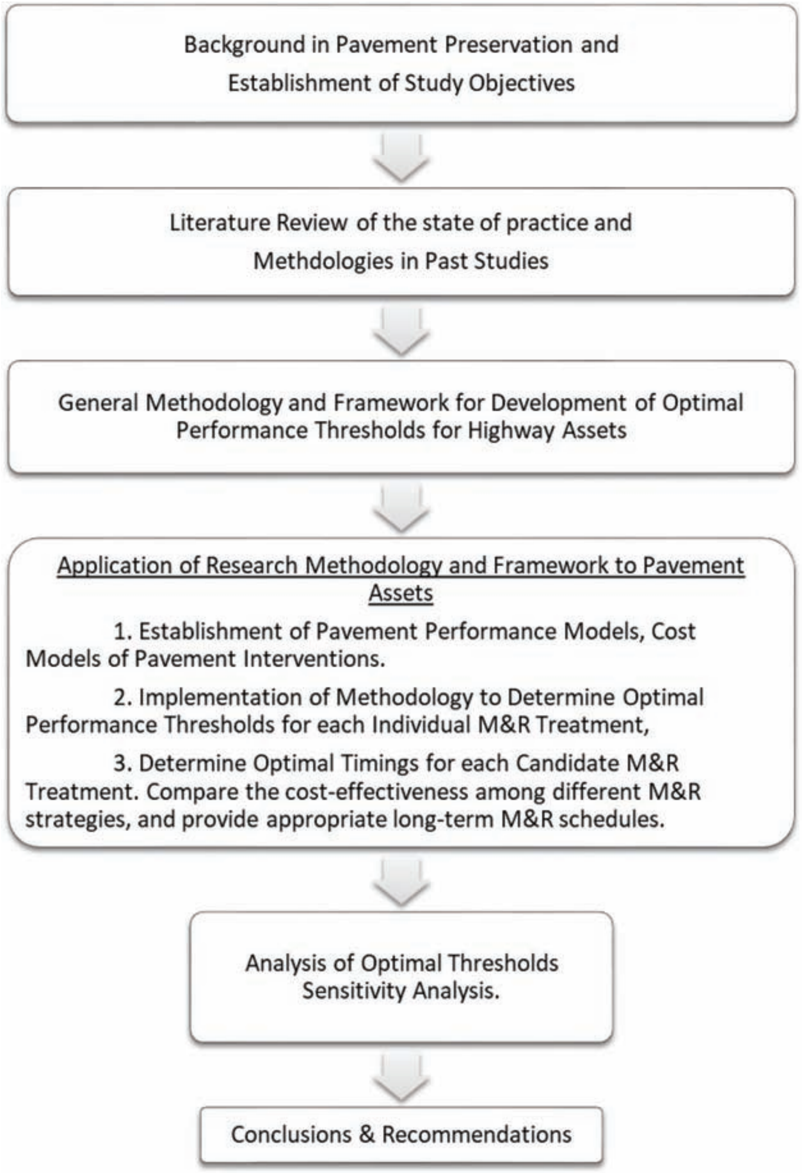


Figure 1.1 Overview of study approach.

of the art techniques and a summary of the literature on existing methodologies for performance modeling, establishing cost models, optimizing cost-benefit, and establishing optimal thresholds. Chapter 3 presents the methodology adopted in this study, including the pavement performance modeling technique, cost-effectiveness measurement, optimization theory, and the study analysis procedure. Chapter 4 presents the results of the developed performance models, jump models, and pavement cost models, followed by a case study based on these models, which were used to demonstrate the analysis procedures proposed in Chapter 3. Then the results of cost-effectiveness optimizations are presented, including the optimal condition for applying a single individual treatment and the optimal schedules for a given sequence of treatments. Sensitivity analysis is also provided to show the effect of various parameters, and the consequence of departure from optimal timings. In addition, the results of cost-benefit optimization for various treatments and different M&R schedules are compared, based on which appropriate long-term M&R schedules and strategies were recommended for each family of assets. Lastly, a summary of the study, a general discussion on the wider impacts of the study outcomes, and recommendations for future research are provided. Figure 1.1 shows the general framework of the study.

2. LITERATURE REVIEW

Extensive work associated with pavement maintenance and repair (M&R) scheduling subject to budgetary constraints has been carried out in past research. This chapter presents a review of practices for pavement preservation, and of past research on the identification and use of performance thresholds in pavement management using a variety of approaches and methods.

2.1 Pavement Performance Indicator

Pavement performance has been defined as “a function of the pavement’s ability to serve traffic over a period of time” (Highway Research Board, 1962). A performance indicator represents the extent (qualitatively or quantitatively) to which a specific function is carried out (Sinha & Labi, 2007). Generally, pavement performance can be categorized into surface roughness, surface distress, and structural condition according to the pavement attribute to be measured (Haas, Hudson, & Zaniewski, 1994).

2.1.1 Pavement Surface Roughness

Pavement surface roughness is a measure of the irregularities in the pavement surface that impair vehicle ride quality. Roughness is an important pavement characteristic because it affects the dynamics of the vehicle as it moves, facilitates wear and tear on the vehicle parts, and therefore has a significant impact on vehicle operating costs, travel speed, safety, and ride comfort. Rougher pavements lead to higher dynamic loadings (imposed by the moving vehicle) on the pavement surface which in turn, quickens pavement deterioration (Paterson & Chesher, 1986). Roughness is a primary criterion by which road users judge the quality of a pavement. This is one of the main reasons why it serves as a basis for pavement investment decision-making at several agencies. Roughness is usually reported using the International Roughness Index (IRI).

The IRI, developed by the World Bank in the 1980s (Sayers, 1995), is a standardized roughness measurement used to describe the longitudinal profile of a traveled wheel track and is a function of the ratio of the accumulated suspension motion (in mm, inches, etc.) and the distance traveled by a standard vehicle (km, mi, etc.) during the measurement (Pantha, 2010). The commonly used units of IRI are millimeters per meter (mm/m), meters per kilometer (m/km), or inches per mile (inch/mi) (Zhou, 2008). The open-ended IRI scale is shown in Figure 2.1.

The widespread use of IRI as a pavement performance indicator has increased over the years due to the potential uses of that indicator. IRI reflects pavement condition and ride quality and influences the operation costs of vehicles that use the highway pavement (Archondo-Callao & Faiz, 1994; Chesher & Harrison, 1987). It was also found that IRI is highly correlated

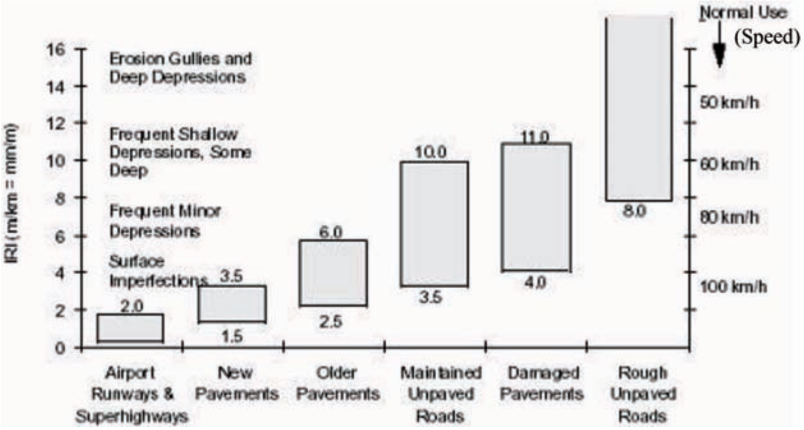


Figure 2.1 IRI roughness scale and interpretation (adapted from Sayers et al., 1986).

with Present Serviceability Rating (PSR) and the Present Serviceability Index (PSI) (Pantha, 2010).

2.1.2 Pavement Surface Distress

Surface distress can be defined as any kind of damage observed on the pavement surface. Distress modes can be categorized into three groups (Paterson & Chesher, 1986):

- *Fractures.* This category contains all types of cracking, and spalling caused by fatigue, excessive loading, and thermal changes.
- *Distortions.* This category contains all forms of deformation resulting from such things as rutting, corrugation, and shoving. For rigid pavements, the rut shape distortion is referred to as wheel path wear (WPW).
- *Disintegration.* This category contains raveling, stripping, and spalling caused by loss of bonding, traffic abrasion, chemical reactivity, aggregate degradation, poor consolidation/compaction or binder aging.

Surface distress is to some extent related to high levels of surface roughness (more distortion, cracks and disintegration will lead to pavement with rougher surface) and poor structural integrity.

Each of these modes of surface distress can constitute a performance indicator for evaluating pavement condition. For example, rutting is a very commonly used performance indicator, and is used to evaluate pavement condition in a significant number of studies (Hall, Correa, & Simpson, 2003; Irfan, Khurshid, & Labi, 2009; Labi, Lamptey, Konduri, & Sinha, 2005). However, given all these different types of distresses, it may not be accurate for rehabilitation decision-making to choose one type of distress for evaluating the overall pavement condition. It should be noted that each situation is different when it comes to pavement maintenance; different types of maintenance are appropriate for different levels of each type of distress (Paterson & Chesher, 1986).

Pavement Condition Rating (PCR) is another commonly used pavement performance indicator for surface distress, which identifies pavement distress in terms of extent and severity. The PCR evaluation scale ranges from 100 (very good condition) to 0 (very poor condition).

2.1.3 Structural Condition

Surface deflection is the most commonly used measure of flexible pavement structural integrity and rigid pavement load transfer, due to its relatively low cost, less severe traffic disruption, and less damage to the pavement during data collection, and data collection economy (Haas et al., 1994). It is measured as the vertical deflection of a pavement surface due to an either static or dynamic load. Surface deflection is an important method in evaluating pavement structure because the shape and magnitude of pavement deflection is a function of traffic, temperature and moisture that affect pavement structure (Pavement Interactive, 2010).

2.1.4 Combined Indicators of Overall Pavement Performance

Some highway agencies have established, for each individual distress type, a distress index such as the transverse crack index. Others have developed an index that collectively represents various combinations of distress types, extent and severity. Similar to PCR, the calculation of combined indices requires the establishment of weights or priority factors among the various distress types. The pavement is assigned a score that represents its overall condition based on measurements of roughness, skid resistance, surface distress, and deflection. This quantifies the pavement's overall performance and, in certain cases, may be used at the initial (scoping) phase of project development to identify the pavements that are most deserving of some M&R or to prioritize the pavement M&R projects.

The first combined pavement condition rating system, the Present Serviceability Rating (PSR), was based on the AASHO Road Test. Previous researchers including Paterson and Chesher (1986) and Al-Omari and Darter (1992) have developed a number of PSR-IRI correlation models, such as those shown in Equations 2.1 and 2.2 respectively:

$$PSR = 5e^{-9.18(IRI)} \tag{2.1}$$

$$SR = 5e^{-0.26(IRI)} \tag{2.2}$$

The Present Serviceability Index (PSI), which is based on data about the road's longitudinal roughness, patch work, rutting, and cracking, ranges from 5 (excellent condition) to 0 (failed). After rating the pavements in terms of PSR, physical measurements were made (on the same pavements) in terms of slope variance (SV), rut depth (RD), cracking (C), and patching (P). These physical measurements were then related to the PSI and the following relationships were developed for flexible rigid pavements (Equations 2.3 and 2.4, respectively):

$$PSI = 5.41 - 1.80\log(1 + SV) - 0.09(C + P)^{0.5} \tag{2.3}$$

$$PSI = 5.03 - 1.91\log(1 + SV) - 1.38RD^2 - 0.01(C + P)^{0.5} \tag{2.4}$$

where *PSI* is the Present Serviceability Index.

2.1.5 Condition Criteria

Based on the performance indicators described above, pavement condition can be categorized into discrete ordered classes, such as good condition, fair condition, and poor condition using a variety of standards. Among all the performance measurements, IRI, PSR, and PCR are the most commonly used indicators for condition criteria in the standards of state agencies. Tables 2.1 and 2.2 present the condition criteria used in FHWA (FHWA, 2002c, 2006). According to FHWA's criteria, pavements

TABLE 2.1
FHWA 2002 Pavement Condition Criteria (FHWA, 2002c)

	IRI Rating		PSR Rating	
Condition Term Categories	**Interstate**	**Other**	**Interstate**	**Other**
Very Good	<60	<60	>4.0	>4.0
Good	60 to 94	60 to 94	3.5 to 3.9	3.5 to 3.9
Fair	95 to 119	95 to 170	3.1 to 3.4	2.6 to 3.4
Mediocre	120 to 170	171 to 220	2.6 to 3.0	2.1 to 2.5
Poor	>170	>220	<2.5	<2.0

TABLE 2.2
FHWA 2006 Pavement Condition Criteria (FHWA, 2006)

	All Functional Classifications	
Ride Quality Terms	**IRI Rating**	**PSR Rating**
Good	<95	≥3.5
Acceptable	≤170	≥2.5
Not Acceptable	>170	<2.5

with an IRI less than 60 in/mi or PSR greater than 4.0 can be considered in very good condition. Also, pavements on Interstate roads with an IRI greater than 170 in/mi (or 220 in/mi for Non-Interstate roads) or with PSR lower than 2.5 (or 2.0 for Non-Interstate roads) are in poor/unacceptable condition. INDOT developed similar performance standards, as presented in Table 2.3, in terms of these two performance indicators: IRI and PCR (INDOT, 2001).

2.2 Typical Pavement Maintenance and Repair Types

A key element in pavement preservation programs is a set of pavement preservation strategies and guidelines. A reliable identification of pavements that are in need of maintenance and repair, specifications of the most appropriate treatment to be applied, and the right timing of the treatment can help prevent resources from being wasted. The typical pavement M&R treatments implemented in Indiana are summarized in Table 2.4. Irfan (2010) grouped pavements into three families of assets based on three types of pavements (flexible pavements, rigid pavements, and composite pavements), and divided treatments into three categories based on treatment type (preventive maintenance, rehabilitation, and new construction). The flexible and rigid pavement M&R treatments considered in the current study are classified into the three categories (Table 2.5).

2.3 Pavement Types and Asset Families

Pavement M&R decisions are influenced by a variety of internal factors associated with pavement (such as pavement type, pavement age) and external factors associated with traffic (such as functional class, traffic loading, truck traffic), environment (such as such as temperature, precipitation, freeze-thaw cycle, and freeze-index) and the agency's budget. The grouping of pavement assets into different families is critical in making M&R decisions; that way, variations in the efficacy of treatments across different pavements is minimized (Irfan, 2010).

In a number of previous studies, pavement families were classified into different groups based on functional class (Interstates, National Highway System (NHS)-Non-Interstates, and Non-NHS) and pavement type (flexible, composite, and rigid) (Irfan, 2010; Labi & Sinha, 2005; Lamptey, 2004) as shown in Figure 2.2. The Arizona Department of Transportation (ADOT) also uses a family-based approach in developing pavement deterioration models, wherein pavements with similar characteristics are grouped into one category. Factors considered in the development of these family classifications include: last rehabilitation activity, pavement type, environmental conditions, traffic, subgrade conditions, and structural thickness (Li, Cheetham, Zaghloul, Helali, & Bekheet, 2006). In the current study, the pavements are classified based on functional class and type of pavement; the classification of pavement families and the corresponding number of miles for each family are presented in Table 2.6.

2.4 M&R Scheduling for Pavement Treatments

In an effective pavement preservation program, one of the most critical elements is a specification of treatment timing in terms of pre-defined time intervals (time-based scheduling) or performance thresholds (condition-based scheduling). We discuss each of these further in Sections 2.4.1 and 2.4.2.

2.4.1 Condition-Based Scheduling: The State of Practice

Cash-strapped highway agencies generally tend to carry out their pavement interventions based on age-based or time-based approaches, as previous studies found (Geoffroy, 1996; Hicks, Seeds, & Peshkin, 2000; Lamptey, 2004; Peshkin, Hoerner, & Zimmerman, 2004; Zimmerman & Peshkin, 2003). This is because the condition-based approach requires frequent and continuous inspection and monitoring of pavement condition and thus involves a high level of resources and expense. In the time-based M&R scheduling, the thresholds are either "age-based" (the treatment is applied at certain age) or based on the preset intervention interval (the treatment is applied at every time interval) which can be constant or variable. In certain cases, it is based on accumulated

TABLE 2.3
INDOT Pavement Performance Standards

Distress Indicator	Performance Indicator Value (INDOT Standards) (m/km)	(in/mi)	Performance
International Roughness Index (IRI)	<1.6	<100	Excellent
	1.6–2.37	100–150	Good
	2.37–3.15	150–200	Fair
	>3.15	>200	Poor
Pavement Condition Rating (PCR)	>90		Excellent
	90–80		Good
	80–70		Fair
	<70		Poor

TABLE 2.4
Treatments Based on INDOT Treatment Guidelines for Pavement Preservation (Lee, 2010)

Asphalt (Flexible) or Composite Pavement	Portland Cement Concrete Pavement (PCCP)
Crack Sealing/Routing and Filling	Crack Sealing/Filling
Fog Seal	PCCP Joint Resealing
Scrub Seal (Sand Seal)	Retrofit Load Transfer
Seal Coat (Chip Seal)	Cross-stitching
Flush Seal	PCCP Profiling (Diamond Grinding) Partial Depth
Microsurfacing	Patching Full-depth
Profile Milling	Patching Undersealing
Thin Hot Mix Asphalt Overlay with Profile Milling (HMA Overlay)	
Ultra-thin Bonded Wearing Course (UBWC)	
Thin Hot Mix Asphalt Mill/Fill (Thin HMA Inlay)	

TABLE 2.5
Categories of M&R Treatments Considered in the Current Study

	Flexible Pavements
Preventive Maintenance	Crack Sealing
	HMA Overlay, Preventive Maintenance
Rehabilitation	HMA Overlay, Minor Structural
	HMA Overlay, Major Structural
New Construction	Pavement Replacement, HMA
	Rigid Pavements
Preventive Maintenance	Crack Sealing
	Diamond Grinding
	PCCP Cleaning and Sealing Joints
Rehabilitation	Crack & Seat PCCP & HMA Overlay
	Rubblize PCCP & HMA Overlay
	PCCP on PCC Pavement
	Repair PCCP & HMA Overlay
New Construction	Pavement Replacement, New PCC
	Composite Pavements
	Crack & Seat Composite Pavement & HMA Overlay
	Rubblize Composite & HMA Overlay

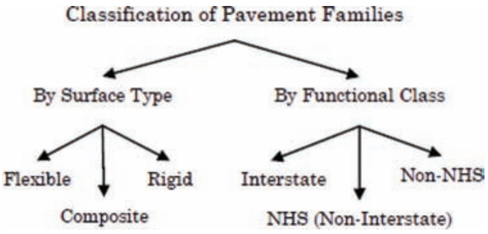


Figure 2.2 Classification of pavement families (Irfan, 2010).

TABLE 2.6
Classification of Indiana Pavement Families and Number of Miles for Each Family

Pavement Classification (Road Class)	Pavement Surface Type (Miles) Rigid	Flexible/Composite
Interstate	378	794
NHS Non-Interstate	199	1,420
Non NHS	135	8,226

traffic load or number of climatic phenomena repetitions (freeze indices or freeze-thaw cycles, for example).

Lamptey, Ahmad, Labi, and Sinha (2005) established various time-based thresholds using the results of a survey of INDOT district engineers and treatment life information from the INDOT Design Manual. Figure 2.3 presents an example of one of the proposed time-based strategies. In a study by Hicks et al. (2000), the optimal timing of applying various treatments on flexible pavements was recommended as shown in Table 2.7. Also, the Nevada Department of Transportation established time-based timing for pavement resurfacing and other preventive maintenance treatments (Table 2.8) (NDOT, 2009).

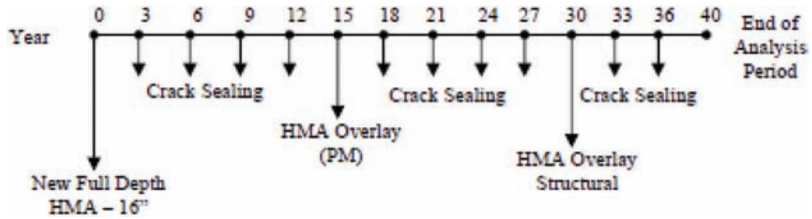


Figure 2.3 Time-based M&R scheduling for new HMA pavements on Interstates (Lamptey et al., 2005).

TABLE 2.7
Optimum Time for Applying Selected Treatments on AC Pavements (Hicks, Seeds, et al., 2000)

Treatment Type	Years
Fog Seals	1–3
Crack Seals	2–4
Chip Seals	5–7
Slurry Seals	5–7
Thin Overlays (including surface recycling)	5–10

2.4.3 State of Practice of Condition-Based Scheduling

In spite of the advantages of avoiding the expense of regular inspection and monitoring of asset performance levels, time-based approaches are based on the assumption that there is only little variation in the pavement deterioration rate. This assumption can lead to unreliable and biased results, because the actual deterioration rates of pavement assets vary greatly, due to inherent variabilities in the influential predictors of pavement condition (loading, climate, construction technology, and so on). Failure to accommodate such variabilities can lead to inaccurate estimations of the asset deterioration rate, which may result in M&R interventions at a time earlier or later than actually needed. This may ultimately lead to inefficiency in asset M&R decision-making and asset management. A performance-based pavement management system, on the other side, can closely track pavement conditions over time and therefore enables asset managers to repair or replace pavements at the most appropriate times.

There are mainly three approaches to identifying performance-based optimal intervention thresholds: (1) conducting surveys to collect expert opinion, (2) using historical practice, and (3) using optimization and other analytical methods. Lamptey (2004) conducted a comprehensive review of available literature on how state agencies establish their M&R strategies, and found that the M&R decision procedures at most agencies were largely based on expert opinion or combination of expert opinion and historical trends.

The Michigan Department of Transportation (MDOT) is known to provide leadership in pavement preventive maintenance program development and implementation (Khurshid, 2010). MDOT developed their M&R treatment thresholds (Table 2.9) using a combination of expert opinion and historical practice. The Remaining Service Life (RSL) concept is a critical consideration in MDOT's PM program development: the PM treatments are applied for pavements with an RSL exceeding two years; rehabilitation or reconstruction should be applied to pavements with an RSL less than two years (MDOT, 2000).

The Ohio Department of Transportation (ODOT) uses Pavement Condition Rating (PCR) to measure pavement distress as the condition threshold to identify/select pavements in need of repair or rehabilitation (Table 2.10) (ODOT, 1999). Pavements with PCR exceeding 85 are stated to be in good condition and are not recommended for M&R actions, pavements with PCR lower than 55 are recommended for major rehabilitation.

Lamptey (2004) developed tentative trigger-based M&R strategies based on multiple performance indicators, including IRI, rutting, and cracking, as presented in Table 2.11. In a recent study by Alberta Infrastructure & Transportation (AIT, 2006), comprehensive decision trees were established based on past practices for selecting pavement treatment and identifying pavements in need of M&R work based on condition thresholds expressed in IRI units. The thresholds are categorized by different traffic levels (AADT): pavements with lower traffic volume are associated with a poorer condition (higher IRI) threshold (Table 2.12).

2.5 Inputs for Pavement M&R Scheduling

In the current and past practice of most states, the condition thresholds for pavement interventions are established primarily based on past practices and expert opinions; however, a significant number of researchers have investigated the development of pavement M&R strategies using optimization approaches. In the following section, a summary of some of the significant studies regarding optimal pavement M&R schedules are presented, followed by a review of other important elements of conducting cost-benefit analysis and optimization. This review includes issues related to pavement performance modeling, effects of pavement interventions (that is, performance jump), pavement agency cost, and user cost models.

2.5.1 Treatment-Specific Pavement Performance Modeling

The accurate prediction of pavement deterioration and performance is the foundation of cost-effectiveness analysis over the pavement life cycle, because the benefit of applying a treatment is measured in terms of its

TABLE 2.8
Time-based Thresholds for Moderate-to-High Volume Routes (Two Way Average Daily Traffic Greater than 400 Vehicles) (INDOT, 2009)

Route Parameters	Pavement Type	Preventive Maintenance	Corrective Maintenance	Overlay	Reconstruction
Interstates, Freeways, and all other Controlled-Access Highways	Asphalt	Age<4	4<Age<8	Age=8	Age>8
	Concrete	Age<10	10<Age<18	N/A	Age>18
Non-Controlled-Access Highway with: ADT>10,000 or ESAL>540	Asphalt	Age<4	4<Age<10	Age=10	Age>10
Non-Controlled-Access Highway with: 1,600<ADT<10,000 or 405<ESAL<540 and National Highway System routes with ADT<10,000	Asphalt	Age<4	4<Age<12	Age=12	Age>12

TABLE 2.9
Flexible and Composite Pavement Treatment Thresholds (MDOT, 2000)

Treatment	Pavement	Minimum RSL (yrs)	DI	RQI	RUT (mm)	Life Extension (Years)
Surface Treatment Non-Structural Bituminous Overlay	Flexible	3	<40	<70	<12	5 to 10
	Composite	3	<25	<70	<12	4 to 9
Surface Milling With Non-Structural Bituminous Overlay	Flexible	5 (double) 6 (single)	<30 (double) <25 (single)	<54	<3	3 to 6 (Single Seal) 4 to 7 (Double Seal)
	Composite	5 (double)	<15 (double)	<54	<3	3 to 6 Double Seal
Chip Seal	Flexible	5 (multiple) 10 (single)	<30 (multiple) <15 (single)	<54	<25	3 to 5 (Single Course) 4 to 6 (Multiple Course)
	Composite	5 (multiple)	<15	<54	<25	NA
Micro-Surfacing	Flexible	10	<15	<54	<3	Up to 3
	Composite	10	<15	<54	<3	Up to 3
Crack Sealing and Crack Filling	Flexible	10	<15	<54	<3	Up to 3
	Composite	10	<15	<54	<3	Up to 3
Ultra-Thin Bituminous Overlay	Flexible	7	<20	<54	<3	3 to 5
	Composite	7	<10	<54	<3	3 to 5

TABLE 2.10
PCR Threshold Ranges for Network Level Corrective Action Category (ODOT, 1999)

Predicted PCR Value	Network Level Corrective Action Category
PCR>85	No action required
85>PCR>75	Preventive maintenance
75>PCR>55	Minor rehabilitation
PCR<55	Major rehabilitation

impact on the condition or service life of the pavement throughout the analysis period. A treatment-specific pavement performance model is used to predict the change of pavement condition and deterioration rate after the application of certain maintenance or rehabilitation work. It is therefore important to explore the effects of M&R treatments on pavement condition before building treatment-specific performance models.

2.5.1.1 Effects of Pavement M&R Treatments on Pavement Condition. In most research studies, the effects of pavement M&R treatment were evaluated based on performance jump, reduced rates of pavement deterioration after the intervention, and pavement service life. The performance jump is the instantaneous improvement in the pavement condition due to the treatment (Colucci-Rios & Sinha, 1985; George, Rajagopal, & Lim, 1989; Labi & Sinha, 2003a; Li & Sinha, 2000; Markow, 1991; Mouaket, Sinha, & White, 1992). Deterioration Rate Reduction (DRR) is the change in the slope of the deterioration curve due to pavement intervention. The concept of DRR has been discussed in conceptual ways (Lytton, 1987; Markow, 1991; Markow et al., 1994) due to the difficulties associated with

TABLE 2.11
Strategy Based on Trigger Values—Asphalt Interstate Pavements (Lamptey, 2004)

		Level of Cracking		
Overall Condition	**Rutting**	**Light**	**Moderate**	**Severe**
Excellent IRI <80	Light	Do Nothing	Seal Cracks	N/A
	Moderate	N/A	N/A	N/A
	Severe	N/A	N/A	N/A
Good 80<IRI<114	Light	Do Nothing	Seal Cracks	Mill and Fill 1″
	Moderate	Thin HMA Overlay 1.5″	Mill and Fill 1.5″	Mill and Fill 2″
	Severe	Thin HMA Overlay 2″	N/A	N/A
Fair 115<IRI<149	Light	N/A	N/A	Mill and Fill 2.5″
	Moderate	HMA Overlay 2.5″	HMA Overlay 3″	Mill 1.5″ and HMA Overlay 4″
	Severe	HMA Overlay 3.5″	Mill 1.5″ and HMA Overlay 3″	Pavement Replacement
Poor	Any	Pavement Replacement	Pavement Replacement	Pavement Replacement

TABLE 2.12
IRI Threshold Values for Selection of PM Treatments (AIT, 2006)

AADT	IRI Trigger (mm/m)	IRI Trigger (in/mi)
<400	3.0	190
400–1500	2.6	165
1501–6000	2.3	146
6001–8000	2.1	133
>8000	1.9	120

identifying and quantifying pavement deterioration rate and the reduction of the rate. Labi and Sinha (2003b) developed equations and case studies to demonstrate DRR computation.

The effect of a preservation treatment can be also measured in terms of the extension in the pavement's RSL due to the applied treatment. The treatment life may be determined by measuring the time elapsed between "successive" preservation treatments, by modeling pavement performance, or by conducting a survival analysis. In the INDOT (2009) Design Manual, typical service lives of various treatments, when applied to different type of pavements, are defined as shown in Table 2.13.

2.5.1.2 Pavement Performance Trend Modeling. Reliable pavement performance models, as the foundation of predicting pavement service life and the effect of pavement intervention, are the basis of much analysis in this study. Pavement performance models in pavement management systems (PMSs) are used for:

- Predicting the pavement performance at a future year and estimating the remaining service life of the pavement.
- Quantifying the benefits of applying any specific pavement M&R intervention.
- Determining the optimal timing for different pavement interventions and identifying the most cost-effective pavement M&R treatment or long-term strategy (schedule).
- Conducting statewide estimation of pavement M&R needs.

Reliable monitoring and prediction of pavement performance plays a vital role in road infrastructure management. If pavement condition and deterioration can be predicted accurately, significant budget savings can be achieved through timely intervention and rational planning. Over the years, various performance prediction models have been proposed. Those prediction models vary significantly in terms of their complexity, comprehensiveness, prediction accuracy, robustness, and level of input data required. Although enormous efforts have been made in developing prediction methods, making accurate predictions of pavement condition and service life is still challenging (Molenaar, 2003). This is primarily due to the limited availability and quality of existing pavement data, including asset condition and M&R history. Moreover, predicting the variations of influential factors that affect pavement performance is also difficult.

The performance prediction models currently available can be classified into two broad categories: empirical and mechanistic-empirical. In addition, there are four main categories of modeling techniques used in pavement performance modeling: deterministic methods, probabilistic approaches, expert opinion–based models, and biologically inspired models, among which deterministic and probabilistic models are the most commonly used models in pavement management.

The majority of asset agencies utilize deterministic models due to ease of development and implementation. The Arizona Department of Transportation (ADOT) has developed deterministic pavement performance models using non-linear regression analysis. The models are based on polynomial functions that produce an S-shaped curve. ADOT utilizes two broad categories of pavement performance models—one based on the Pavement Serviceability Rating (PSR), which is a function of the International Roughness Index (IRI), and another based on the extent of cracking at a given age. ADOT uses a family-based approach wherein pavements with similar characteristics are grouped into one category. The following categories are considered for the

TABLE 2.13
Recommended Design Lives (INDOT, 2009)

Pavement Treatment	Design Life (years)
New PCCP	30
Concrete Pavement over Existing Pavement	25
New Full Depth HMA Pavement	20
HMA Overlay over Rubblized PCCP	20
HMA Overlay over Asphalt Pavement	15
HMA Overlay over Cracked and Seated PCCP	15
HMA Overlay over Jointed Concrete	12
PCCP Joint Sealing	8
Mill and Overlay of Existing Asphalt	8
Concrete Pavement Rehabilitation (CPR) Techniques	7
Microsurface Overlay	6
Chip Seal	4
Asphalt Crack Sealing	3

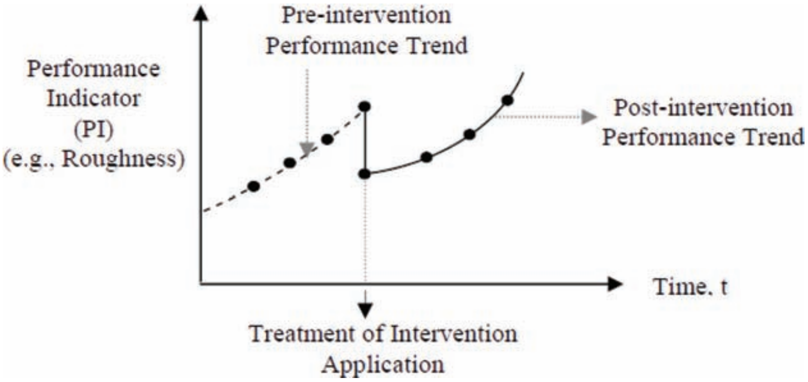


Figure 2.4 Illustration of pre-treatment and post-treatment pavement deterioration (Khurshid, 2010).

development of the family classifications: last rehabilitation activity, pavement type, traffic and environmental conditions, subgrade conditions, and structural thickness (Li et al., 2006).

Haider, Chatti, and Baladi (2012) developed performance models for pavement deterioration before and after a treatment application using a standard exponential form: $f_{pre}(t)=\alpha_1 e^{\beta_1 t}$and $f_{post}(t)=\alpha_2 e^{\beta_2 t}$. An illustration of the deterioration is shown in Figure 2.4. Similarly, Lu (2012) developed models with the same exponential equation using Long Term Pavement Performance (LTPP) data, the models were established for pavement in six different climatic zones measured by freeze-thaw cycles and precipitation.

In all the studies above, however, age was the only explanatory variable used in the model functional form. Other variables were taken into account by grouping pavements into different families. Some other researchers have developed more complex models by including additional variables, such as traffic, weather, and construction techniques in their equations, in addition to pavement age. The effect of these variables has been extensively investigated and analyzed in past studies. For example, asphalt pavements in the wet-freeze zone have been found to have the highest potential for change in roughness (Golabi & Pereira, 2003). Khurshid (2010) and Irfan (2010) developed similar pavement performance models, in which IRI as the primary measurement of pavement condition is modeled in exponential form:

$$IRI=\exp(\alpha+\beta * AATT * t+\gamma * AAFI * t) \quad (2.5)$$

where $AATT$ is accumulated annual truck traffic loadings (millions/year) and $AAFI$ is accumulated annual freezing index (thousands/year).

Some other studies, instead of using external variables, focus on the internal variables related to pavement itself. For example, the Kansas Department of Transportation (KDOT) has developed very sophisticated performance prediction equations dependent upon a variety of variables. For example, the impact of the change in IRI due to a structural action has the predictive equation:

$$IRI=-35.1+\left(0.6888 * IRI_{prior}\right)-(5.16 * Composite)$$

$$-(2.64 * EqThick)+(0.0467 * IRI_{prior} * EqThick) \quad (2.6)$$

where IRI_{prior} is the IRI before the action, $Composite$ is an indicator variable, indicating if the pavement is composite or not, and $EqThick$ is equivalent thickness (in inches) of the planned action.

2.5.1.3 Pavement Performance Jump Modeling. Performance jump (PJ) is the improvement of pavement condition (reflected in an increase or drop in certain performance indicators) due to the application of a specific treatment. PJ is commonly used as a measurement for evaluating the short-term effectiveness of pavement maintenance and repair activities (Labi & Sinha, 2003a). The concept of performance jump has been discussed extensively in pavement performance modeling (Lytton, 1987) but its application is still not widespread.

Early in 1985, the concept of performance jump was used in estimating the reduction in pavement roughness (IRI) due to the application of HMA overlays with different thicknesses (Colucci-Rios & Sinha, 1985). Similarly, George et al. (1989) developed performance jump models as a function of the thickness of HMA overlays to estimate the difference in PCR immediately before and after applying a treatment. Using data from Mississippi, Rajagopal and George (1991) found a 19%–44% increase in PCR due to the application of seal coating. It was also found in that study that the performance jump decreases as initial pavement condition increases. Contrary to this finding, some researchers estimated the gain in PSI after chip sealing as a function of initial pavement condition, and found that higher PSI gains are associated with higher initial pavement condition (Al-Mansour & Sinha, 1994). Similarly, Labi and Sinha (2003a, 2004) developed performance jump models for PCR using both linear and nonlinear regression to link the relation between the jump in PCR due to seal coating treatments and the initial pavement condition. The model results indicate that the higher the initial pavement condition (PSI), the lower the performance jump.

2.5.3 Pavement Agency Cost Models and User Cost Issues

Estimation of agency costs and user costs is a significant foundation of pavement life-cycle cost analysis (LCCA). An illustration of pavement life-cycle cost is shown in Figure 2.5. The life-cycle costs include initial construction cost, pavement maintenance cost, rehabilitation cost, and salvage value in the end of asset service life. Agency cost and user cost are involved in each of these stages over pavement life.

2.5.3.1 Pavement Agency Cost. In a pavement management system, the agency costs consist of the initial construction cost, inspection costs, and routine maintenance costs. In the context of pavement intervention activities, the agency costs contain, but are not limited to, materials, equipment, personnel, engineering, and acquisition costs. Typically, agencies use two approaches to estimate the cost of pavement interventions: estimating average unit costs, or building statistical models based on past contract cost data.

Average unit costs over the various pavement treatments has been investigated extensively. This approach has been used frequently in the context of budgeting and planning. Collura et al. (1993) applied the average cost approach to estimate the unit cost of two rehabilitation and maintenance treatments in the New England region. In that study, the average unit cost of chip seal is estimated at \$0.80/yd^2 (with a standard deviation of \$0.32), and the average unit cost of overlay is estimated at \$30.36/ton of material (with a standard deviation of \$3.88). According to a study conducted by the Washington DOT (2002) on highway construction costs, the cost of constructing a single lane-mile of highway can range from \$1 million to \$8.5 million, with an average of \$2.3 million per lane per mile. Based on data from several states, FHWA (2002a) determined that the unit cost of constructing a typical four-lane divided highway can range from \$3.1 to \$9.1 million per lane per mile depending on the terrain type. However, the range of cost per lane-mile increased by \$16.8–\$74.7 million in urban areas, due to additional restrictions (such as high volume traffic control, high cost of right-of way and evening work restrictions, etc.) (Guerrero, 2003). Using pavement contract data (1997–2001) from the INDOT Contracts Division, Lamptey (2004) provided the average unit cost (\$1000/lane-mile) for various pavement treatments as presented in Figure 2.6.

While the average cost approach can be used easily and efficiently in estimating budgets for network-level M&R planning, such unit rates (or averages) estimations generally tend to be unreliable from location to location in project-level application, because there is a high level of variation, such as topography, land prices, environment, and traffic loads, and also the economies of scale (Irfan, 2010). Developing costs models using statistical methods takes some of the variations and economics of scale into account. In typical cost models, the cost of construction is modeled as a function of various influential factors that affect construction costs.

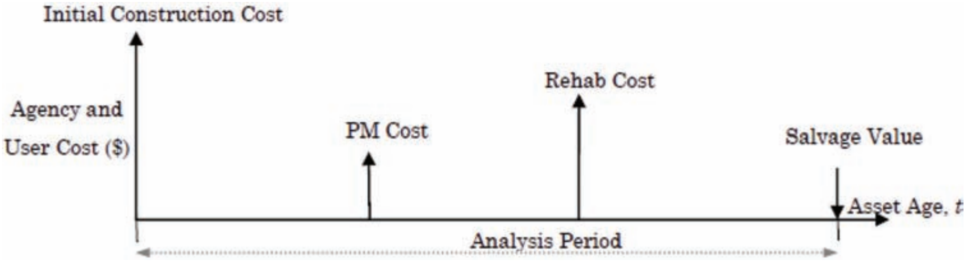


Figure 2.5 Illustration of pavement life-cycle cost.

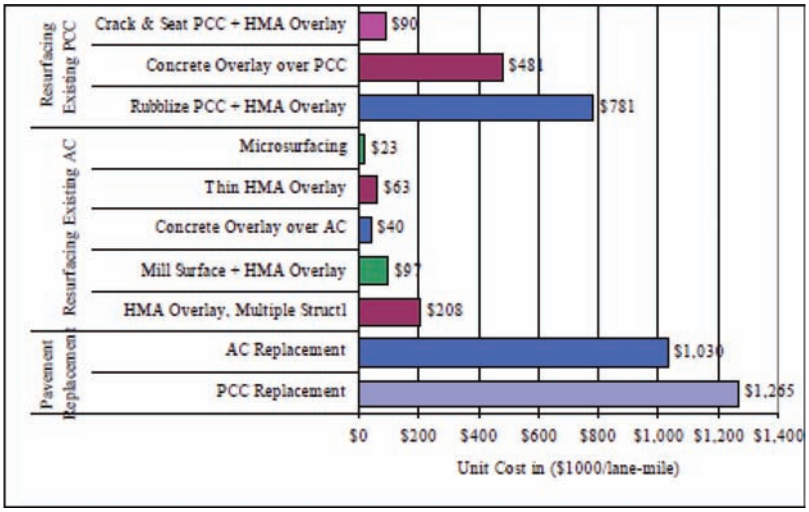


Figure 2.6 Units costs of major pavement treatments by contract (Lamptey, 2004).

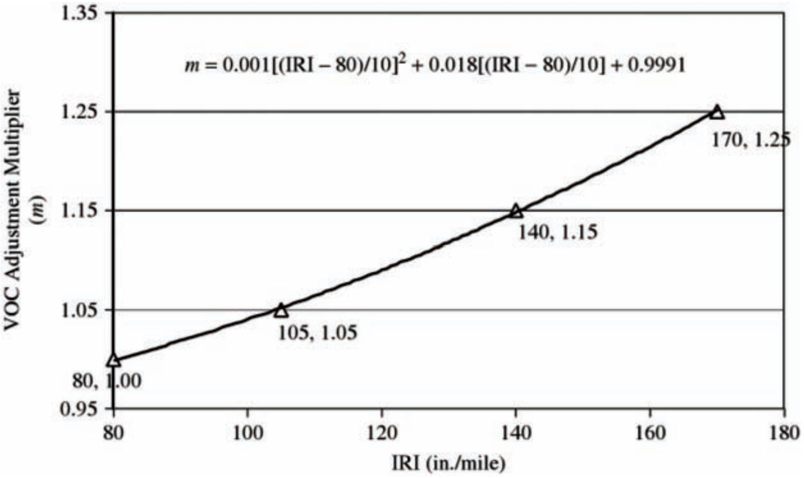


Figure 2.7 VOC adjustments for pavement roughness level.

2.5.3.2 Pavement User Cost. Typically, pavement user costs include the costs associated with normal vehicle operation, including VOC and safety costs associated with the pavement condition, and the extra user cost incurred because of travel time delays or detouring in work zones due to pavement maintenance, rehabilitation, and replacement activities. Although these user costs are not direct costs for the agency, they affect the road users' and the public's perceptions of the agency's performance (FHWA, 2002b). The user cost is therefore critical in making M&R decisions.

Researchers have conducted a number of studies on the evaluation and calculation of user cost. It has been found that a unit increase in IRI (in m/km) can result in an increase of $200 in vehicle maintenance and repair costs alone (Papagiannakis & Delwar, 1999). Figure 2.7 presents the VOC adjustment factors as a function of pavement condition, developed by Barnes and Langworthy (2003). The function can be used to estimate, for a given pavement section, the VOC at an IRI baseline of 85 in/mi or higher. A small decrease in the VOC rate due to the reduction on pavement roughness could lead to significant VOC reductions for the road users (Barnes & Langworthy, 2003).

Incorporating user cost in an appropriate way in the analysis or decision-making process is, however, still a challenging problem. The primary reasons are (1) although the method of user cost calculation is not difficult, the data required for these calculations is limited in term of both availability and quality; and (2) user costs are often so large that they may substantially exceed agency cost, particularly for investment being considered in high-traffic roads. This causes challenges as to how to incorporate user cost in cost analysis and LCCA estimation. Some researchers consider user costs and agency costs separately, while some others combine user costs and agency costs into a single weighted index. A suggestion from Lamptey (2004) is to consider only a fraction of the user costs, instead of adding the entire user costs to the agency cost. The "fraction" can vary greatly, depending on the purpose of the study. A sensitivity analysis is often helpful to the selection of the appropriate weight. In a study by Labi and Sinha (2005), such sensitivity analysis was conducted to evaluate the cost-effectiveness of intervention treatments under different agency cost to user cost ratios. Two ratios were tested in that study: (1) 1:0 (i.e., only agency costs were considered) (2) 1:1 (i.e., agency and user costs were equally considered). A higher cost-effectiveness ratio (benefit divided by the total costs) was found for scenario 1 when only agency costs were considered, due to the reduced total costs by not including the user costs.

In spite of the important role of user cost in LCCA implementation, and the extensive work conducted on this topic, most highway agencies don't rely on user cost in their current practice of M&R decision making, because of the difficulty in valuing user delay and the uncertainty that exists about the effects of agency activities on VOC and road safety.

2.6 Optimization Techniques for Developing M&R Schedules Over Life Cycle

In general, there are three methods of developing an M&R schedule: (1) establishing an M&R schedule based on expert opinion; (2) continuing the past practice of M&R based on historical data; and (3) applying rational and data-driven approaches for developing M&R strategy through optimization techniques or other analytical methods. Thresholds developed based on expert opinion and past practice are normally not the most cost-effective, because they are either inherently subjective or vulnerable to inconsistency due to policy changes and funding uncertainties (Khurshid et al., 2010; Labi et al., 2004; Lamptey, 2004; Pasupathy et al., 2007). The application of optimization can effectively address the limitations associated with expert opinion and historical practices.

Finding an optimal scheduling of pavement maintenance and rehabilitation intervention activities was first formulated as an optimization problem by Friesz and Fernandez (1979). They later extended their work to the problem of finding the optimal timings for highway stage construction (Fernandez & Friesz, 1981). Since then, numerous studies have made efforts to establish an optimal strategy for pavement maintenance, repair, rehabilitation, and replacement activities. Different optimization techniques have been used, including linear programming, integer programming, dynamic programming, and goal programming (Irfan, 2010). Many studies carried out multi-objective optimization, in which the objective functions include, but are not limited to, maximizing asset performance, maximizing safety and reliability of pavement facility, minimizing life-cycle costs, and maximizing service life or cost-effectiveness index of pavement intervention. The constraints include, but are not limited to, performance threshold, safety and reliability indices, and the agency's budget. However, most past studies only provided an optimal solution for a single intervention activity, and few studies focus on the optimal long-term scheduling of multiple treatments due to the high computational complexity involved in solving the problem and the lack of necessary data for developing treatment-specific performance and cost models for some treatment types.

In general, M&R optimization can be classified into two broad categories: (1) project-level or facility-level optimization (analysis conducted for an individual asset over the asset's life cycle or a certain time period), and (2) network-level optimization (decision-making related to assets in the entire network). Network-level analysis allows for the minimization of overall costs for the entire network of assets (Seeds, 1980), but it might ignore some important factors associated with design at the project level. Despite of its lower capability of producing network-wide solutions, the project-level approach is more effective in dealing with problems that only involve individual assets. In the context of M&R decision-making, project-level analysis can also be very useful in characterizing most of the investment analyses in current pavement management (Shahin, 2006).

Project-level M&R strategy optimization uses data from the individual asset to identify the most cost-effective solution for that asset. Project-level programming requires higher quality data and detailed models. For example, the average unit cost of pavement construction and intervention could be used for estimating network-level costs, but this data may not be suitable for a project-level analysis in which reliable cost models are expected to deal with the variability of each individual project.

3. STUDY FRAMEWORK

Identifying the optimal trigger condition for pavement maintenance and rehabilitation treatments that obtain the highest cost-effectiveness through analytical analysis was the main focus of this study. This chapter presents the overall methodology and framework for developing appropriate treatment thresholds. The main work conducted in this study includes data collection; grouping pavement assets into families; identifying standard preservation treatments; and developing performance jump models, post-treatment performance trend models and agency cost models. This work was followed by a cost-effectiveness analysis and the establishment of threshold values for each type of treatment application in each family of pavement.

3.1 Data Collection and Data Cleanup

3.1.1 Data Collection and Data Collation

The study began with data collection and collation from different sources and preparation of input data for developing pavement performance and cost models. The data sources used in this study include pavement inventory data, condition data, and contract data, etc.

There are 11,538 pavement segments in the inventory dataset. Each pavement segment is identified based on "milepost" in the pavement referencing system. The "milepost" of each segment is unique; it can be used as the basis for merging multiple datasets into one comprehensive dataset. The inventory data contains pavement characteristics, including length, number of lanes, pavement type, route number, and functional class: Interstate (IS), NHS Non-Interstate, and Non-NHS. This information can be used to group pavement into families.

The pavement condition dataset contains measurements of roughness, rutting, and PCR, from year 1994 to 2006, inspected annually on Interstate routes, and every two years on NHS Non-Interstate and Non-NHS highways. The treatment-specific performance trend and performance jump models were developed using the merged dataset, based on condition data and contract data.

The contract data in the Indiana Department of Transportation (INDOT) database contained contracts that were carried out before 2006. The dataset includes contractor number, contract starting and ending dates, contract location, type of pavement work, contract cost and fiscal year. Table 3.1 lists all types of pavement work in the database that had been done by contract during the years 1901–2006 in the state of Indiana.

TABLE 3.1
Type of Pavement Work and Number of Past Applications in Indiana

Pavement Treatment	Number of Past Treatment Applications in Indiana Routes (Contracts)	If Considered in This Study
Added Travel Lanes	34	No
Added Travel Lanes, Composite	4	No
Added Travel Lanes, Construct Turn Lanes	7	No
Added Travel Lanes, HMA	35	No
Added Travel Lanes, PCC	40	No
Asphalt Patching	51	Yes
Auxiliary Lanes, Accel & Decel or Turn Lanes	2	No
Auxiliary Lanes, Passing	2	No
Auxiliary Lanes, Truck Climbing Lanes	1	No
Auxiliary Lane Construction	1	No
Crack & Seat Composite Pavement & HMA Overlay	32	Yes
Crack & Seat PCCP & HMA Overlay	32	Yes
Crack Sealing	4	Yes
Diamond Grinding	5	Yes
Dual Lane Existing Route	9	No
HMA Overlay, Functional	785	Yes
HMA Overlay, Preventive Maintenance	270	Yes
HMA Overlay, Structural	1718	Yes
New Road Construction	20	Yes
New Road Construction, HMA	20	Yes
New Road Construction, PCC	413	Yes
New Road, Grading Only	23	No
New Road, HMA Paving Only	2	No
New Road, PCC Paving Only	36	No
Resurfacing (Partial 3-R)	818	Yes
Patch and Rehab PCC Pavement	1	Yes
Pavement Replacement	22	Yes
Pavement Replacement, HMA	12	Yes
Pavement Replacement, New PCC	17	Yes
PCCP Cleaning and Sealing Joints	15	Yes
PCCP on PCC Pavement	3	Yes
PCCP Patching	96	Yes
Repair PCCP & HMA Overlay	51	Yes
Resurface over Asphalt Pavement	3	Yes
Resurface PCC Pavement (Partial 3/R Standards)	8	Yes
Road Reconstruction (3R/4R Standards)	22	Yes
Road Rehabilitation (3R/4R Standards)	299	Yes
Rubblize Composite & HMA Overlay	8	Yes
Rubblize PCCP & HMA Overlay	18	Yes
Shoulder Rehabilitation and Repair	9	No
Sight Distance Improvement	22	No
SPOT IMP	1	No
Surface Treatment, PM	24	Yes
Vertical Sight Correction	3	No
Wedge and Level	298	No

3.1.2 Data Cleanup

One of the biggest challenges in the current study is pavement performance modeling, due to the poor quality of available condition data. Many problems have been identified in the current pavement condition dataset. For instance, IRI is a non-decreasing performance measurement, however, in the current dataset, many pavement segments have been found to have IRI that do not always increase with age. Figure 3.1 shows an example of time-series IRI data from a single pavement section that illustrates this problem.

With these unexpected errors, developing reliable pavement models becomes quite challenging, especially for the post-treatment performance trend models, which are developed entirely based on the pavement's condition over time. In order to deal with this problem, a method of data cleaning was proposed. For each pavement segment in the condition dataset, do the following: (1) Identify the year of treatment application 't' by tracking the change in pavement conditions between each two years, and finding the year that has the biggest condition improvement; (2) Fit the data points after year 't' of the segment using linear form; (3) Set an appropriate threshold value (positive number), and keep the segment in the dataset only if its fitted curve (straight line) has a slope greater the threshold.

Figure 3.2 presents an example of applying the proposed methodology to a single pavement segment. In Figure 3.2(a), the treatment application was identified at year 1996 because the biggest IRI improvement occurred at 1996. All data points after 1996 were fitted using a straight line, shown in Figure 3.2(b). The slope of the fitted line is 5.509 in this case. Whether to filter this segment out from the dataset is determined by the preset threshold value mentioned in step (3) of the data cleaning process.

Generally, the higher the threshold, the less error will remain in the dataset. There is, however, a trade-off between the data quality and data quantity. With a higher threshold value, we may filter out more unexpected error, and therefore obtain higher data quality. However, fewer data points will remain in the dataset. Table 3.2 presents the data cleaning results under different thresholds for each type of treatment in the interstate portion of the database. As expected, the number of remaining pavement segments decreases as the threshold value increases. In the current study, a threshold of 6 was finally selected for most types of treatments. For some treatments that have less data available, a smaller threshold value was chosen.

3.2 Pavement Performance Modeling

Pavement performance modeling is the most commonly used data-driven approach in predicting pavement deterioration or performance as a function of a set of influential variables (e.g., age, pavement thickness, pavement design, traffic loads and climatic factors, etc.). In a typical pavement performance model, the variable to be predicted can be primary response (mechanical reactions of deflection, strain, stress, etc.), structural performance (pavement distresses such as rutting and spalling in rigid pavements) or functional performance (riding quality).

In this study, IRI was considered the most important performance measure for determining the cost-effectiveness of pavement maintenance and rehabilitation treatments. Therefore, the performance models developed in the study focus on pavement roughness. Two types of performance models were investigated regarding performance jump (improvement in pavement condition rating due to a pavement M&R treatment application) and post-performance trend (pavement deterioration trend after a pavement M&R treatment is carried out). The concept of treatment performance jump (sudden change in pavement condition due to the treatment application) and post-treatment performance (deterioration curve immediately after the treatment application) is illustrated in Figure 3.3 (Irfan, 2010).

The general forms of treatment-specific performance jump and post-treatment performance trend models are

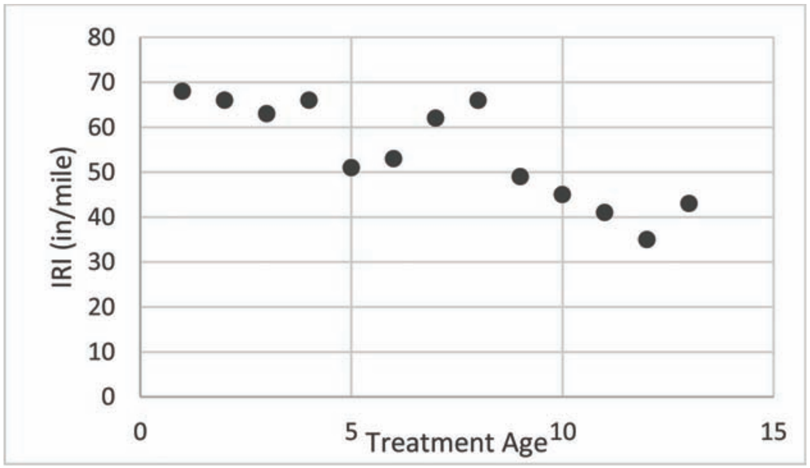
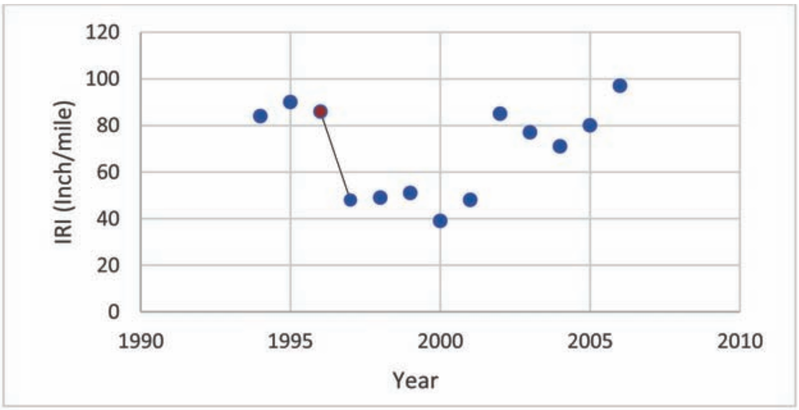
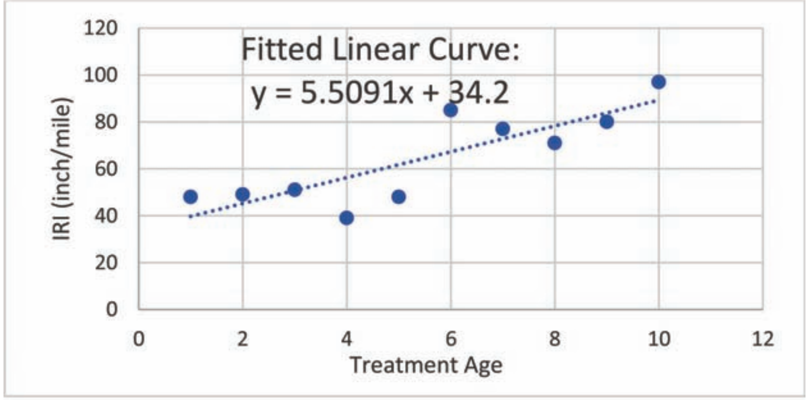


Figure 3.1 Example of pavement segment that has generally decreasing IRI.



(a) Step 1: Identify time of treatment application



(b) Step 2: Fit data points after performance jump using linear curve

Figure 3.2 Example of the data cleanup procedure.

given in the following equations (Geoffroy, 1996; Irfan et al., 2009; Labi & Sinha, 2005):

$$PJ = f(y)$$

where PJ = Performance jump (IRI (in/mi)) due to the treatment application; f(y) = Function of pre-treatment performance.

$$PI = f(t)$$

where PI = Performance indicator (IRI (in/mi)) for a pavement section t years after treatment application; f(t) = Function of treatment age and other influential variables.

As discussed in Section 2.3, pavements can be categorized into nine families, based on pavement type (flexible, rigid and composite) and functional class (Interstate, NHS Non-Interstate, and Non-NHS). In this study, treatment-specific performance jump and trend models were developed for each family of pavement assets.

3.2.1 Treatment-Specific Performance Jump Model

Performance jump is defined in the current study as the improvement in the pavement condition rating (reduction in IRI) after a pavement M&R treatment application. Performance (IRI) jump is often related to the pre-treatment pavement condition (IRI immediately before the treatment application): the higher the IRI before the treatment, the greater the IRI jump will typically be. Figure 3.4 shows the actual data points of pre-treatment IRI and corresponding performance jump to illustrate the effect of pre-condition on IRI jump after a specific M&R treatment (HMA functional overlay).

The jump models were developed for various treatments in the current study, with IRI as the dependent variable and pretreatment IRI as the independent variable, using the following two types of functional formulae:

Linear formula: $IRI\ Jump = \beta_0 + \beta_1 * PreIRI$

Logarithmic formula: $IRI\ Jump = \beta_0 + \beta_1 * ln\ (PreIRI)$

The logarithmic formula was adopted in developing jump models for most maintenance work, while the linear formula was adopted for all rehabilitation work and reconstruction or replacement. The classification of M&R treatments into maintenance, rehabilitation, and reconstruction was discussed in Section 2.2. The main difference between the two types of jump model is that when the condition is poor (high IRI value), the IRI jump is higher in the linear model than it is in the logarithmic model, illustrated in Figure 3.5. Typically, preventive maintenance treatments such as HMA thin

TABLE 3.2
Data Cleanup Results for Interstate

	Interstate								
Threshold of Slope	**None**	**>0**	**>1**	**>2**	**>3**	**>4**	**>5**	**>6**	**>7**
Treatment Type	**Number of Remaining Pavement Segments after Data Cleaning**								
All	2756	2589	2313	1897	1526	1163	841	620	488
Asphalt Patching	27	27	23	18	13	10	9	3	1
Crack & Seat Composite Pavement & HMA Overlay	137	128	116	81	53	29	15	9	8
Crack & Seat PCCP & HMA Overlay	56	53	32	20	17	12	10	8	7
Crack Sealing	15	15	15	15	13	10	9	9	8
Diamond Grinding	5	5	5	5	5	5	3	2	1
HMA Overlay, Functional	225	214	174	139	112	86	59	40	32
HMA Overlay, Preventive Maintenance	47	45	38	33	25	18	3	1	1
HMA Overlay, Structural	154	128	110	87	71	60	48	34	31
New Road Construction, PCC	576	548	494	406	330	254	188	147	120
New Road, Grading Only	62	49	40	28	18	9	3	2	2
New Road, HMA Paving Only	9	9	8	7	6	6	5	1	0
New Road, PCC Paving Only	93	79	63	43	26	18	15	12	10
Partial 3-R	112	105	101	80	51	43	34	23	18
Pavement Replacement, New PCC	8	5	4	3	1	1	1	1	0
PCCP Cleaning and Sealing Joints	3	3	3	2	1	1	1	1	1
PCCP on PCC Pavement	9	9	8	7	7	4	1	1	1
PCCP Patching	306	296	269	232	208	171	125	85	63
Repair PCCP & HMA Overlay	89	81	78	71	62	51	38	33	25
Road Reconstruction (3R/4R Standards)	46	43	42	30	17	14	9	7	4
Road Rehabilitation (3R/4R Standards)	669	640	588	500	418	312	235	179	139
Rubblize Composite & HMA Overlay	22	22	22	21	17	9	3	3	2
Rubblize PCCP & HMA Overlay	6	6	6	5	5	5	5	5	5
Surface Treatment, PM	40	38	37	34	26	18	14	8	7
Wedge and Level	42	41	37	30	24	17	8	6	2

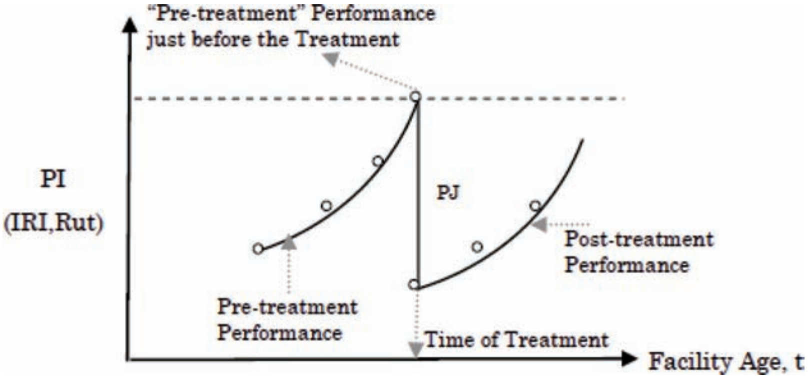


Figure 3.3 Performance jump and post-treatment performance trend (Irfan, 2010).

overlay, microsurfacing, and PCC patching are more effective in addressing minor defects than in improving pavement in poor condition. The reduction rate of IRI is therefore decreasing as pre-treatment IRI increases. The logarithmic functional formula is capable of capturing this pattern. Treatments that were categorized into rehabilitation, replacement, or reconstruction, on the other hand, are more effective in improving pavement condition, even when the condition is poor, and the IRI reduction rate is more likely to have a linear trend.

To make the developed models more realistic in representing the performance jump in real life, some constraints were applied:

1. $IRI\ Jump \geq 0\ (in/mi)$ (the change in IRI should be positive number)
2. $Pretreatment\ IRI - IRI\ Jump \geq 50\ (in/mi)$ (the post-treatment IRI should be greater than 50 in/mi)

The jump model results for different treatments and pavement families will be presented in Section 4.1.1.

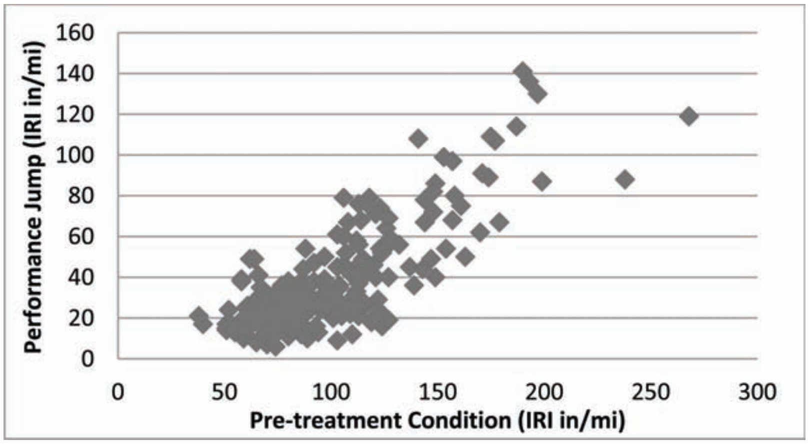


Figure 3.4 Effect of pre-treatment IRI on performance jump after HMA functional overlay.

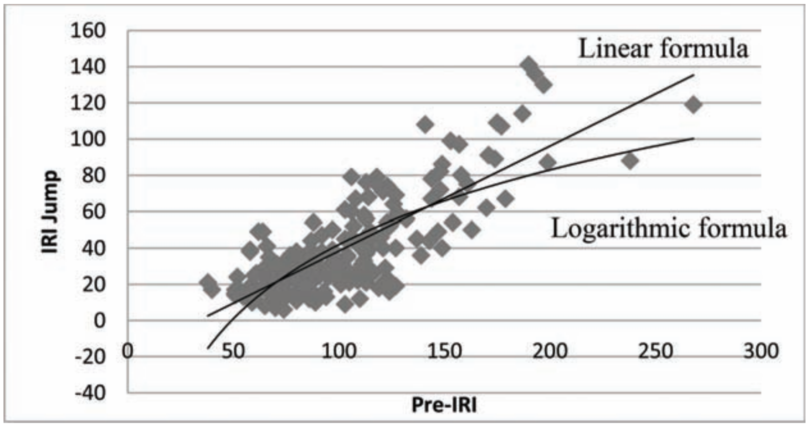


Figure 3.5 Comparison of linear and logarithmic formulae for performance jump modeling.

TABLE 3.3
Investigated Functional Formulae of Post-Treatment Performance Model

Functional Formula	Mathematical Expression
Exponential (1)	$IRI_t = PostIRI * \exp(\beta_1 * t)$
Exponential (2)	$IRI_t = PostIRI * \exp(\beta_0 + \beta_1 * AADT * t + \beta_2 * NFTC)$
Exponential (3)	$IRI_t = PostIRI * \exp(\beta_0 + \beta_1 * AADT * t + \beta_2 * FTI)$
Power Function	$IRI_t = PostIRI + \beta_0 * t^{\beta_1}$
Polynomial	$IRI_t = \beta_0 + \beta_1 * t + \beta_2 * t^2$

Note: IRI_t is the IRI at year t after the last treatment application; $PostIRI$ is the IRI after the improvement due to treatment application, post-treatment $PostIRI$ = pre-treatment IRI - Jump; $AADT$, $NFTC$, and FTI represent traffic loads, number of freeze-thaw cycles, and freeze-thaw index, respectively. $\boldsymbol{\beta_0}$ is a constant value, and $\boldsymbol{\beta_1}$ and $\boldsymbol{\beta_2}$ are estimated coefficients for the independent variables.

3.2.2 Treatment-Specific Post-Performance Trend Model

A post-treatment performance trend model is used in modeling the pavement deterioration process after a pavement M&R treatment application. This process is generally non-linear, in that the older the treatment age, the higher the deterioration rate is likely to be. Exponential, power, and polynomial formulae are the most common functional formulae used for performance trend models in past studies. The explanatory variables that are commonly used include treatment age, pre-treatment condition (pavement condition before the application of treatment), traffic loads, climatic factors, and pavement design parameters.

A variety of functional formulae and influential explanatory factors (Table 3.3.) were investigated using statistical software, and the model that best fit the actual data was selected.

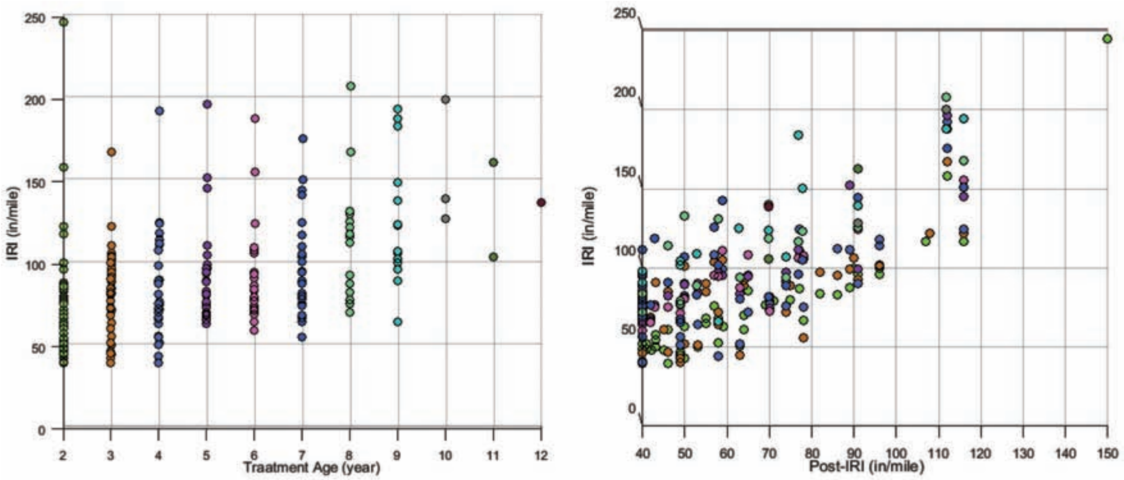
The final selected model (Exponential 1) only contains two explanatory variables: post-treatment IRI and treatment age. The effect of the two variables on the post-treatment performance trend is illustrated by the 2D plots and 3D plot in Figure 3.6, where data points with the same color represent pavement segments that have the same treatment age. The post-performance trend model results for all the types of treatments will be presented in Section 4.1.2.

3.3 Pavement Cost Model

Pavement costs considered in this study are agency costs (M&R treatment costs) and user costs (during both work zone and normal highway operation). For agency costs, both average unit costs from contract data and the developed cost models were provided. The average cost was used for treatments for which the cost model is unavailable (due to limited data availability). For user cost, existing models from past studies were adopted for the calculation of work zone duration, travel time delay, and VOC due to road roughness. All the costs were converted into 2010 US dollars.

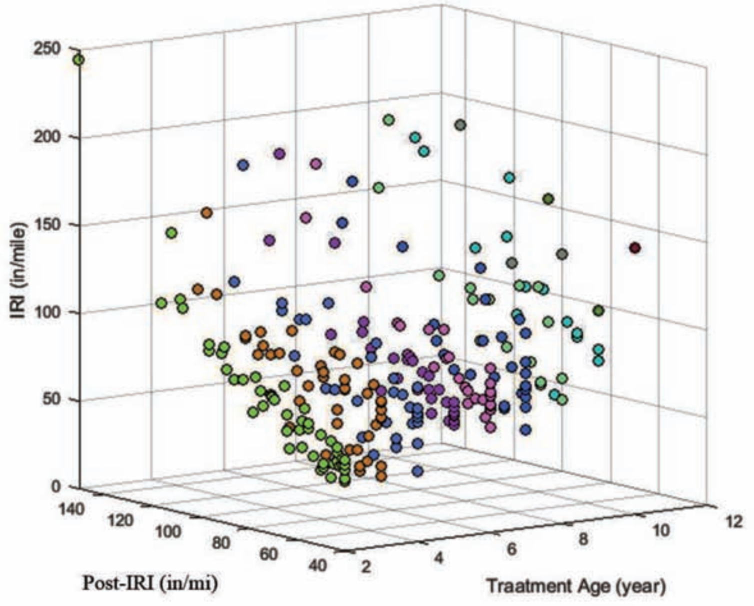
3.3.1 Agency Cost

In this paper, average agency unit cost ($1000 per lane-mile) and agency cost models were developed using both the pavement contract database containing contract costs from Year 1994 to Year 2010 and the pavement inventory dataset that contains pavement information such as number of lanes, and segment



(a) 2D View of Effect of Treatment Age on Post-treatment Pavement Condition

(b) 2D View of Effect of Post-IRI on Pavement Condition at Certain Treatment Age



(c) 3D View of Effect of Pre-treatment Condition, and Treatment Age on Post-treatment Pavement Condition

Figure 3.6 Relation between pre-treatment condition, treatment age and post-treatment pavement condition.

length. All costs were converted into their equivalent 2010 constant dollars before conducting any analysis.

3.3.1.1 The Inflation Rate of Agency Costs. To appropriately adjust for inflation, the cost in different years was converted into 2010 constant dollars using FHWA's CPI based on the following equation:

$$C_{AY} = C_{BY} \frac{CPI_{AY}}{CPI_{BY}}$$

where C_{BY} = Cost of intervention work in the analysis year; C_{AY} = Cost of intervention work in the base year; CPI_{AY} = the construction price indices for the analysis year, and CPI_{BY} = the construction price indices for the base year.

The average annual inflation rate of the agency costs was calculated based on the National Highway Construction Cost Index (NHCCI) by FHWA (2015). The equation used to calculate the average annual inflation rate is:

$$Index_i \times (1+r)^{j-i} = Index_j$$

where r is the average annual inflation rate to be determined, $Index_i$ and $Index_j$ are the NHCCI in Year i and j, respectively, and i = 2003 in the calculation (since NHCCI set the index for 2013 as 1.0).

Based on the NHCCI from Year 2003 to Year 2015, the average annual inflation rate of agency M&R costs used in this study is determined as 1.33%. In addition, a discount rate of 4% is chosen for the life-cycle cost calculation, which is the typical rate used by INDOT (Jiang et al., 2011).

3.3.1.2 Average Agency Unit Cost. Many of the past studies use average unit cost (dollar per mile per lane) to estimate the agency cost of various types of treatments and for pavement life-cycle cost analysis. In the current study, the unit cost ($/lane-mile) of each pavement intervention project was calculated using the contract data discussed in Section 3.1 for each functional class. Table 3.4 presents the sample average unit cost estimations for contracts on Interstates, NHS Non-Interstate, and Non-NHS pavement.

3.3.2 Agency Cost Model

While using the average number as the unit cost is easy and convenient, this approach is only suitable in budget estimation for network-level planning when the overall cost is more important than the cost of individual projects. Using the average cost tends to be unreliable in estimating the cost for one project because of economies of scale and the high variation with regard to site conditions. It can also be seen that the standard deviation is very high compared to the average cost for most types of treatments in Table 3.4 under Section 3.3.1. Developing separate cost models for each type of treatment is therefore preferable in project-level planning.

The issue of economies of scale can be addressed by introducing pavement length and number of lanes into the cost model as explanatory variables. Figure 3.7 illustrates the effect of these two variables on the unit cost ($1000/mile*lane). Typically, within a certain range, the larger the project size, the lower the unit cost will be.

The agency cost models were developed using the same data as was used for the average cost models. Due to limited data availability, the cost models were not developed for each functional class separately. Two types of functional formulae were applied:

$$Unit\ Cost\ (\$1000/lane * mile) = \beta_0 + * \ln(\text{length} * \text{Lanes})$$

$$Final\ Cost\ (\$1000) = exp(\beta_0 * length^{\beta_1} * lanes^{\beta_2})$$

The model that obtained better result was selected for each type of treatment. The final model selected for each type of treatment and the corresponding statistical results will be presented in Section 4.2.

3.3.3 User Cost Model

The user costs considered in the current study are the "incremental" vehicle operating costs (VOC) caused by increased wearing surface roughness and the extra user cost incurred because of travel time delays in work zones during pavement M&R treatments. The extra cost incurred by detours is not considered in the work zone user costs in this study, due to the lack of detour length data. Costs in different years were converted into their equivalent 2010 dollars. In addition, the annual growth of traffic is also considered, because more road users lead to higher user costs.

3.3.3.1 The Inflation Rate of User Costs. To consider inflation for user costs, the study adopted an average annual inflation rate calculated using the consumer price index (CPI) reported by the Bureau of Labor Statistics (BLS, 2016). Similar to the method used in calculating the inflation rate for agency costs, the equation of calculating the inflation rate for user costs is shown as follows:

$$CPI_i \times (1+r)^{j-i} = CPI_j$$

where r is the average annual inflation rate to be determined, and CPI_i and CPI_j are the CPIs for Year i and j, respectively.

Using 1995–2015 CPI data, the average annual inflation rate for the user costs is calculated as 2.27%. The same average inflation rate is used for the entire period of analysis in the current study.

3.3.3.2 Incremental User Costs due to Surface Roughness. Typically, vehicle operating costs (VOCs) include the costs of fuel, oil, tires, vehicle depreciation, and maintenance and repair. The base level VOC is the total operating cost for vehicles on roads that are in perfect condition (IRI lower than 80 in/mi). The VOC

TABLE 3.4
Average Unit Agency Costs ($1000/Lane-Mile)

	Unit Cost ($1000 Per Lane-Mile) Year 2010				
Treatment	**Sample**	**Mean**	**Min**	**Max**	**Stdv**
(a) Contracts on Interstates					
Asphalt Patching	1	144	444	444	0
Crack & Seat Composite Pavement & HMA Overlay	20	574	278	1128	248
Crack & Seat PCCP & HMA Overlay	10	386	183	702	144
HMA Overlay, Functional	27	114	11	850	186
HMA Overlay, Preventive Maintenance	1	38	38	38	0
HMA Overlay, Structural	1	338	338	338	0
New Road Construction, HMA	1	2594	2594	2594	0
New Road Construction, PCC	7	1656	294	5581	1856
New Road, HMA Paving Only	1	460	460	460	0
Partial 3-R	8	204	28	489	137
Pavement Replacement, New PCC	4	1582	878	2008	541
PCCP Cleaning and Sealing Joints	1	40	40	40	0
PCCP on PCC Pavement	2	1486	1027	1944	648
PCCP Patching	3	20	8	29	11
Repair PCCP & HMA Overlay	15	532	47	2135	528
Road Rehabilitation (3R/4R Standards)	51	810	80	5034	958
Rubblize Composite & HMA Overlay	1	620	620	620	0
(b) Contracts on NHS Non-Interstates					
Asphalt Patching	2	85	268	302	24
Crack & Seat Composite Pavement & HMA Overlay	2	1561	573	2549	1397
Crack & Seat PCCP & HMA Overlay	8	310	3	615	184
Crack Sealing	1	100	100	100	0
Diamond Grinding	1	131	131	131	0
HMA Overlay, Functional	69	144	3	774	144
HMA Overlay, Preventive Maintenance	7	110	15	206	76
HMA Overlay, Structural	22	398	12	2352	592
New Road Construction	1	973	973	973	0
New Road Construction, PCC	17	2923	647	6175	1625
New Road, PCCPaving Only	2	983	587	1379	560
Partial 3-R	68	235	15	2199	337
Pavement Replacement	1	1153	1153	1153	0
Pavement Replacement, New PCC	1	680	680	680	0
PCCP Cleaning and Sealing Joints	3	49	20	86	34
PCCP Patching	12	102	13	505	143
Repair PCCP & HMA Overlay	1	33	33	33	0
Road Reconstruction (3R/4R Standards)	2	1468	1256	1679	299
Road Rehabilitation (3R/4R Standards)	23	327	21	1792	380
Rubblize PCCP & HMA Overlay	3	286	84	682	343
Surface Treatment, PM	1	25	25	25	0
Wedge and Level	8	110	4	504	177
(c) Contracts on Non-NHS Roads					
Asphalt Patching	2	67	26	108	58
Crack & Seat Composite Pavement & HMA Overlay	1	35	35	35	0
Crack & Seat PCCP & HMA Overlay	5	130	58	204	61
HMA Overlay, Functional	106	151	4	1018	180
HMA Overlay, Preventive Maintenance	25	134	5	361	95
HMA Overlay, Structural	45	414	8	2383	564
New Road Construction, PCC	9	2661	97	6091	1799
Partial 3-R	119	152	12	1243	170
Pavement Replacement	1	1284	1284	1284	0
PCCP Patching	6	69	24	121	43
Repair PCCP & HMA Overlay	1	193	193	193	0
Resurface PCC Pavement (Partial 3/R Standards)	1	148	48	48	0
Road Rehabilitation (3R/4R Standards)	14	649	9	3206	818
Surface Treatment, PM	2	33	23	42	13
Wedge and Level	2	32	3	60	40

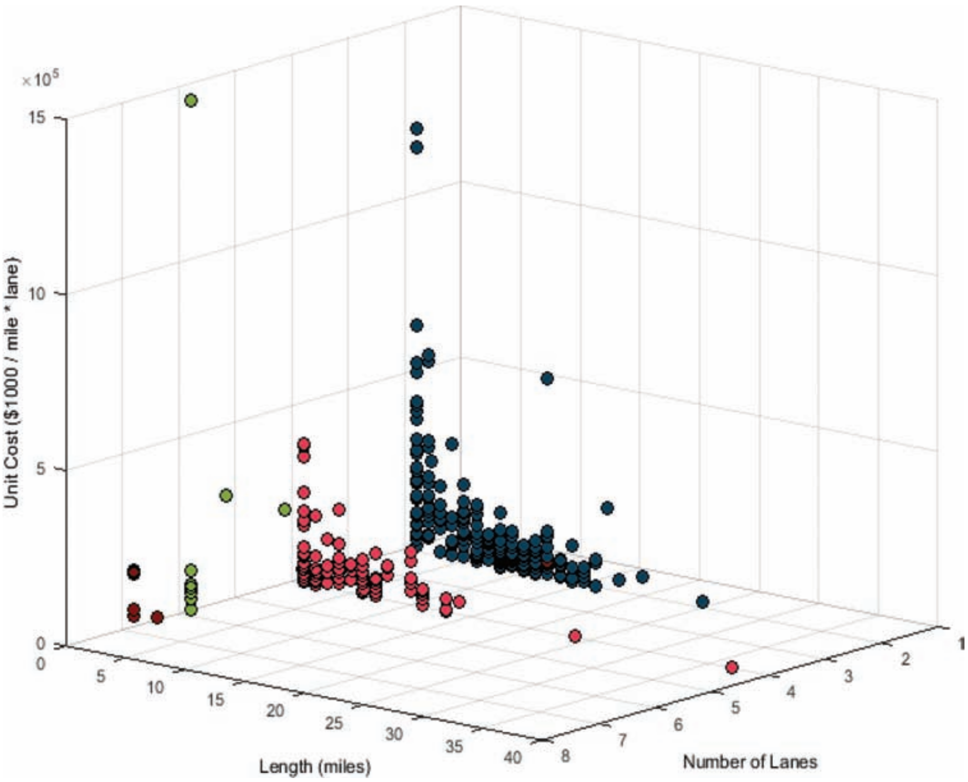


Figure 3.7 Effect of length and number of lanes on unit cost (HMA functional overlay).

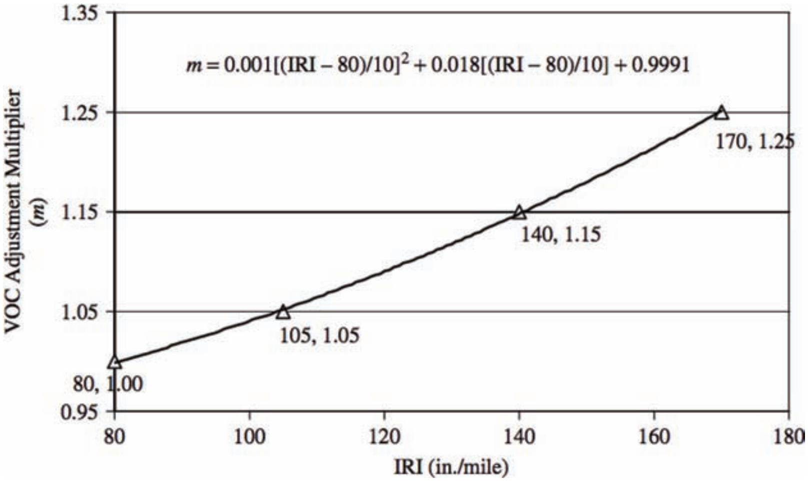


Figure 3.8 VOC adjustment factors for surface roughness (Barnes & Langworthy, 2003).

due to roughness is assumed to be the difference in cost compared to this base level (Opus, 1999). In the current study, the VOCs considered in the user costs are the "incremental" VOCs caused by increased pavement roughness (i.e., the total VOCs minus the base VOCs for a smooth road). The VOC adjustment factor is obtained using an equation from Barnes and Langworthy (2003):

$$m = 0.001 * [(IRI - 80)/10]^2 + 0.018 * [(IRI - 80)/10] + 0.9991$$

where *IRI* is the international roughness index of the pavement surface, and *m* is the VOC adjustment factor. The concept and the equation are illustrated in Figure 3.8. The equation sets the base IRI at 80 in/mi and its m as 1.00. As the IRI increase, m increases, and the incremental VOCs (calculated as Base VOC * (m – 1.0)) also increase.

For the base VOC, the current study adopted the value from *Transportation Decision Making* (Sinha & Labi, 2007): $143 per 1000 vehicle-miles for all vehicle types, in 2007 dollars. This study used $153 per 1000 vehicle-miles, in 2010 dollars (converted from \$143 per 1000 vehicle-miles in 2007 dollars using the inflation rate 2.27%, as calculated in Section 3.3.2.1).

3.3.3.3 Travel Time Costs due to Work Zone Delays. In addition to normal operating costs, the user cost can also increase because of the reduced roadway capacity and reduced travel speed in the work zones of pavement intervention projects. This increased user costs is defined as work zone travel time delay user costs, and it varies depending on the level, duration, and character of the capacity restriction (e.g., traffic during road closure, number of lanes closed and length of closure) (Irfan, 2010). The incremental user costs due to travel time delay in the work zone are given in the following equation (AASHTO, 2003; Irfan, Khurshid, Labi, & Flora, 2009):

$$User\ Cost\ (Travel\ Time\ Delay) = D_{WZ} \sum_{j}^{J} (NV_j * AT_j * DC_j)$$

where D_{WZ} = work zone duration (in hours); NV_j = traffic (number of vehicles) for vehicle class j; AT_j = increase of travel time (in hours) for vehicle class j caused by reduced speed due to work zone activities; and DCj = rate of delay cost for vehicle class j (\$/hour).

The average work zone durations of various M&R activities were estimated using the following equations (Irfan, Khurshid, Anastasopoulos, Labi, & Moavenzadeh, 2010):

$$Road\ Maintenance\ Projects: y = \exp(4.87 + 0.299 * COST + 0.268 * CONTRACT_{TYPE})$$

$$Road\ Resurfacing\ Projects: y = \exp(4.60 + 0.340 * COST + 0.253 * CONTRACT_{TYPE})$$

$$Road\ Construction\ Projects: y = \exp(4.70 + 0.307 * COST + 0.237 * CONTRACT_{TYPE})$$

where D_{WZ} = project duration in days, $COST$ = Final contract cost in \$million (converted to 2010 constant dollars based on FHWA CPI); $CONTRACT_{TYPE}$ = Indicator variable: 1 indicating a fixed deadline date, and 0 indicating specified available days for project completion. A sample calculation for work zone travel delay cost from various M&R treatments is presented in Section 4.1.2 using the method discussed above.

3.4 Cost Benefit Analysis and Optimization

The main focus of this study is determining the optimal trigger condition for various pavement treatments through cost-effectiveness analysis, based on pavement performance jump models, trend models and pavement cost models. The cost-effectiveness of a treatment can be defined as the relationship between the cost of the treatment and the improvement in condition or serviceability of the asset over a given evaluation period (Hicks, Dunn, & Moulthrop, 1997). The costs consist of agency costs involved in construction, routine maintenance and M&R treatment costs, and user costs that are associated with work zone delay and pavement condition. Two types of benefits can be used in a typical benefit-cost analysis: monetized benefits and non-monetized benefits. Typically, the monetized benefit can be quantified based on reduced maintenance and repair costs, enhanced road safety (or reduced crash rates), savings in travel time and vehicle operating costs for road users, and capital expenditure savings (Geoffroy, 1996; Lamptey, 2004; O'Brien, 1989). The non-monetized benefits can be quantified based on the improved asset condition or the extended service life, or the area bounded by the asset performance curve over the analysis years. Cost-effectiveness can be measured at network-level for the entire network of assets, at project level for individual M&R strategies or at treatment level for individual treatments. In addition, cost-effectiveness can be measured in the short-term, such as by improved condition (performance jump) or in the long-term, such as by the extended service life or reduced deterioration rates over the treatment life.

Analysis based on cost-only or effectiveness-only criteria can lead to biased results. Therefore, in the current study, alternative pavement interventions and M&R strategies were evaluated based on both cost and effectiveness over the life cycle of pavement assets, and the long-term cost-benefit analyses were conducted at a project level.

Non-monetized benefits (represented as the area bounded by the asset performance curve) were adopted in the current study and all the costs were converted into their equivalent uniform annual cost (EUAC).

The general equation used to calculate cost-effectiveness (CE) is given as:

$$CEI = \frac{Benefit}{LCC}$$

where CEI = cost effectiveness index, $Benefit$ = area bounded by performance curve, and LCC = life-cycle cost.

3.4.1 Cost Analysis

The costs considered in the context of the cost-benefit analysis in the current study are agency costs and user costs estimated using the methods discussed in Section 3.3. All the costs were converted into 2010 dollars using the inflation rate calculations discussed in Section 3.3. The total cost in each year is the sum of agency cost and weighted user costs. The relative weight, w, considered in this study was varied from

0.1 to 1. The total cost was then converted into EUAC with a certain discount rate using the equation below:

$$EUAC = \sum_{t=1}^{L} \left[(AC_t + w * UC_t) \cdot \frac{1}{(1+r)^T} \right] \cdot \frac{r(1+r)^T}{(1+r)^T - 1}$$

where AC_t and UC_t are the agency costs and user costs incurred in year t; w is the weight for user costs; T is the service life of the pavement; and r is the discount rate.

3.4.2 Area Bounded by Performance Curve

Among all the long-term effectiveness measures, the area bounded by performance curve is probably the most superior because it captures the remaining service life and average condition of the asset (Fwa & Sinha, 1992; Geoffroy, 1996; Khurshid et al., 2010; Labi et al., 2005; Peshkin et al., 2004; Paterson & Chesher, 1986; Wei & Tighe, 2004). The underlying rationale of the area bounded by the performance curve is that that a well-maintained asset will generally have a lower deterioration rate and longer service life, and subsequently, a larger area bounded by the deterioration curve. The larger area indicates a better average condition over the asset's service life, which provides greater benefits for both road users and agencies (Geoffroy, 1996; Khurshid et al., 2010; Labi & Sinha, 2005).

In the current study, the area bounded by the performance curve is the incremental area between the curve of the "do-nothing" or pre-intervention scenario and the post-intervention scenario, as illustrated in Figure 3.9. PI_{UBC} is a preset boundary condition (the upper boundary for IRI in this study). Assets reaching this boundary condition are in a fairly poor state, requiring replacement or reconstruction. The pre-treatment performance curve f_2 (t_p) can be the condition deterioration curve after new construction, or since the last treatment. The post-treatment performance curve f_2 (t) is the performance curve after the treatment application i at year t_a (i) when the performance indicator reaches the condition threshold S_i. The variable t_1 is the pavement service life without treatment i, t_2 is the service life with treatment i, and t_2- t_1 is therefore the extended service life of the asset due to treatment i.

The area over the performance curve (AOC) can be calculated using the following equation:

$$AOC_{(i)} = \left[PI_{UBC} * \left(t_2 - t_{a(i)} \right) \right]$$

$$- \int_{0}^{(t_2 - t_{a(i)})} f_2(t)dt - (PI_{UBC} * \left(t_1 - t_{a(i)} \right) - \int_{t_{a(i)}}^{t_1} f_1\left(t_p\right)dt)$$

where:

$AOC(i)$ = Area over the performance curve for candidate threshold Si

PI_{UBC} = Upper bound of pavement condition

t = Analysis Time

$t_a(i)$ = Analysis time at treatment application

t_1 = Analysis time at S_{UBC} or S_{LBC} for f(tp)

t_2 = Analysis time at S_{UBC} or S_{LBC} for f(t)

$f_1(t_p)$ = Pre-treatment performance function

$f_2(t)$ = Post-treatment performance function

3.4.3 Optimization Problem Formulation

3.4.3.1 Determination of Optimal Trigger Values for an Individual Treatment. The cost-effectiveness (in terms of non-monetized benefits) associated with the candidate condition trigger (possible condition of treatment application) S_i is calculated using the benefit-cost ratio (BCR) method. The objective is to find the optimal threshold that maximizes cost-effectiveness (or AOC). The optimization problem is illustrated in Figure 3.10, and the mathematical formulation of this problem is:

$$argmax_{S_i} \Delta CE_i = argmax_{S_i} \frac{\Delta AOC_{(i)}}{\Delta EUAC_{(i)}}$$

Subject to contraints:

$$S_{LBC} \leq S_i \leq S_{UBC}$$

$$f_1(t_a(i)) = S_i$$

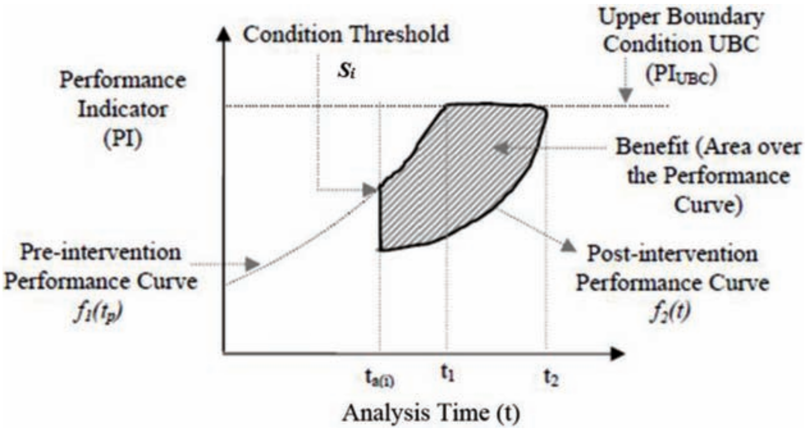


Figure 3.9 Area over the performance curve (AOC) for non-decreasing performance indicator(s) (e.g. IRI, faulting, and corrosion index, etc.) (Irfan, 2010).

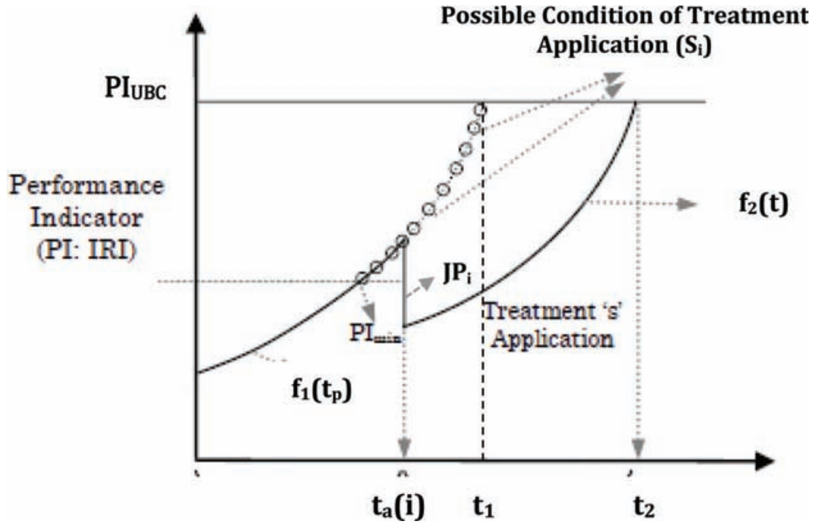


Figure 3.10 Illustration of problem formulation for an individual treatment.

$$f_2(t_a(i)) = S_i - PJ_i$$

$$f_1(t_1) = PI_{UBC}$$

$$f_2(t_2) = PI_{UBC}$$

where:

$$\Delta EUAC_{(i)} = \sum_{t=1}^{t_2} \left[(AC_t + w * UC_t) \cdot \frac{1}{(1+r)^{t_1}} \right] \cdot \frac{r(1+r)^{t_2}}{(1+r)^{t_2} - 1}$$

$$\Delta AOC_{(i)} = \left[S_{UBC} * \left(t_2 - t_{a(i)} \right) \right] - \int_0^{(t_2 - t_{a(i)})} f_2(t) dt$$

$$- (S_{UBC} * \left(t_1 - t_{a(i)} \right) - \int_{t_{a(i)}}^{t_1} f_1\left(t_p\right) dt)$$

t = Analysis Time
$t_a(i)$ = Analysis time at treatment application
t_1 = Analysis time at S_{UBC} or S_{LBC} for $f(t_p)$
t_2 = Analysis time at S_{UBC} or S_{LBC} for f(t)
$f_1(tp)$ = Pre-treatment performance function
$f_2(t)$ = Post-treatment performance function
AC_t = Agency costs incurred in year t
UC_t = User costs incurred in year t
w = the weight for user costs
r = discount rate
PJ_i = Performance jump due to treatment application i at condition S_i
CE_i = Cost-effectiveness index corresponding to candidate trigger condition S_i (Incremental cost-effectiveness comparing to doing nothing after last treatment);
$\Delta AOC_{(i)}$ = Area over the performance curve for candidate condition trigger $S_{i.,}$ (Incremental area comparing to do nothing after last treatment)
$\Delta EUAC_{(i)}$ = Equivalent uniform annual cost converted from pavement life cycle cost with treatment application at condition S_i (at year t_a(i)) (Incremental cost comparing to doing nothing after last treatment)

3.4.3.2 Determination of Optimal Trigger Values for Multiple Treatments. Determining multiple trigger values for a sequence of treatments is a requirement for long-term M&R scheduling. Figure 3.11 illustrates an example of identifying optimal trigger condition S_i for three treatment applications during the life cycle of a pavement. The problem formulation for identifying multiple trigger values in the current study is similar to the one for finding a single optimal trigger, presented in Section 3.4.3.1. There are, however, three additional assumptions that simplify the original problem without losing its essential relationships.

First of all, in reality, the performance jump after the same type of treatment under the same pavement conditions can be different for interventions at different times, because an M&R treatment may be less effective in improving older pavements than in improving newer pavements, as mentioned in Section 2.5.1.1. In the current study, however, because of the lack of pavement condition data during two continuous M&R interventions, only one jump model was developed for each type of treatment, and the only explanatory variable included was the pre-treatment condition. Therefore, the performance jump of the same treatment was assumed to be the same when pre-treatment conditions were the same. For the same reason, the post-treatment performance trend model was assumed to be unchanged for the same type of treatment over the pavement life cycle.

Second, PI_{min} (the minimum value of the indicator) and PI_{UBC} (the upper bound condition) could be different for different types of treatment applications. In the current study, however, they are assumed to have constant values over the pavement service life when there are multiple treatments.

Finally, each treatment application is assumed to be independent of the others. In other words, the condition

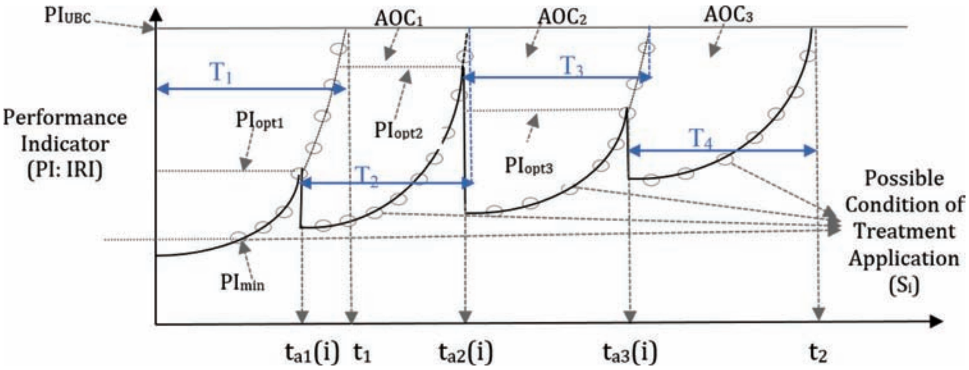


Figure 3.11 Illustration of problem formulation for multiple treatments (three applications).

at which a treatment is applied will not affect the optimal solution (trigger condition) for the previous treatment applications, although it will affect total AOC, overall life-cycle costs, EUAC, and overall CE Index.

Figure 3.10 illustrates an example of the multiple treatments scenario, where T_1, T_2, T_3, and T_4 are the analysis times for each of four treatment applications, respectively. The analysis time of treatment i(T_i) is the time period from the application time of treatment i-1 to the end of pavement service life with the first i-th treatments. All the threshold candidates (possible conditions that could trigger treatment application) for treatment i are the conditions given by the pre-treatment performance curve within the analysis period T_i. The pre-treatment performance curve of treatment i becomes the post-treatment performance curve of treatment i+1, and the post-treatment condition of treatment i becomes the initial IRI of treatment i+1. As discussed in the assumptions above, the optimal solution for treatment i will not be affected by treatments applied after it.

3.4.3.3 Solution and Program Development. To solve the optimization problem formulated in Sections 3.4.3.1 and 3.4.3.2, a MATLAB program was developed to iteratively search for the optimal trigger condition PI_{opti} through calculating the AOC and EUAC associated with each possible condition of treatment application S_i, and identifying the one that would obtain the largest benefit to cost ratio (Cost-effectiveness index: CE_i). The user-specific inputs to the program include initial IRI (IRI at the beginning of analysis), PI_{UCB} (IRI upper bound), pavement length, number of lanes, user cost weight (ratio of user cost to agency cost), discount rate, inflation rate, and type of individual treatment (or sequence of treatments). The output results include the optimal trigger condition for an individual treatment (or for multiple treatments), and the associated benefit area, EUAC, CE index, and pavement service life.

4. APLLICATION, RESULTS AND ANALYSIS

This chapter applies the methods proposed in Sections 3.2 and 3.3 to develop the basic models (jump models, post-treatment performance trend models, and pavement cost models), then applies the framework discussed in Section 3.4.3 to identify the optimal trigger condition for different treatments and pavement families. A case study is given in Section 4.3.1 to clarify the details of how to apply the framework, followed by a sensitivity study and long-term M&R strategies.

4.1 Treatment-Specific Performance Model Results

4.1.1 Jump Model Results

Table 4.1 presents the model results using the two model formulae discussed in Section 3.2.1 for different types of treatments and different families of pavements:

Linear form: $IRI\ Jump = \beta_0 + \beta_1 * PreIRI$

Logarithmic form: $IRI\ Jump = \beta_0 + \beta_1 * ln\ (PreIRI)$

Figure 4.1 presents examples of two model plots: actual observation and fitted curve. Figure 4.2 presents the comparison of the estimated performance jump for different types of treatments on Interstate highways, using the developed performance jump models for flexible/composite and rigid pavements, respectively.

4.1.2 Post-Performance Trend Model Results

Table 4.2 presents the statistical model results of post-performance trend modeling using the exponential (1) functional form proposed in Table 3.2 under Section 3.2.2. For each type of treatment and each family of pavement:

$$IRI_t = PostIRI * exp(\beta_1 * t)$$

where IRI_t is IRI condition at year t after the last application of treatment, $PostIRI$ is the IRI after the improvement due to treatment application:

$$PostIRI = PreIRI - Jump$$

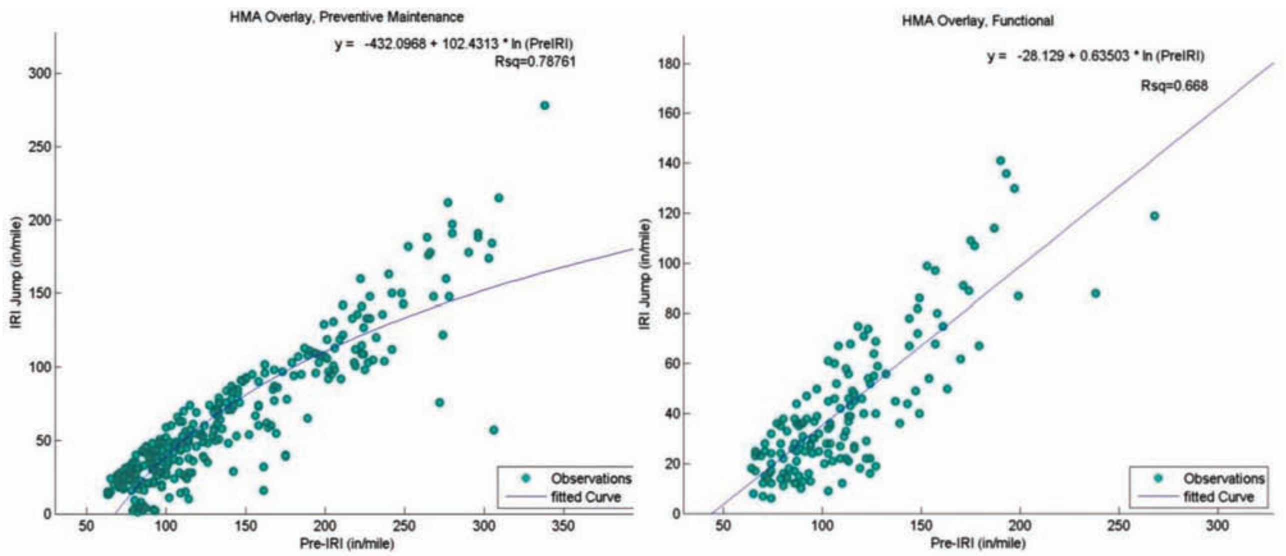
In the proposed exponential equation, $PostIRI$ can be viewed as the initial IRI at age 0 (the time of treatment application), because when $t = 0, IRI_t = PostIR.\hat{a}_1$ is the pavement deterioration rate after the treatment application. The developed models were not available

TABLE 4.1
Treatment-Specific Performance Jump Modeling Results

				Parameter Estimation		
Pavement Treatment		**Model Form**	**Sample Size**	β_0	β_0	**Adjusted R^2**
(a) Interstate Model Results						
		Flexible Pavements				
Preventive Maintenance	Crack Sealing	NA				
	HMA Overlay, Preventive Maintenance	Logarithmic	39	-235.84	59.2	0.24
Rehabilitation	HMA Overlay, Minor Structural	Linear	189	-28.13	0.64	0.67
	HMA Overlay, Major Structural	Linear	134	-28.88	0.65	0.73
New Construction	Pavement Replacement, HMA	NA				
		Rigid Pavements				
Preventive Maintenance	PCCP Cleaning and Sealing Joints	NA				
	Diamond Grinding	Logarithmic	5	-378.25	86.41	0.87
	Crack Sealing	NA				
Rehabilitation	Crack & Seat PCCP & HMA Overlay	Linear	43	-53.17	0.90	0.65
	Rubblize PCCP & HMA Overlay	Linear	5	-39.23	0.68	0.60
	PCCP on PCC Pavement	Linear	9	-68.95	0.79	0.88
	Repair PCCP & HMA Overlay	Linear	82	-45.97	0.86	0.92
New Construction	Pavement Replacement, New PCC	Linear	452	-37.51	0.93	0.75
		Composite Pavement				
Crack & Seat Composite Pavement & HMA Overlay		Linear	92	-13.75	0.58	0.69
Rubblize Composite & HMA Overlay		NA				
(b) NHS Non-Interstate Model Results						
		Flexible Pavements				
Preventive Maintenance	Crack Sealing	NA				
	HMA Overlay, Preventive Maintenance	Logarithmic	294	-432.10	102.43	0.79
Rehabilitation	HMA Overlay, Functional	Linear	1176	-35.30	0.74	0.76
	HMA Overlay, Structural	Linear	588	-41.32	0.78	0.81
New Construction	Pavement Replacement, HMA	Linear	21	-51.27	1.01	0.90
		Rigid Pavements				
Preventive Maintenance	PCCP Cleaning and Sealing Joints	Logarithmic	27	-386.29	92.62	0.59
	Diamond Grinding	Logarithmic	10	-698.14	152.83	0.31
	Crack Sealing	NA				
Rehabilitation	Crack & Seat PCCP & HMA Overlay	Linear	86	-38.12	0.78	0.81
	Rubblize PCCP & HMA Overlay	Linear	38	-85.16	1.08	0.94
	PCCP on PCC Pavement	NA				
	Repair PCCP & HMA Overlay	Linear	36	1.78	0.48	0.57
New Construction	Pavement Replacement, New PCC	Linear	1304	-41.46	0.79	0.84
		Composite Pavement				
Crack & Seat Composite Pavement & HMA Overlay		Linear	33	5.28	0.44	0.65
Rubblize Composite & HMA Overlay		Linear	27	-10.98	0.70	0.71

TABLE 4.1
(Continued)

				Parameter Estimation		
Pavement Treatment		**Model Form**	**Sample Size**	β_0	β_0	**Adjusted R^2**
(c) Non-NHS Model Results						
		Flexible Pavements				
Preventive Maintenance	Crack Sealing	Logarithmic	28	-492.89	113.65	0.54
	HMA Overlay, Preventive Maintenance	Logarithmic	1962	-484.57	112.10	0.72
Rehabilitation	HMA Overlay, Functional	Linear	364	-34.09	0.71	0.80
	HMA Overlay, Structural	Linear	833	-35.01	0.70	0.77
New Construction	Pavement Replacement, HMA	Linear	26	-54.02	0.76	0.87
		Rigid Pavements				
Preventive Maintenance	PCCP Cleaning and Sealing Joints	NA				
	Diamond Grinding	NA				
	Crack Sealing	Logarithmic	28	-492.89	113.65	0.54
Rehabilitation	Crack & Seat PCCP & HMA Overlay	Linear	94	-58.92	0.92	0.86
	Rubblize PCCP & HMA Overlay	Linear	22	-44.56	0.86	0.88
	PCCP on PCC Pavement	NA				
	Repair PCCP & HMA Overlay	NA				
New Construction	Pavement Replacement, New PCC	Linear	553	-38.79	0.71	0.67
		Composite Pavement				
Crack & Seat Composite Pavement & HMA Overlay		Linear	38	-30.76	0.73	0.74
Rubblize Composite & HMA Overlay		Linear	22	-44.56	0.86	0.88

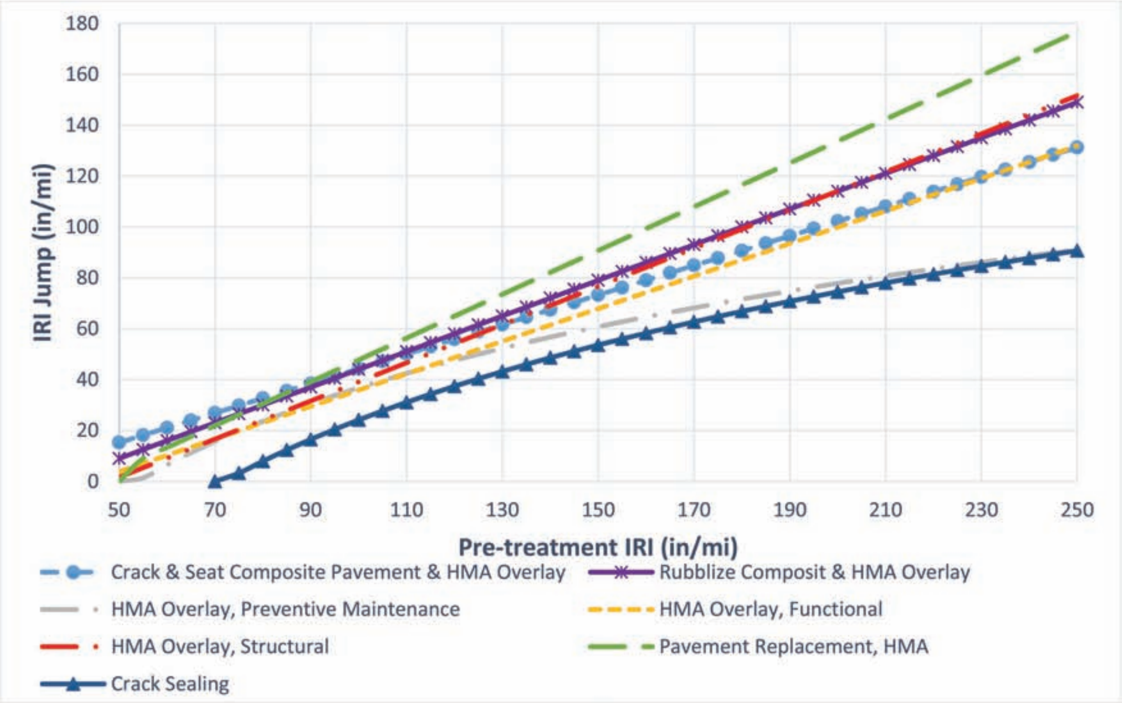


(a) HMA Thin Overlay (NHS)

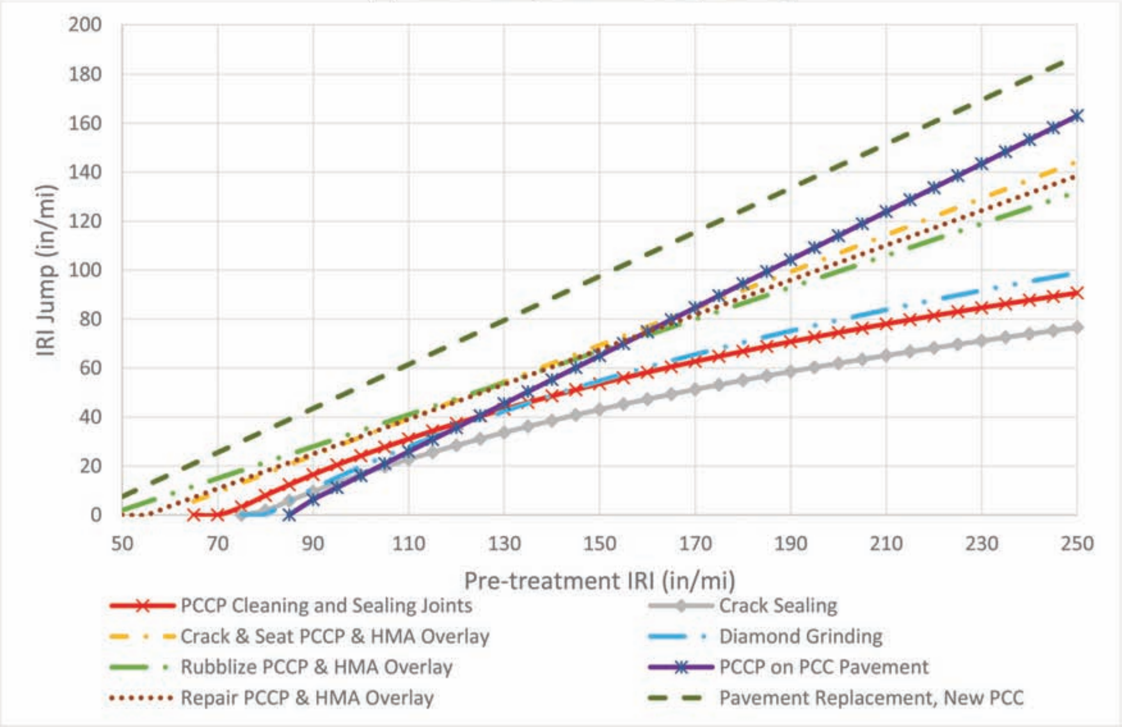
(b) HMA Functional Overlay (Interstate)

Figure 4.1 Jump model examples for various treatments.

for some of the treatments in each functional class, due to limited data availability or data quality. For these unavailable models, the model from other functional classes will be used for the same type of treatment. For example, the performance model for crack sealing is only available for Interstates, and not available for either



(a) Flexible/Composite Pavements (Interstate)



(b) Rigid pavements (Interstate)

Figure 4.2 Comparison of jump models for various treatments.

NHS Non-Interstates or Non-NHS roads. The model built for Interstates will be used for all functional classes.

A comparison between the estimated rates β_1 across different type of treatments found that pavements generally deteriorate faster after preventative maintenance than after more intensive rehabilitation or reconstruction. Comparing β_1 across different families of pavements showed that pavements on interstate roads are in general associated with higher deterioration rates than pavements on NHS Non-Interstate and Non-NHS roads, especially after preventative maintenance, such as asphalt patching, HMA

TABLE 4.2
Treatment-Specific Post-Treatment Performance Trend Modeling Results

Pavement Treatment		β_1	R^2	**Sample Size**
(a) Interstate Model Results				
Flexible Pavements				
Preventive Maintenance	Crack Sealing	0.099	0.407	38
	HMA Overlay, Preventive Maintenance	0.097	0.809	7
Rehabilitation	HMA Overlay, Minor Structural	0.070	0.804	133
	HMA Overlay, Major Structural	0.061	0.741	95
New Construction	Pavement Replacement, HMA	0.044	0.746	11
Rigid Pavements				
Preventive Maintenance	PCCP Cleaning and Sealing Joints	0.082	0.641	4
	Diamond Grinding	0.090	0.700	15
	Crack Sealing	0.099	0.407	38
Rehabilitation	Crack & Seat PCCP & HMA Overlay	0.062	0.454	61
	Rubblize PCCP & HMA Overlay	0.068	0.866	12
	PCCP on PCC Pavement	0.050	0.812	3
	Repair PCCP & HMA Overlay	0.068	0.674	229
New Construction	Pavement Replacement, New PCC	0.034	0.526	8
Composite Pavement				
Crack & Seat Composite Pavement & HMA Overlay		0.073	0.748	32
Rubblize Composite & HMA Overlay		0.080	0.496	14
(b) NHS Model Results				
Flexible Pavements				
Preventive Maintenance	Crack Sealing	0.084	0.536	122
	HMA Overlay, Preventive Maintenance	0.083	0.761	36
Rehabilitation	HMA Overlay, Minor Structural	0.07	0.767	744
	HMA Overlay, Major Structural	0.059	0.808	15020
New Construction	Pavement Replacement, HMA	0.048	0.907	20
Rigid Pavements				
Preventive Maintenance	PCCP Cleaning and Sealing Joints	0.078	0.692	114
	Diamond Grinding	0.039	0.759	32
	Crack Sealing	0.084	0.536	122
Rehabilitation	Crack & Seat PCCP & HMA Overlay	0.056	0.673	644
	Rubblize PCCP & HMA Overlay	0.065	0.811	384
	PCCP on PCC Pavement	NA	NA	3
	Repair PCCP & HMA Overlay	0.037	0.961	52
New Construction	Pavement Replacement, New PCC	0.043	0.772	20
Composite Pavement				
Crack & Seat Composite Pavement & HMA Overlay		0.046	0.465	28

TABLE 4.2
(Continued)

Pavement Treatment		β_1	R^2	Sample Size
Rubblize Composite & HMA Overlay		0.072	0.924	32
(c) Non-NHS Model Results				
Flexible Pavements				
Preventive Maintenance	Crack Sealing	0.085	0.920	24
	HMA Overlay, Preventive Maintenance	0.087	0.793	266
Rehabilitation	HMA Overlay, Minor Structural	0.065	0.458	4682
	HMA Overlay, Major Structural	0.057	0.659	14042
New Construction	Pavement Replacement, HMA	0.042	-0.081	20
Rigid Pavements				
Preventive Maintenance	PCCP Cleaning and Sealing Joints	NA		
	Diamond Grinding	0.061	0.685	6
	Crack Sealing	0.085	0.920	24
Rehabilitation	Crack & Seat PCCP & HMA Overlay	0.054	0.636	62
	Rubblize PCCP & HMA Overlay	0.036	0.610	12
	Rubblize PCCP & HMA Overlay	NA		
	PCCP on PCC Pavement	NA		
New Construction	Repair PCCP & HMA Overlay	0.037	0.766	6
Composite Pavement				
Crack & Seat Composite Pavement & HMA Overlay		0.063	0.829	60
Rubblize Composite & HMA Overlay		NA		

thin overlay, PCCP Cleaning and Sealing Joints, PCCP Patching and crack sealing. This might due to the fact that, even though Interstate roads have higher design standards and stricter requirements for maintenance and rehabilitation, the much higher traffic volume (especially truck traffic) that these roads carry compared to other roads causes pavements on Interstates to deteriorate faster, especially after those treatments that have less protective effects on pavements.

Figure 4.3 presents some of examples of actual observations and fitted curves. Figure 4.4 compares the estimated post-treatment performance on Interstate highways, using the developed performance trend models for flexible/composite pavements and rigid pavements, respectively.

4.2 Pavement Cost Model Results

4.2.1 Agency Cost Model Results

As proposed in Section 3.3.1, two functional formulae were applied to develop the agency cost model for different types of treatments. The models developed were not for each functional class separately, due to the limited availability of data. The statistics for all contract data can be found in Table 4.3.

The two functional formulae are:

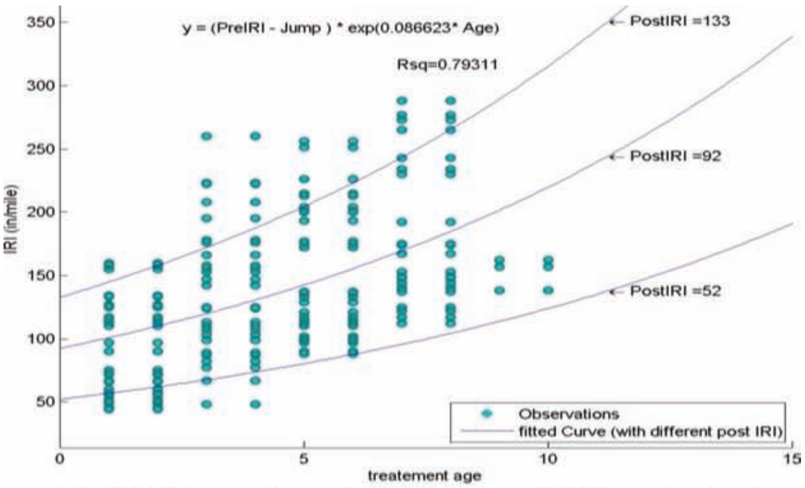
$$\text{Formula (1): Unit Cost (\$1000 / lane * mile)} = \beta_0 + \beta_1 * \ln(length * Lanes)$$

$$\text{Formula (2): Final Cost (\$1000)} = \exp(\beta_0 * length^{\beta_1}\, lanes^{\beta_2})$$

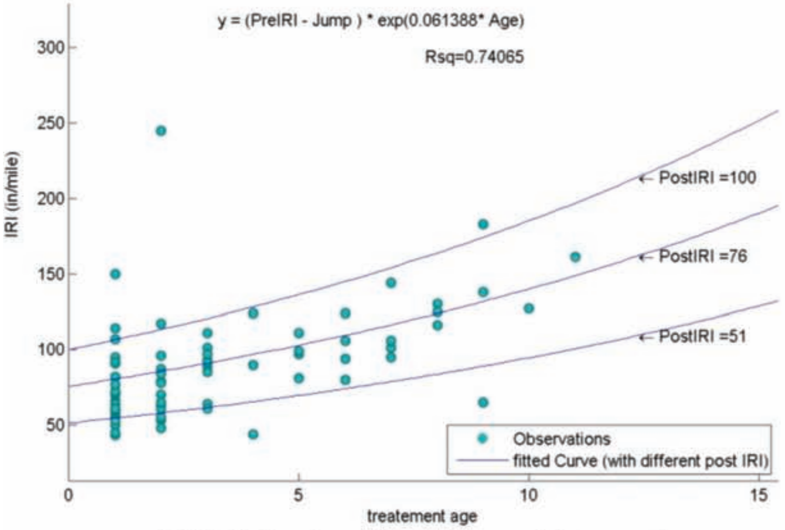
Using statistical software, the functional formula with the higher R^2 was selected for each type of treatment. To make the estimated unit cost (based on the developed models) more realistic, a lower bound on the unit cost was applied using the following equation for each type of treatment:

$$Unit\ Cost\ (treatment\ i) \geq UC_{mean}\ (treatment\ i) - r * UC_{std}\ (treament\ i)$$

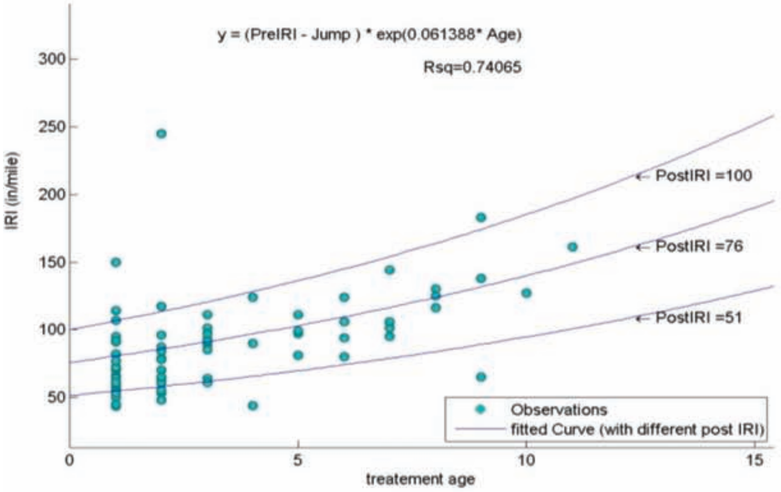
where *Unit Cost* (*treatment i*) is the estimated unit cost for treatment i using developed cost model, UC_{mean} (*treatment i*) is the average unit cost for treatment i, UC_{std} (*treatment i*) is the standard deviation of unit cost for treatment i. UC_{mean} and UC_{std} can be found in Table 4.3. The ratio r is between 0 and 1. The lower bounds



(a) HMA Overlay, Preventive Maintenance (NHS Non Interstate)

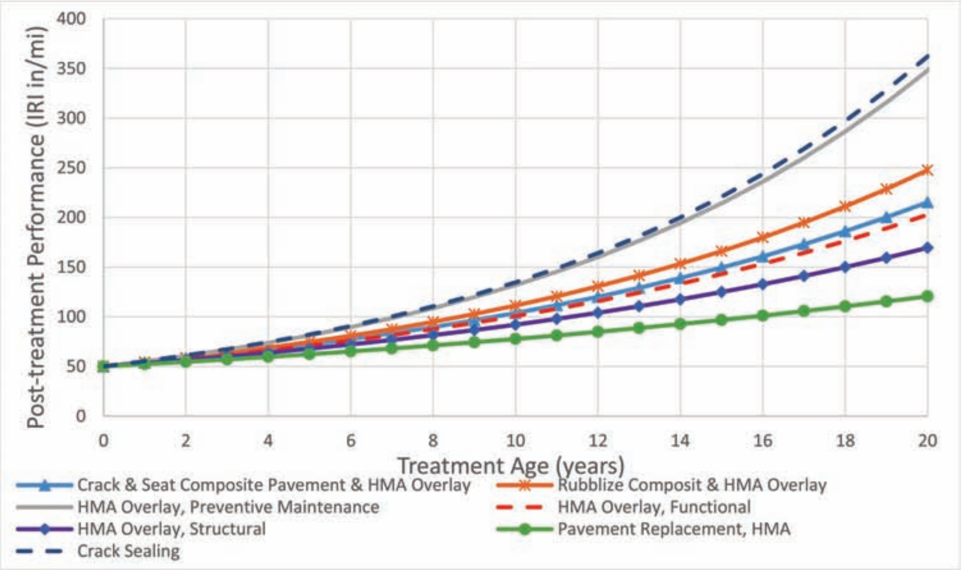


(b) HMA Overlay, Minor Structural (Interstate)

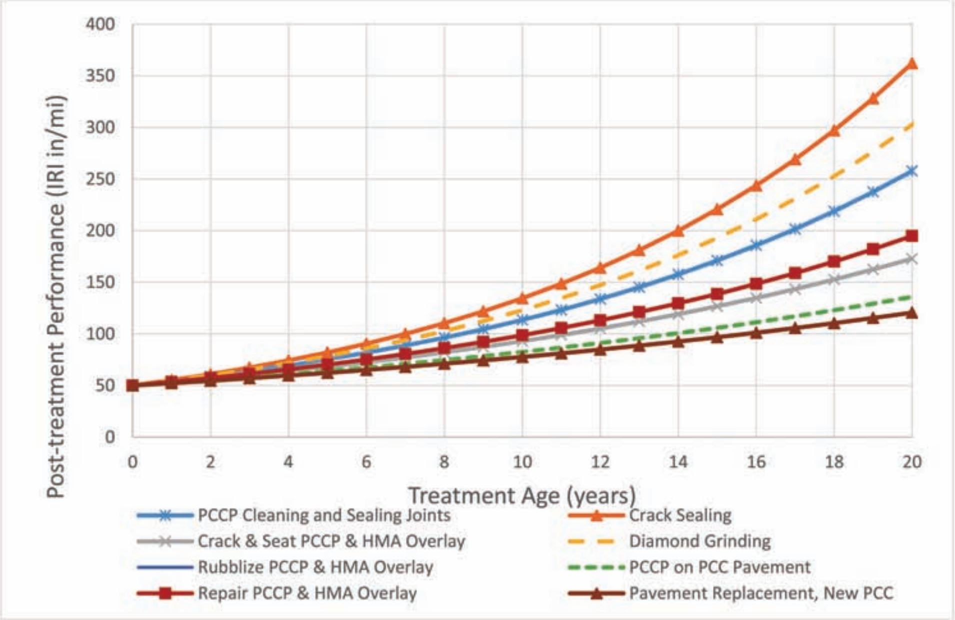


(c) HMA Overlay, Major Structural (Non-NHS)

Figure 4.3 Post-treatment performance trend model.



(a) Flexible/Composite Pavements (Interstate, initial IRI: 50)



(b) Rigid Pavements (Interstate, initial IRI: 50)

Figure 4.4 Comparison of jump models for various treatments.

calculated using different ratios were compared, and 0.7 was selected for the current study, based on analysis.

The model results are presented in Table 4.4. For some treatments, however, there are not enough observations for statistical modeling. The unit costs from Table 4.3 were used instead for these treatments. A summary of the final results is presented in Table 4.5. Figure 4.5 illustrates the estimated unit cost for an HMA functional overlay for different pavement lengths and numbers of lanes, using the developed model. Figure 4.6 compares the unit costs among different type of treatments and project sizes.

4.2.3 User Cost Sample Calculation

This section presents sample calculations for user costs associated with pavement M&R treatments. They include the incremental VOC due to surface roughness and the travel delay costs in M&R treatment work zones using the methods presented in Section 3.3.2.

TABLE 4.3
Unit Agency Costs of All Contracts ($1000/Lane-Mile in 2010 Dollars)

		Unit Cost ($ 1000 Per Lane-Mile) Year 2010 Constant $			
Treatment	**Sample Size**	**Mean**	**Min**	**Max**	**Stdv**
Asphalt Patching	5	89	21	335	124
Crack & Seat Composite Pavement & HMA Overlay	23	515	26	1922	376
Crack & Seat PCCP & HMA Overlay	22	240	2	529	136
Diamond Grinding	1	98	98	98	0
HMA Overlay, Functional	202	113	2	821	131
HMA Overlay, Preventive Maintenance	33	104	4	313	75
HMA Overlay, Structural	67	183	6	949	202
New Road Construction	1	733	733	733	0
New Road Construction, HMA	1	1956	1956	1956	0
New Road Construction, PCC	30	1463	200	4279	1199
New Road, HMA Paving Only	1	347	347	347	0
New Road, PCC Paving Only	2	769	459	1078	438
Partial 3-R	195	111	7	1439	150
Pavement Replacement	2	886	869	902	23
Pavement Replacement, New PCC	5	1174	513	1746	517
PCCP Cleaning and Sealing Joints	4	38	15	67	22
PCCP on PCC Pavement	2	372	242	503	130
PCCP Patching	21	66	7	439	94
Repair PCCP & HMA Overlay	17	392	24	1729	420
Resurface PCC Pavement (Partial 3/R Standards)	1	148	40	40	0
Road Reconstruction (3R/4R Standards)	2	973	536	1409	617
Road Rehabilitation (3R/4R Standards)	88	461	5	3535	614
Rubblize Composite & HMA Overlay	1	539	539	539	0
Rubblize PCCP & HMA Overlay	3	245	68	593	302
Surface Treatment, PM	3	22	18	28	5
Wedge and Level	20	46	3	454	103

TABLE 4.4
Pavement Treatments Costs Modeling Results

Treatment	**Sample Size**	**Functional Form**	β_0	β_1	β_2	R^2
Partial 3-R	195	Form (1)	395.43	-108.44	-	0.30
HMA Overlay, Functional	202	Form (2)	3.93	0.071	0.058	0.19
HMA Overlay, Preventive Maintenance	33	Form (2)	5.54	0.070	0.051	0.12
HMA Overlay, Structural	67	Form (2)	6.50	0.080	0.095	0.15
PCCP Patching	21	Form (1)	202.73	-51.87	–	0.27
Repair PCCP & HMA Overlay	17	Form (1)	1239.21	-408.97	–	0.62
Crack & Seat Composite Pavement & HMA Overlay	23	Form (1)	1055.27	-301.15	–	0.51
Crack & Seat PCCP & HMA Overlay	22	Form (1)	571.05	-104.81	–	0.26
New Road Construction, PCC	30	Form (1)	3719.30	-1080.97	–	0.25
Pavement Replacement, New PCC	5	Form (1)	2965.94	-715.22	–	0.15
Road Rehabilitation (3R/4R Standards)	88	Form (1)	1469.55	-352.95	–	0.36
Wedge and Level	20	Form (1)	145.62	-40.93	–	0.22

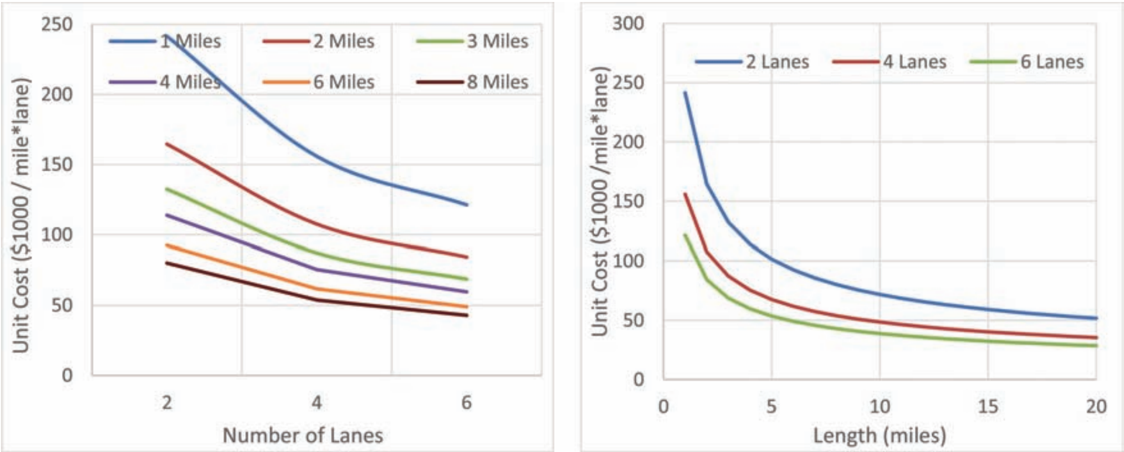
4.2.3.1 Incremental VOC Due to Surface Roughness. A sample calculation of incremental VOC due to roughness during normal vehicle operation is given in Table 4.6 using the method discussed in Section 3.3.2.2. The VOC adjustment factor *m* is estimated using the following equation:

$$m = 0.001 \cdot [(IRI - 80)/10]^2 + 0.018 \cdot [(IRI - 80)/10] + 0.9991$$

4.2.3.2 Work Zone Travel Delay Cost. A hypothetical case study of a one-mile section of a two-lane road is conducted to illustrate the sample calculations of user cost (Table 4.7). The original posted speed limit is 65 mph. During work zone operations, the closure of one lane was required, and the speed limit within work zones was assumed to be 45 mph. The travel time difference due to speed reduction is therefore 0.0068 hours/mile. The user cost per mile per passenger vehicle = 0.0068 × $16.13 = $0.11/lane-mi, and the user cost per mile per single-unit/combination-truck = 0.0068 × $26.89 = $0.183/lane-mi. The amounts of $16.13 and $26.89 are the travel time values (in 2010 dollars) for a passenger vehicle and a single-unit truck/combination-truck respectively, updated from 1996 values ($11.78 and

TABLE 4.5
Final Results of Pavement Treatments Costs

			Sample Size		
Pavement Treatment		**Model Form**	**β_0/Unit Cost**	**β_1**	**β_2**
		Flexible Pavements			
Preventive Maintenance	Crack Sealing	Unit Cost	100		
	HMA Overlay, Preventive Maintenance	Form (2)	5.93	0.071	0.058
Rehabilitation	HMA Overlay, Minor Structural	Form (2)	5.54	0.07	0.051
	HMA Overlay, Major Structural	Form (2)	6.5	0.08	0.095
New Construction	Pavement Replacement, HMA	Form (1)	3719.3	-1080.97	
		Rigid Pavements			
Preventive Maintenance	PCCP Cleaning and Sealing Joints	Unit Cost	38		
	Diamond Grinding	Unit Cost	98		
	Crack Sealing	Unit Cost	100		
Rehabilitation	Crack & Seat PCCP & HMA Overlay	Form (1)	571.05	-104.81	
	Rubblize PCCP & HMA Overlay	Unit Cost	539		
	PCCP on PCC Pavement	Unit Cost	803		
	Repair PCCP & HMA Overlay	Form (1)	392		
New Construction	Pavement Replacement, New PCC	Form (1)	2965.94	-715.22	
		Composite Pavement			
Crack & Seat Composite Pavement & HMA Overlay		Form (1)	1055.27	-301.15	
Rubblize Composite & HMA Overlay		Unit Cost	245		



(a)
(b)

Figure 4.5 Estimated unit cost for (a) different number of lanes and (b) different pavement lengths using developed model (HMA functional overlay, Interstate).

$19.64, respectively) in a past FHWA study (FHWA, 1998). The costs (in $1000s) were estimated using the developed agency cost models presented in Section 4.2.1. The work zone duration was estimated using the following equations provided in Section 3.3.2.3:

Road Maintenance Projects:

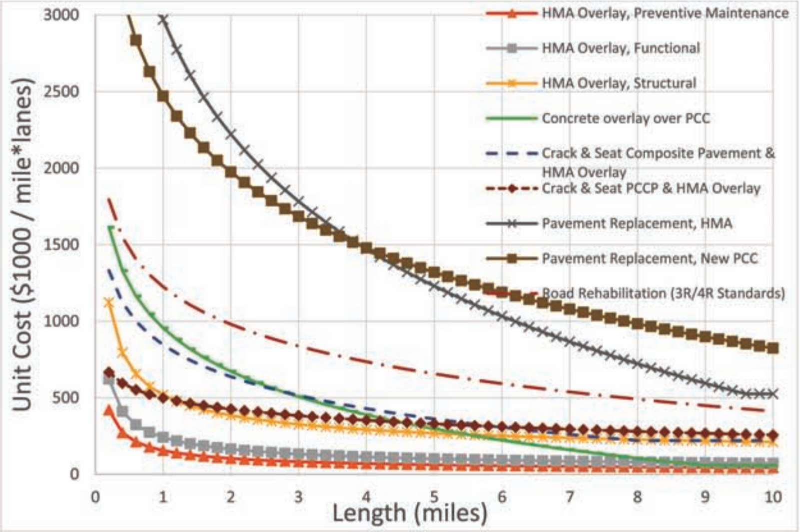
$$y = \exp(4.87 + 0.299 * \mathrm{COST} + 0.268 * \mathrm{CONTRACT}_{\mathrm{TYPE}})$$

Road Resurfacing Projects:

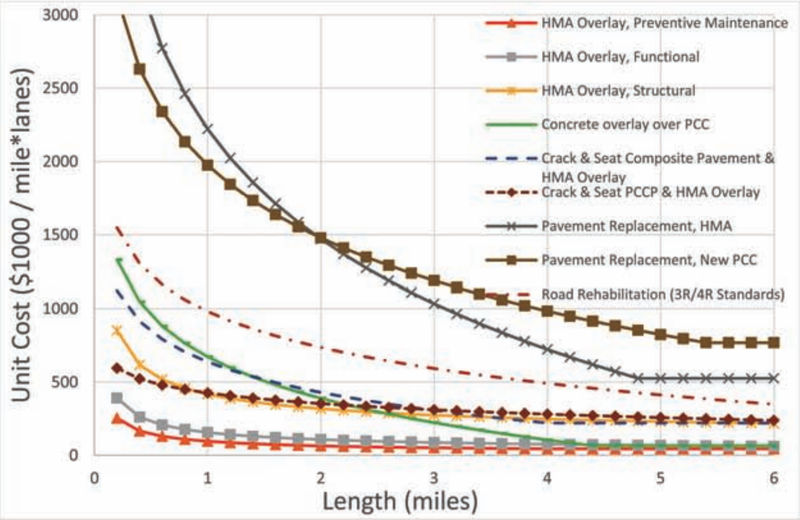
$$y = \exp(4.60 + 0.340 * \mathrm{COST} + 0.253 * \mathrm{CONTRACT}_{\mathrm{TYPE}})$$

Road Construction Projects:

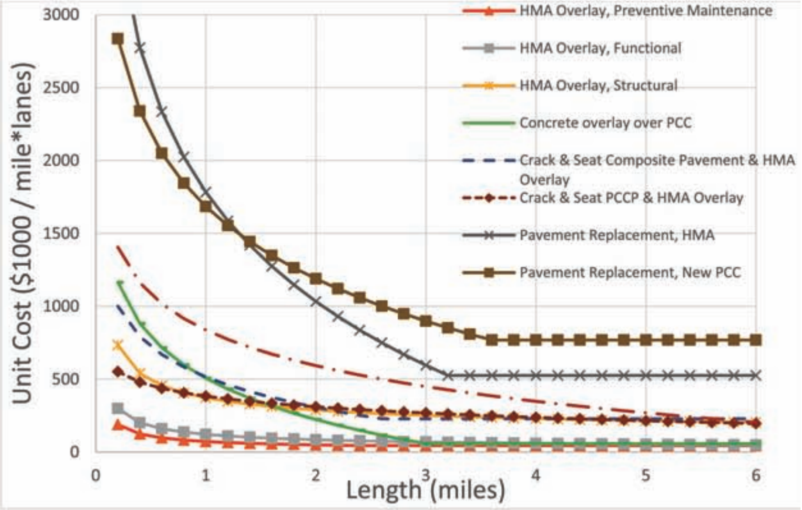
$$y = \exp(4.70 + 0.307 * \mathrm{COST} + 0.237 * \mathrm{CONTRACT}_{\mathrm{TYPE}})$$



(a) 2 Lanes Road



(b) 4 Lanes Road



(c) 6 Lanes Road

Figure 4.6 Comparison of estimated agency cost for various treatments under different project sizes.

TABLE 4.6
Sample Calculation for Estimating Incremental VOC due to Surface Roughness (2010$)

		AADT(Vehicles/Day)		
IRI Condition (in/mi)	**m**	**1,000**	**5,000**	**10,000**
80	1.000	0	0	0
90	1.018	$1,051	$5,256	$10,512
100	1.039	$2,278	$11,388	$22,776
110	1.062	$3,621	$18,104	$36,208
120	1.087	$5,081	$25,404	$50,808
130	1.114	$6,658	$33,288	$66,576
140	1.143	$8,351	$41,756	$83,512
150	1.174	$10,162	$50,808	$101,616
160	1.207	$12,089	$60,444	$120,888
170	1.242	$14,133	$70,664	$141,328
180	1.279	$16,294	$81,468	$162,936
190	1.318	$18,571	$92,856	$185,712
200	1.359	$20,966	$104,828	$209,656
210	1.402	$23,477	$117,384	$234,768
220	1.447	$26,105	$130,524	$261,048
230	1.494	$28,850	$144,248	$288,496
240	1.543	$31,711	$158,556	$317,112
250	1.594	$34,690	$173,448	$346,896

TABLE 4.7
Sample Calculations of Work Zone Travel Time Delay Cost

				Unit Travel Time User Costs[3]		User Costs ($-Per Lane-mi) (2010$)		
Treatment Type	**Final Cost $1,000**	**WZ (Days)[1]**	**65% WZ[2]**	**Auto**	**Truck**	**Auto**	**Truck**	**Sum Total**
Asphalt Patching	$178	137	89	0.11	0.183	$64,255	$12,262	$12,262
HMA Overlay, Preventive Maintenance	$480	150	98	0.11	0.183	$70,322	$13,420	$13,420
HMA Overlay, Functional	$311	111	72	0.11	0.183	$51,694	$9,865	$9,865
HMA Overlay, Structural	$1,035	141	92	0.11	0.183	$66,131	$12,620	$12,620
Resurfacing (Partial 3R)	$245	108	70	0.11	0.183	$50,551	$9,647	$9,647
Pavement Replacement, HMA	$2,221	217	141	0.11	0.183	$101,638	$19,395	$19,395
PCCP Cleaning and Sealing Joints	$76	133	87	0.11	0.183	$62,325	$11,893	$11,893
PCCP Patching	$131	136	88	0.11	0.183	$63,355	$12,090	$12,090
Crack Sealing	$202	138	90	0.11	0.183	$64,718	$12,350	$12,350
Crack & Seat PCCP & HMA Overlay	$426	115	75	0.11	0.183	$53,753	$10,258	$10,258
Diamond Grinding	$196	106	69	0.11	0.183	$49,714	$9,487	$9,487
Rubblize PCCP & HMA Overlay	$1,078	144	93	0.11	0.183	$67,099	$12,804	$12,804
PCCP on PCC Pavement	$2,494	232	151	0.11	0.183	$108,593	$20,723	$20,723
Repair PCCP & HMA Overlay	$672	125	81	0.11	0.183	$58,452	$11,154	$11,154
Resurface PCC Pavement Partial 3-R Standards	$296	142	93	0.11	0.183	$66,563	$12,702	$12,702
Pavement Replacement, New PCC	$1,974	202	131	0.11	0.183	$94,235	$17,983	$17,983
Crack & Seat Composite Pavement & HMA Overlay	$638	124	80	0.11	0.183	$57,771	$11,024	$11,024
Rubblize Composite & HMA Overlay	$490	118	76	0.11	0.183	$54,940	$10,484	$10,484

[1] Contract duration (estimated as a function of contract type and final contract cost) (Irfan, 2010).

[2] Work zone duration (estimated as 65% of contract duration) (Lamptey, 2004).

[3] Travel Time Cost (converted to 2010 dollar value) (BLS, 2016; FHWA, 1998).

TABLE 4.8
Summary of Pavement Information and Program Inputs

Parameters	Input
Analysis beginning Year	2015
Age at analysis beginning Year	5
Functional Class	Interstate
Pavement Length	5 miles
Number of lanes	4 drive lanes
AADT at Year 0	5000 vehicles/day
Average annual traffic growth factor	1.18%
Truck Percentage	15%
Treatment Type	HMA Functional Overlay
Pre-treatment Performance Model	IRI (t) = Pre-treatment IRI * $e^{0.08}$ (Existing Pavement)
Jump Model	Jump = -28.13 + 0.64 * Pre-treatment IRI
Post-treatment Performance Model	IRI (t) = Pre-treatment IRI * $e^{0.07}$
Treatment Cost Model	Unit Cost ($1000/lane * mile) = 5.54 * $\text{Length}^{0.07}$ * $\text{Lanes}^{0.051}$
Initial IRI (IRI at the beginning of analysis period)	90 inch/mile
PI_{UBC} (Upper bound for IRI)	250 inch/mile
PI_{min} (Lower bound for IRI after improvement due to treatment)	50 inch/mile
AC:UC Ratio (Agency Cost :User Cost)	1:0 5:1 1:1
Discount Rate	4%
Inflation Rate for agency cost	1.33%
Inflation Rate for user cost	2.27%
Contract Type	0 (indicating specified available days for project completion)
Speed limit at non-work zones	65 mph
Speed limit for work zone section	45 mph

TABLE 4.9
Example of Possible IRI Triggers and Corresponding Years of Application, Pre-IRI, Performance Jump and Post-IRI

IRI Trigger	100	120	145	165	185	205	225	245	265
Year of Treatment Application	2016	2019	2021	2023	2024	2025	2027	2028	2029
Pavement Age	6	9	11	13	14	15	17	18	19
Pre-IRI	100	120	145	165	185	205	225	245	265
Performance Jump	36	49	65	77	90	103	116	129	141
Post-IRI	64	71	80	88	95	102	109	116	124

4.3 Application of Framework and Optimization Results

4.3.1 A Case Study of Applying the Methodological Framework

To clarify how to apply the method proposed in Section 3.4 based on the developed basic models (jump model, post-treatment performance model and cost model), a case study is conducted in this section. The pavement information and program inputs are given in Table 4.8.

Optimization Problem Formulation. Objective: Maximize CE Index (AOC/EUAC)

Decision Variable: IRI_{trig} (IRI trigger value)
Constraints: 40 inch/mile $\leq IRI_{trig} \leq$ 250 inch/mile
Jump $>$ 0 and Pre-IRI – Jump $\geq$ 50 inch/mile

Problem Solution. To solve the problem, the EUAC and AOC were calculated for each possible IRI_{trig} that meets the constraints. Table 4.9 presents an example of applying the treatment at different IRI conditions. Only some of the IRI triggers were listed due to limited space.

To illustrate the application more clearly, a sample calculation for an IRI trigger of 140 is given below. The agency cost and user cost were calculated using the method presented in Section 3.3 and the cost model developed in Section 4.2. The costs were combined using the AU weights (agency costs:user costs) given in Table 4.8 and then converted into EUAC. The AOC (area over curve) was estimated using the equation provided in Section 3.4.2.

1. Agency Cost:

$$Agency\ Cost\ (\$2010) = exp(5.54 * length^{0.07} * lanes^{0.051}) = \$776{,}594$$

$$Agency\ Cost\ (\$2021) = \$776594 * (1 + 1.33\%)^{(2021-2010)} = \$898{,}074$$

2. Work Zone Delay User Cost:

$$Contract\ Duration = \exp(4.60 + 0.340 * COST + 0.253 * CONTRACT_{TYPE}) = exp(4.60 + 0.340 * 0.9221(million) + 0.253 * 0) = 136\ \text{days}$$

D_{WZ} =0.65 * *Contract Duration* = 0.65 * 136 days = 88 days (Work zone duration estimated at 65% of contract duration (Lamptey, 2004))

Estimated travel time difference = $\frac{1}{45} - \frac{1}{65}$ = 0.0068 hours/mile

User cost for passenger car = 0.0068 * \$16.13 = \$0.11 /(lane-mile)

User cost for single-unit/combination-truck = 0.0068 * \$26.89 = \$0.183/(lane-mile)

$$\text{User Cost (Work Zone Travel Time Delay \$2010)} = D_{WZ} \sum_{j}^{J} (NV_j * AT_j * DC_j)$$

$$= D_{WZ} * [AADT * (1 - Truck_{Percent}) * \$0.11 + AADT * Truck_{Perc} * \$0.183]$$

$$= 88 * [5000 * (1 - 0.15) * \$0.11 + 5000 * 0.15 * \$0.183] = \$53,218$$

$$\text{User Cost(\$2021)} = \$53218 * (1 + 2.27\%)^{(2021-2010)} = \$68,122$$

3. User Cost due to road roughness:
The VOC due to IRI was calculated using the equation provided in Section 3.3.2.1. The VOC in each year during the life cycle is presented in Table 4.10.

4. EUAC:

$$\text{EUAC (Agency)} = \$898074 * \frac{1}{(1+0.04)^{2021-2015}} * \frac{0.04 * (1+0.04)^{2038-2015}}{(1+0.04)^{2038-2015} - 1} = \$47,773$$

$$\text{EUAC (Work Zone User Cost)} = \$68,122 * \frac{1}{(1+0.04)^{2021-2015}} * \frac{0.04 * (1+0.04)^{2038-2015}}{(1+0.04)^{2043-2015} - 1} = \$2,656$$

EUAC (Incremental VOC due to Roughness) = \$64,648 (Calculated using the costs from Table 4.10)

EUAC (Total) = EUAC (Agency) + w * (EUAC (Work Zone User Cost) + EUAC (VOC due to Roughness)) = \$47773+ w * (\$646582 + \$2656)

With AU ratio 1:0: EUAC (Total) = \$47,773

With AU ratio 5:1: EUAC (Total) = \$177,620

With AU ratio 1:1: EUAC (Total) = \$697,011

5. AOC (Benefit):

$$AOC_{(i)} = [S_{UBC} * (t_2 - t_{a(i)})] - \int_0^{(t_2 - t_a(i))} f_2(t)dt - (S_{UBC} * (t_1 - t_{a(i)}) - \int_{t_{a(1)}}^{t_2} f_1(t_p)dt) = 1,257$$

6. Pavement Service Life:
From Figure 4.7, it can be concluded that, without any intervention, it takes 18 years (from construction) for the pavement to reach the IRI upper bound (250 in/mi) at

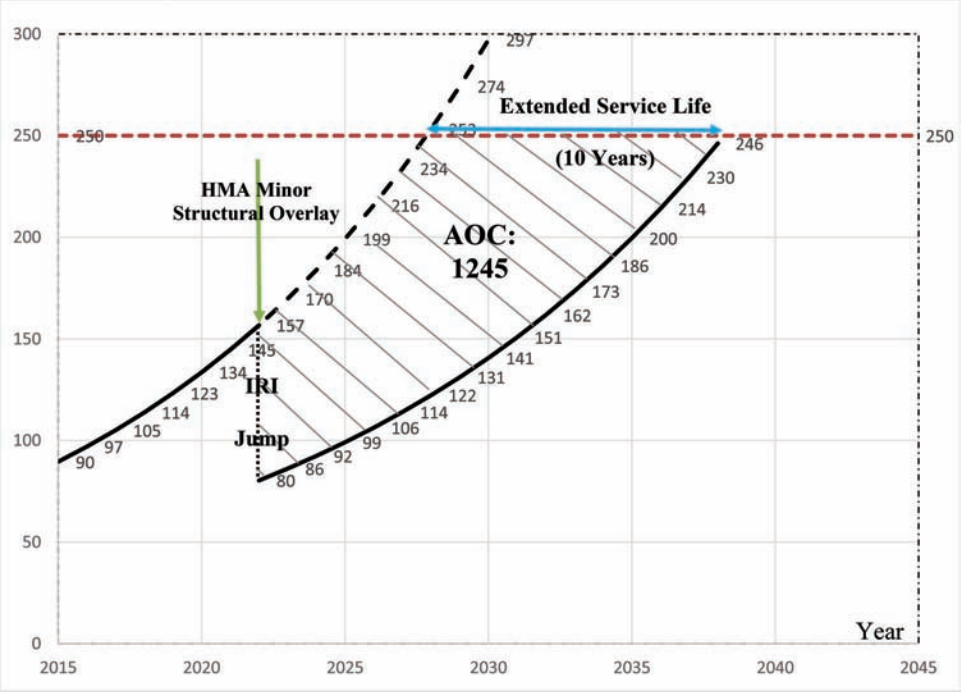


Figure 4.7 Illustration of pre-treatment and post-treatment IRI condition and AOC.

TABLE 4.10
Calculations of Incremental VOC due to Road Roughness (IRI) at Each Evaluation Year

Year	Pavement/Treatment Age	IRI	m	Incremental VOC due to IRI (2010 $)	VOC with Inflation (2010 $)
2015 (Beginning of analysis)	5	90	1.017	$4,964	$5,554
2016	6	97	1.033	$9,636	$11,025
2017	7	105	1.050	$14,600	$17,084
2018	8	114	1.071	$20,732	$24,810
2019	9	123	1.096	$28,032	$34,307
2020	10	134	1.124	$36,208	$45,320
2021	11	145	1.157	$45,844	$58,683
Treatment application 2022	0	80	1.000	0	0
2023	1	86	1.011	$3,212	$4,300
2024	2	92	1.023	$6,716	$9,196
2025	3	99	1.037	$10,804	$15,129
2026	4	106	1.053	$15,476	$22,163
2027	5	114	1.072	$21,024	$30,792
2028	6	122	1.093	$27,156	$40,676
2029	7	131	1.117	$34,164	$52,334
2030	8	141	1.145	$42,340	$66,331
2031	9	151	1.177	$51,684	$82,807
2032	10	162	1.213	$62,196	$101,912
2033	11	173	1.255	$74,460	$124,777
2034	12	186	1.303	$88,476	$151,629
2035	13	200	1.357	$104,244	$182,708
2036	14	214	1.420	$122,640	$219,830
2037	15	230	1.492	$143,664	$263,361
2038 (End of service life)	16	246	1.574	$167,608	$314,229

Year 2028. The service life is therefore 18 years, if no treatment is applied. If HMA functional overlay is applied when the pavement's IRI is 145 in/mi (at year 2022), the service life will be 16 years more after the application of treatment, until the IRI reaches 250 in/mi at Year 2038. The total service life is therefore 28 years, and the extended service life due to HMA functional overlay is 10 years.

7. CE Index (AOC/EUAC)

$$\text{With AU ratio 1:0: } CE_{(i)} = \frac{AOC_{(i)}}{EUAC_{(i)}} = \frac{1257}{47773} = 0.026312$$

$$\text{With AU ratio 5:1: } CE_{(i)} = \frac{AOC_{(i)}}{EUAC_{(i)}} = \frac{1257}{177620} = 0.007077$$

$$\text{With AU ratio 1:1: } CE_{(i)} = \frac{AOC_{(i)}}{EUAC_{(i)}} = \frac{1257}{697011} = 0.001803$$

The given example may not yield the maximum CE Index. To obtain the optimal solution, a MATLAB program was developed to iteratively search for the optimal IRI trigger, or that which yields the largest CE Index (with AC:UC = 1:1), by calculating all the outputs listed in Table 4.11 and following steps 1–7 given in the sample calculation. The results are presented in Table 4.12. The largest CE Index is 0.0196, at year 2018. The optimal IRI trigger is 114 in/mi. Figure 4.8 illustrates how the EUAC, AOC and CE indices change with different IRI triggers.

Next, the case study was extended to illustrate the procedure of identifying optimal trigger conditions for multiple treatments, as discussed in Section 3.4.3.3. Assume now, instead of applying only one treatment (HMA overlay, minor structural), more M&R treatments will be applied during the pavement's service life. In this case study, one candidate M&R strategy was analyzed: HMA overlay, minor structural + HMA overlay, a second minor structural + HMA overlay, then major structural + HMA pavement replacement. The optimal trigger found for each treatment is presented in Table 4.13. Figure 4.9 presents the optimal timings for the proposed four pavement treatments, and the IRI conditions under such optimal M&R timings over the pavement's life cycle. The analysis ends at the time of pavement replacement, though the cost of pavement replacement is still included in the analysis. Table 4.14 represents the overall EUAC, AOC, and CE Index under the established optimal timings of the evaluated M&R strategy.

4.3.2 Optimal Trigger Condition Results for Individual Treatment

By applying the proposed framework to all the treatments considered in the current study, and following the process presented in the case study in this section, the optimal trigger conditions were obtained for each type of treatment for different pavement families. Table 4.15 presents the initial settings of the input parameters for each family of pavement. The results are presented in Table 4.16 for Interstates, NHS Non-Interstates and Non-NHS roads, respectively. Figure 4.10(1)–(15) presents the optimal trigger conditions for all the M&R treatments on different functional classes, and illustrates how the cost-effectiveness of each treatment type changes with changing trigger conditions.

TABLE 4.11
Summary of Sample Calculation Results with IRI Trigger 140

IRI Trigger		145	
Year of application		2021	
Pavement Age		11 + 5 = 16	
Jump		65	
Post-IRI		80	
Post-treatment Performance		IRI (t) = 80 * $e^{0.07}$	
Agency Cost		$898,074	
Work Zone User Cost		$71,250	
EUAC(Agency)		$47,773	
EUAC(Work Zone User Cost)		$2,656	
giEUAC(Incremental VOC due to roughness)		$64,648	
Service Life after 2015		2038–2015 = 23 years	
Extended Service Life		23 – 13 = 10 years	
AOC (Benefit)		1245	
AC:UC Ratio	1:0	5:1	1:1
Total EUAC	$47,773	$61,233	$11,5077
CE Index	0.0263	0.0205	0.0109

TABLE 4.12
Optimization Results of the Case Study with AC:UC Ratio 5:1 (Output from MATLAB)

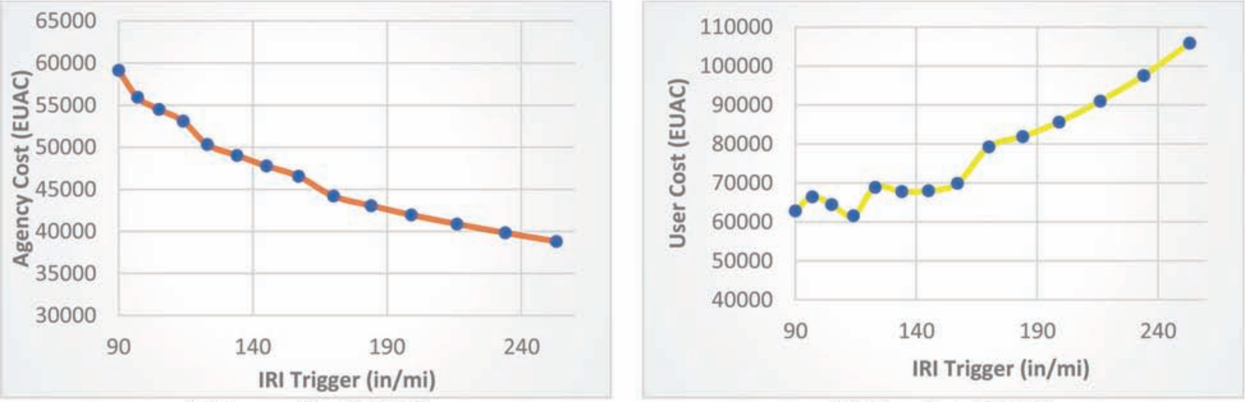
Year	Trigger IRI	EUAC (Agency Cost)	EUAC (Work Zone User Cost)	EUAC (VOC)	EUAC (Total)	AOC	CE Index
2015	90	59136	3139	597048	71705	1166	0.0163
2016	97	55936	2997	634404	69223	1212	0.0175
2017	105	54500	2947	615094	67391	1229	0.0182
2018	114	53100	2898	586853	65417	1257	0.0192
2019	123	50324	2772	660873	64096	1258	0.0196
2020	134	49032	2726	650761	62593	1259	0.0201
2021	145	47773	2681	653292	61375	1245	0.0203
2022	157	46547	2636	672473	60524	1207	0.0199
2023	170	44192	2526	767223	60041	1169	0.0195
2024	184	43057	2484	794269	59439	1119	0.0188
2025	199	41952	2443	831872	59078	1056	0.0179
2026	216	40875	2402	885793	59071	973	0.0165
2027	234	39825	2362	951889	59335	877	0.0148
2028	253	38803	2323	1035427	59976	763	0.0127

4.4 Sensitivity Analysis

In the previous sections, fixed parameters and deterministic models were used throughout the analysis. However, the optimal trigger values can be affected by the dynamics of various influential factors, such as project size, which affects agency costs; the relative weights given to agency costs and user costs, which affect the total cost; the upper bound of IRI (PI_{UBC}) and pre-treatment performance deterioration rate, which affect the benefit area; traffic volume which affects user costs; and discount rates that affect EUAC. To investigate the robustness of the optimal triggers results, sensitivity analysis was conducted with respect to various explanatory variables, i.e., how the change in these influential factors influences the optimal triggers.

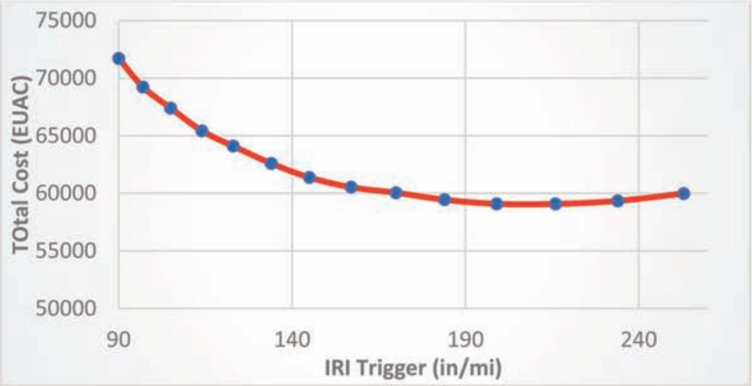
4.4.1 Effect of Weight between Agency Costs and User Costs

First, the ratio of agency costs to user costs was tested. As discussed in Chapter 2, the issue of whether and how (with what weight) to incorporate user costs has long been a major challenge in pavement M&R scheduling. The current study does not set a fixed weight for user costs, but provides results for different assumed weights. Thus, INDOT can decide on the weights based on their needs. In the current study, the user costs are much larger than the agency costs and therefore the weight selected should be relatively small. The AC:UC ratio of 5:1 is recommended, based on the need for a reasonable balance between agency cost and user cost. The sensitivity analysis results in terms of user cost weight are presented in Table 4.17 and Figure 4.11. The optimal trigger IRI decreases significantly as the AC:UC

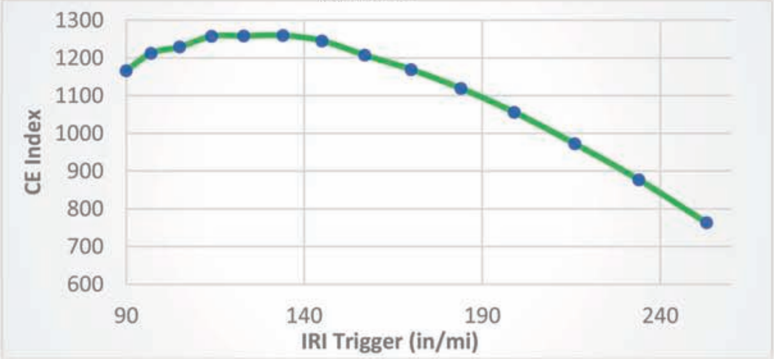


(a) Agency Cost (EUAC)

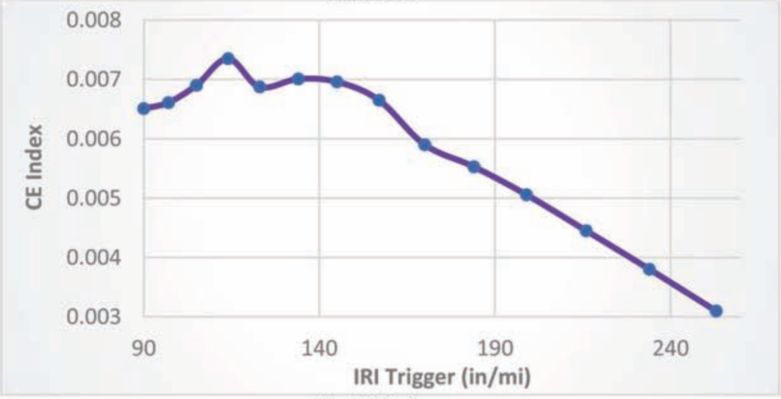
(b) User Cost (EUAC)



(c) EUAC



(d) AOC



(e) CE Index

Figure 4.8 Change of various measurements with different IRI triggers.

TABLE 4.13
Results of Optimal Trigger IRI for Multiple Treatments with 5:1 AU Weight

	HMA Overlay, PM	HMA Overlay, Minor Structural	HMA Overlay, Major Structural	HMA Pavement Replacement
Optimal Trigger IRI	114	130	162	215
Year of treatment application	3	13	25	43
AOC	1257	1204	1724	–
EUAC(agency cost)	$53,100	$40,202	$209,891	$337,238
EUAC(work zone user cost)	$2,898	$2,319	$7,641	$27,512
EUAC(VOC due to surface roughness)	$590,944	$531,126	$597,046	$731,810
EUAC(Total)	$171,869	$146,891	$330,829	$489,102
CE Index	0.00732	0.00819	0.00521	–

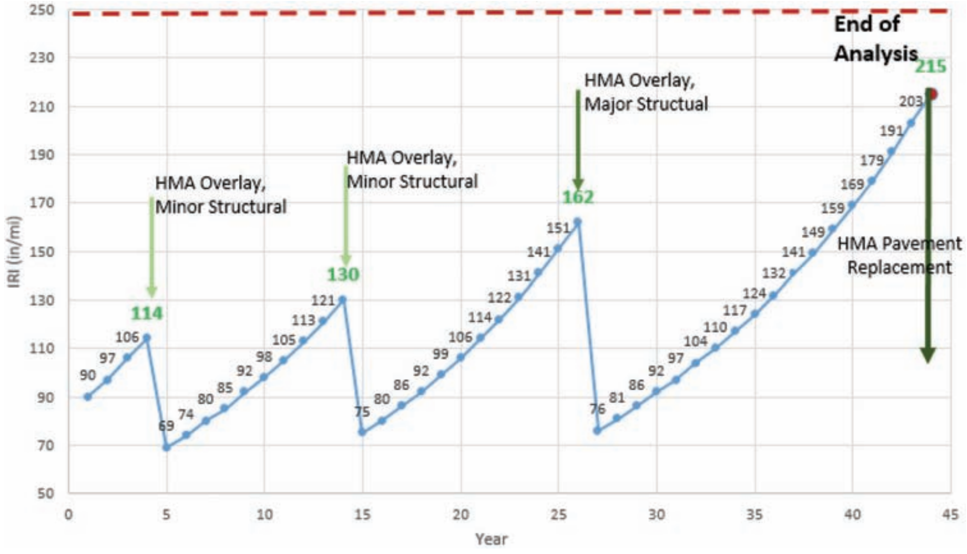


Figure 4.9 Illustration of optimal solution for the evaluated M&R strategy.

TABLE 4.14
Overall EUAC, AOC, and CE Index over Service Life under the Evaluated M&R Strategy (HMA Pavement Replacement Not Included)

Measurement	Output
EUAC (Agency cost)	$84,726
EUAC (Work zone user cost)	$43,402
EUAC (VOC due to surface roughness)	$4,106,317
EUAC (Total)	$1,677,205
Overall AOC	6,242
Overall CE Index	0.00372
Total Service Life	44 years
Extended Service Life (Compared to doing nothing)	29 years

ratio decreases. This is intuitive, because the user costs begin dominating the total costs as the AC:UC ratio decreases, and the user costs would be smaller for a pavement with a lower trigger IRI than for pavements that are repaired later when the IRI is higher.

4.4.2 Effect of Traffic Volume

Traffic volume, an important factor that influences user costs profoundly, was then tested. The sensitivity analysis results are presented in Table 4.18 and Figure 4.12 for HMA minor structural overlay on an Interstate. An increasing traffic volume was found to have a similar effect on the optimal triggers to that of the increasing weight of user costs, because user costs largely depend on traffic volume. Therefore, when traffic volume increases, the optimal IRI trigger (the one yields the highest cost-effectiveness) decreases.

4.4.3 Effect of IRI Upper Bound (PI_{UBC})

The third tested factor was IRI Upper Bound (PI_{UBC}). The sensitivity analysis results are presented in Table 4.19 and Figure 4.13. The optimal trigger IRI increases significantly, under all the tested AC:UC ratios, as the IRI upper bound increases. It is intuitive that the optimal trigger IRI could be higher for pavements that have a higher tolerance for poor conditions.

4.4.4 Effect of Pre-Treatment Performance Curve

Another important factor to consider is the pre-treatment performance deterioration rate (β_1). These sensitivity analysis results are presented in Table 4.20 and Figure 4.14. The optimal trigger IRI decreases

TABLE 4.15
Initial Settings of Input Parameters for Pavements in Different Families

Parameters	**Initial IRI**		**Pre-treatment Performance Deteriorating Rate**		**IRI Upper Bound**	
Pavement Family	Flexible/ Composite	Rigid	Flexible/ Composite	Rigid	Flexible/ Composite	Rigid
Interstate	45	40	0.059	0.052	240	250
NHS Non-Interstate	50	45	0.061	0.055	240	230
Non-NHS	55	50	0.061	0.057	230	220

TABLE 4.16
Results of Optimal Trigger Conditions for Various M&R Treatments

Pavement Treatment		**AC:UC**				
		1:0	**10:1**	**5:1**	**2:1**	**1:1**
(a) Interstate Results						
Flexible Pavements						
Preventive Maintenance	Crack Sealing	172	159	152	152	152
	HMA Overlay, Preventive Maintenance	143	127	127	119	119
Rehabilitation	HMA Overlay, Minor Structural	172	135	135	127	119
	HMA Overlay, Major Structural	183	172	152	152	135
New Construction	Pavement Replacement, HMA	234	220	183	183	152
Rigid Pavements						
Preventive Maintenance	PCCP Cleaning and Sealing Joints	152	143	143	143	143
	Diamond Grinding	179	159	159	159	159
	Crack Sealing	179	159	159	159	159
Rehabilitation	Crack & Seat PCCP & HMA Overlay	202	190	169	150	150
	Rubblize PCCP & HMA Overlay	190	179	169	150	150
	PCCP on PCC Pavement	257	179	179	179	179
	Repair PCCP & HMA Overlay	202	169	169	150	150
New Construction	Pavement Replacement, New PCC	257	242	215	202	179
Composite Pavements						
Crack & Seat Composite Pavement & HMA Overlay		162	143	127	127	127
Rubblize Composite & HMA Overlay		183	172	152	152	135
(b) NHS Non-Interstate Results						
Flexible Pavements						
Preventive Maintenance	Crack Sealing	169	169	169	150	150
	HMA Overlay, Preventive Maintenance	159	141	125	125	125
Rehabilitation	HMA Overlay, Minor Structural	169	159	159	133	133
	HMA Overlay, Major Structural	191	180	159	159	133
New Construction	Pavement Replacement, HMA	216	203	191	169	166
Rigid Pavements						
Preventive Maintenance	PCCP Cleaning and Sealing Joints	150	133	133	133	133
	Diamond Grinding	178	168	168	168	151
	Crack Sealing	178	168	168	168	168

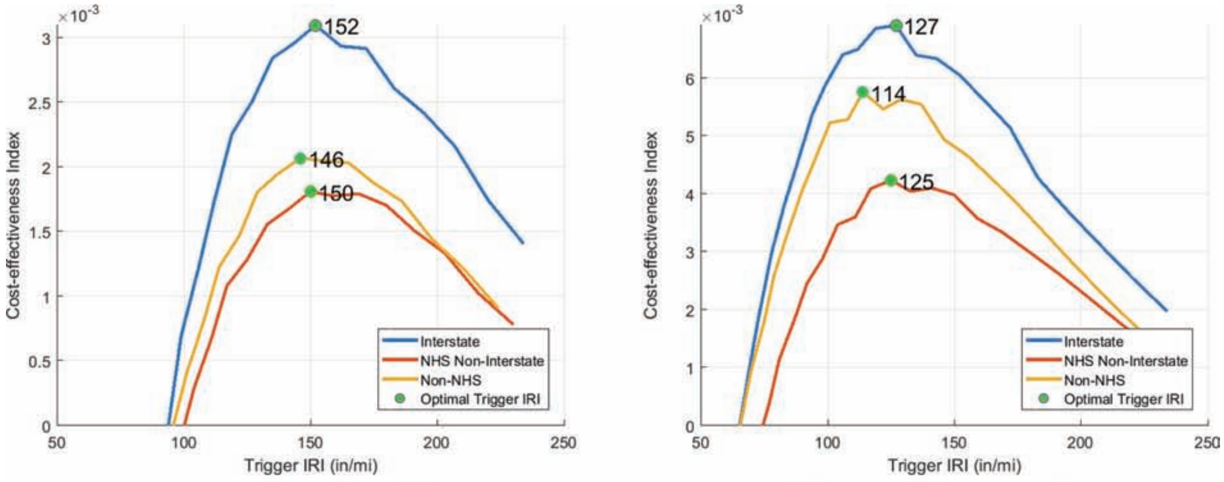
TABLE 4.16
(Continued)

		AC:UC				
Pavement Treatment		**1:0**	**10:1**	**5:1**	**2:1**	**1:1**
Rehabilitation	Crack & Seat PCCP & HMA Overlay	188	178	168	168	151
	Rubblize PCCP & HMA Overlay	178	168	168	151	151
	PCCP on PCC Pavement	222	188	159	159	159
	Repair PCCP & HMA Overlay	199	168	168	151	135
New Construction	Pavement Replacement, New PCC	234	234	234	210	199
Composite Pavements						
Crack & Seat Composite Pavement & HMA Overlay		169	141	133	133	111
Rubblize Composite & HMA Overlay		191	169	159	141	141
(c) Non-NHS Results						
Flexible Pavements						
Preventive Maintenance	Crack Sealing	175	165	155	155	146
	HMA Overlay, Preventive Maintenance	137	129	129	114	114
Rehabilitation	HMA Overlay, Minor Structural	175	165	146	129	129
	HMA Overlay, Major Structural	175	165	155	155	137
New Construction	Pavement Replacement, HMA	210	210	186	175	175
Rigid Pavements						
Preventive Maintenance	PCCP Cleaning and Sealing Joints	146	137	137	137	137
	Diamond Grinding	156	156	156	139	139
	Crack Sealing	185	175	175	156	156
Rehabilitation	Crack & Seat PCCP & HMA Overlay	175	175	175	166	148
	Rubblize PCCP & HMA Overlay	156	156	156	156	148
	PCCP on PCC Pavement	208	166	166	166	166
	Repair PCCP & HMA Overlay	175	175	156	148	148
New Construction	Pavement Replacement, New PCC	233	220	220	208	185
Composite Pavements						
Crack & Seat Composite Pavement & HMA Overlay		175	175	165	146	146
Rubblize Composite & HMA Overlay		186	165	165	155	155

significantly, under all the tested AC:UC ratios, as the deterioration rate increases. If the pavement deteriorates faster, it will be more cost-effective to repair it quickly rather than waiting and allowing the deterioration to continue.

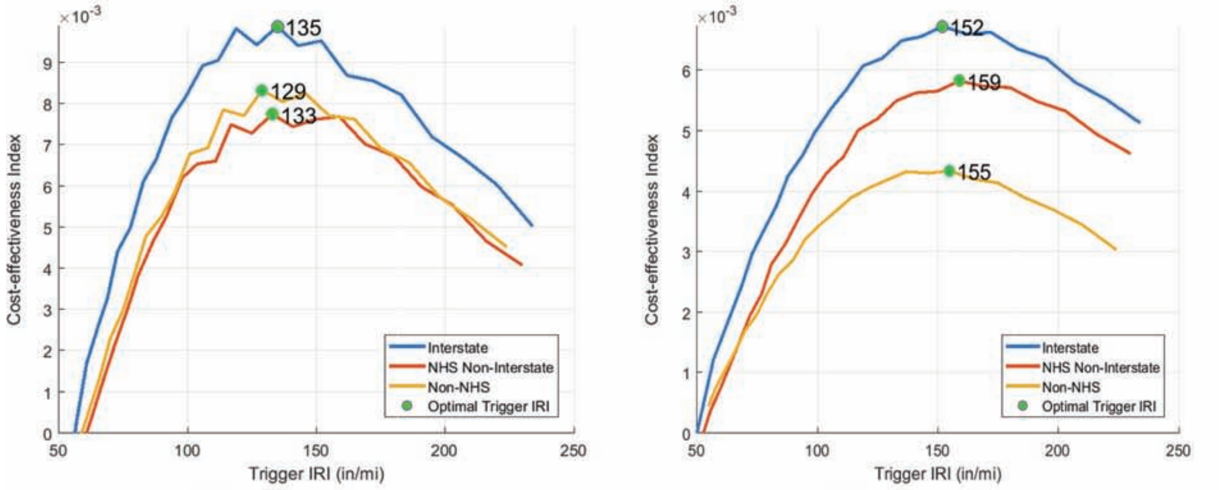
4.4.5 Effect of Discount Rate

The last tested factor is discount rate. The results are presented in Table 4.21 and Figure 4.15. The optimal trigger IRI increases as the discount rate increases under all the tested AC:UC ratios except for the AC:UC ratio of 1:1. This increase is more significant when the AC:UC ratio is 1:0 or 10:1 (when agency costs dominate the total cost). This is because the agency costs only occur at the year of treatment application, while the main user costs (VOC due to surface roughness) are calculated for each year over the pavement's service life. Therefore, the change in discount rate has a more significant impact on agency costs than on user costs. The higher the discount rate, the lower the EUAC. If a treatment is applied later (with higher IRI trigger), the benefit of EUAC saving would be more significant with a higher discount rate. Therefore, when the agency costs dominate total costs, the optimal IRI trigger increases as discount rate increases.



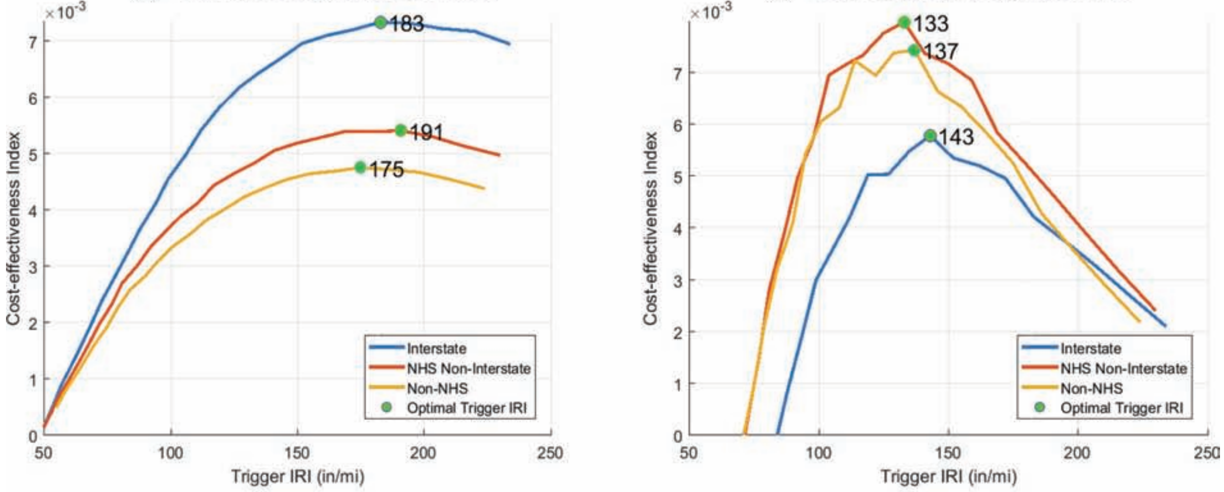
(1) Crack Sealing, HMA

(2) HMA Overlay, Preventive Maintenance



(3) HMA Overlay, Minor Structural

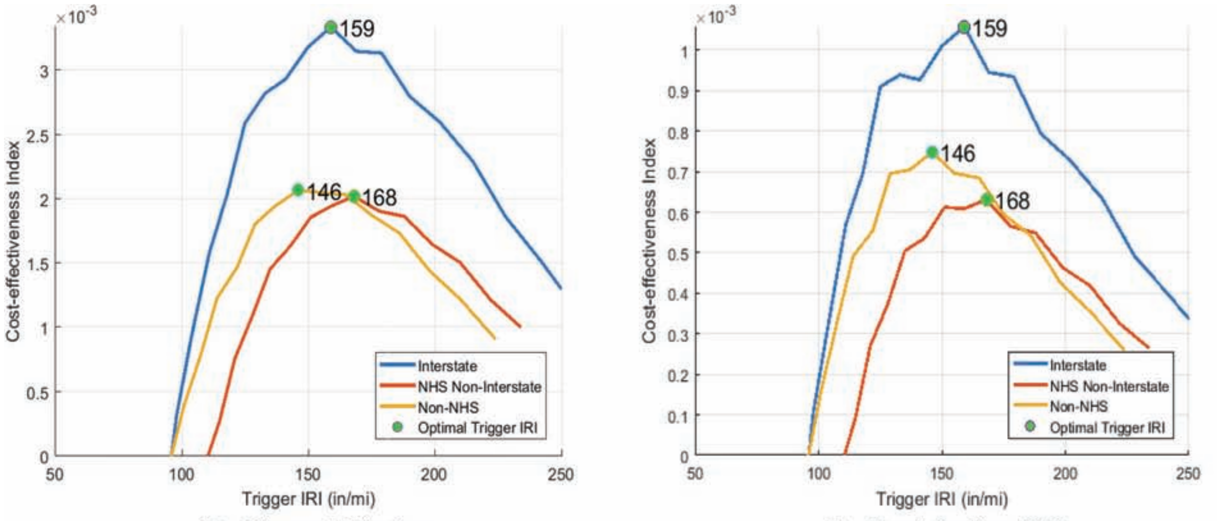
(4) HMA Overlay, Major Structural



(5) Pavement Replacement, HMA

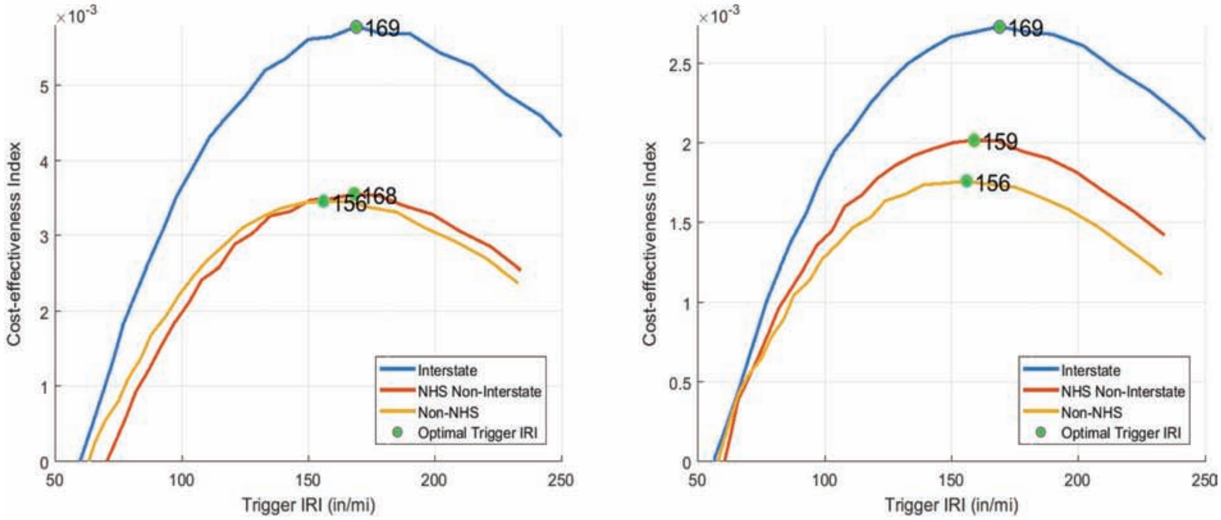
(6) PCCP Cleaning and Sealing Joints

Figure 4.10 Examples of M&R cost-effectiveness under different trigger conditions on Interstate, NHS Non-Interstate and Non-NHS roads.



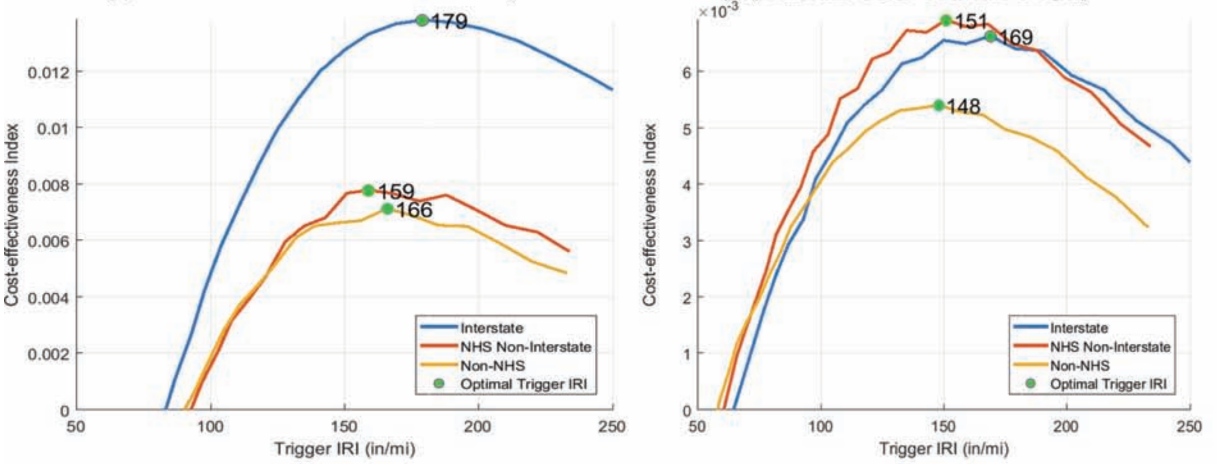
(7) Diamond Grinding

(8) Crack Sealing, PCC



(9) Crack & Seat PCCP & HMA Overlay

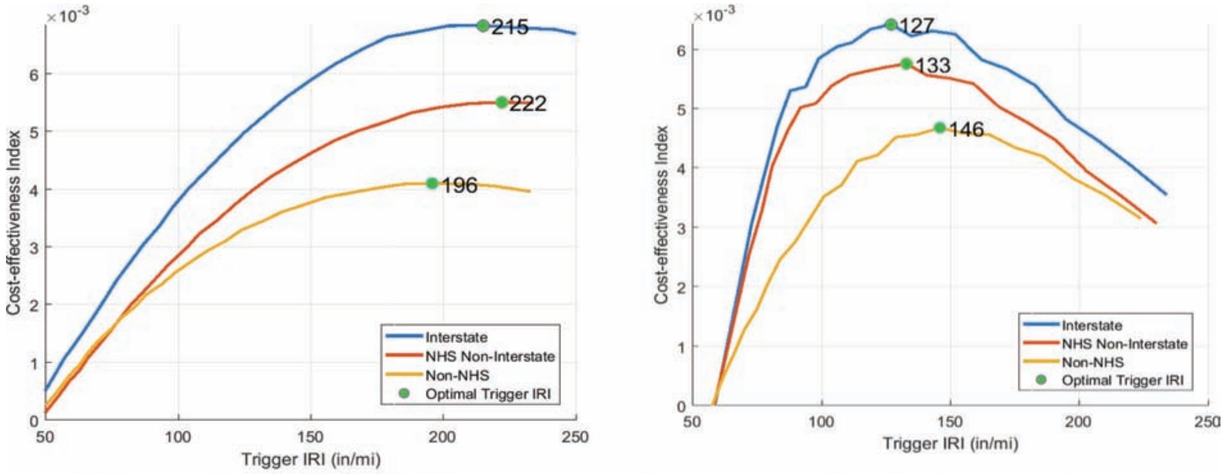
(10) Rubblize PCCP & HMA Overlay



(11) Repair PCCP & HMA Overlay

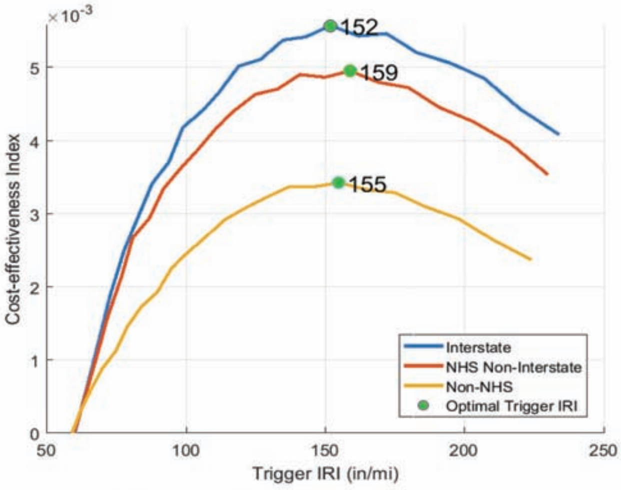
(12) PCCP on PCC Pavement

Figure 4.10 (Continued)



(13) Pavement Replacement, New PCC

(14) Crack & Seat Composite Pavement & HMA Overlay



(15) Rubblize Composite & HMA Overlay

Figure 4.10 (Continued)

TABLE 4.17
Sensitivity Analysis for User Cost Weight (User Cost/Agency Cost), HMA Minor Structural Overlay, Interstate

AC:UC	1:0	1:10	5:1	10:3	5:2	5:3	5:4	1:1
Optimal Trigger IRI	171	145	145	145	145	145	114	114
EUAC(Agency)	44192	47773	47773	47773	47773	47773	53100	53100
EUAC(Work Zone User Cost)	2526	2681	2681	2681	2681	2681	2898	2898
EUAC(VOC due to roughness)	76722	65329	65329	65329	65329	65329	58685	58685
Total EUAC	44192	54574	61375	68176	74977	88579	102367	114684
AOC (Benefit)	1178	1232	1232	1232	1232	1232	1242	1242
CE Index	0.0266	0.0226	0.0201	0.0181	0.0164	0.0139	0.0121	0.0108
Total Service Life	23	22	22	22	22	22	21	21

4.5 Consequences of Departure from Optimal Timings

A critical task in highway asset management is to evaluate and quantify the consequences of deferring a pavement intervention beyond its optimal performance threshold. It is intuitive that the larger the gap between the optimal timing and the actual application time of a treatment, the lower the cost-effectiveness of the intervention. However, how to quantify this effect has not been adequately explored by past studies. Based on the framework of developing optimal thresholds established in this study, the consequences of departure from optimal timing, in terms of the corresponding cost-effectiveness (CE), can be easily estimated. For all the treatments considered in the current study, the consequences of departure from optimal timings, in terms of

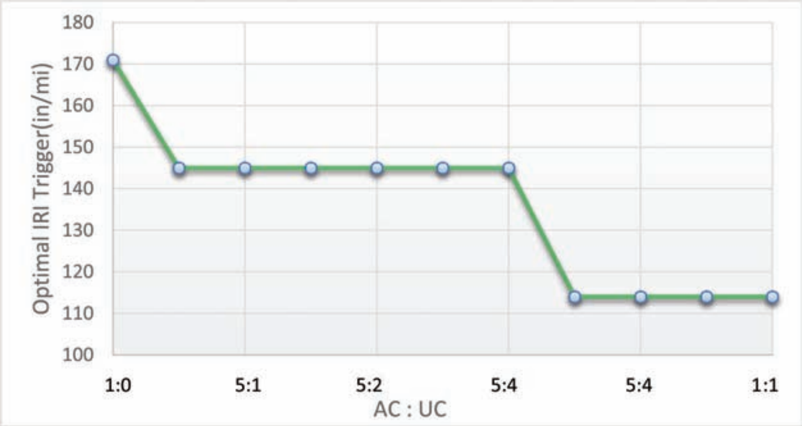


Figure 4.11 Optimal trigger IRI under different AC:UC ratios (HMA functional overlay, Interstate).

TABLE 4.18
Sensitivity Analysis for Traffic Volume (ADT), HMA Minor Structural Overlay, Interstate

ADT	1000	2000	3000	4000	5000	6000	7000	8000	9000	10000	11000	12000
	Optimal IRI Trigger											
AC:UC 1:0	211	211	211	211	211	211	211	211	211	211	211	211
AC:UC 10:1	203	203	187	187	187	187	187	187	180	180	180	180
AC:UC 5:1	187	180	180	166	166	166	166	166	166	166	147	147
AC:UC 2:1	180	166	166	166	166	147	147	147	147	147	147	147
AC:UC 1:1	147	147	147	147	147	147	147	147	147	147	147	147

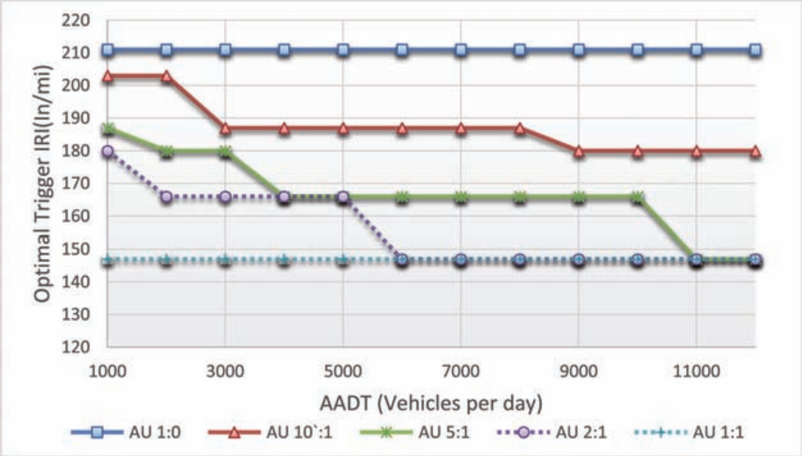


Figure 4.12 Optimal trigger IRI under different traffic volumes (HMA Overlay, Minor Structural, Interstate).

TABLE 4.19
Sensitivity Analysis IRI Upper Bound (PI_{UBC}), HMA Minor Structural Overlay, Interstate

PI_{UBC}	150	160	170	180	190	200	210	220	230	240	250	260	270	280
	Optimal IRI Trigger													
AU Weight 1:0	141	147	159	166	180	187	195	211	211	229	229	238	248	258
AU Weight 10:1	141	147	153	159	166	173	187	187	195	203	203	211	220	229
AU Weight 5:1	125	136	141	147	159	159	166	166	173	187	180	187	195	187
AU Weight 2:1	125	125	136	147	147	141	153	166	159	166	159	166	180	187
AU Weight 1:1	111	111	121	131	131	125	136	147	141	153	159	166	159	187

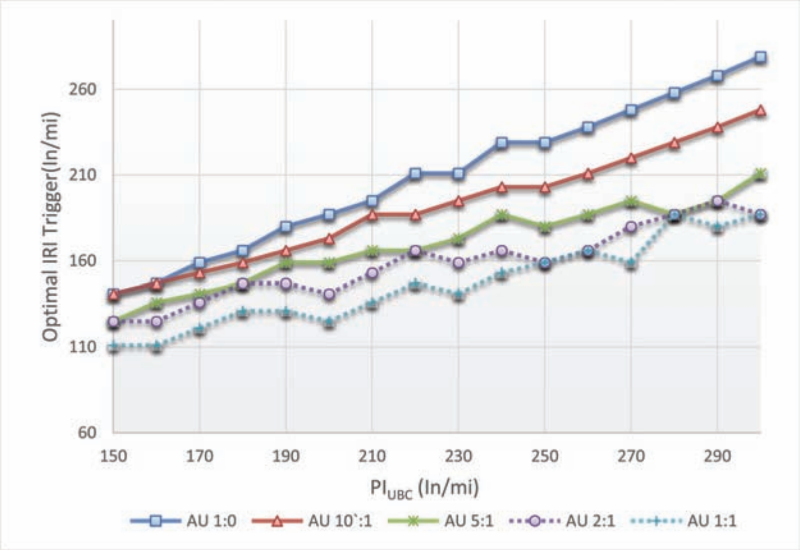


Figure 4.13 Optimal trigger IRI under different IRI upper bounds (HMA Minor Structural Overlay, Interstate).

TABLE 4.20
Sensitivity Analysis for Pre-Treatment Performance Deterioration Rate (β_1), HMA Functional Overlay, Interstate

â$_1$	0.04	0.045	0.05	0.055	0.06	0.065	0.07	0.075	0.08	0.085	0.09	0.095	0.1
							Optimal IRI Trigger						
AC:UC 1:0	211	202	193	187	187	183	176	166	153	151	147	142	136
AC:UC 10:1	187	184	183	177	166	161	164	154	153	151	147	142	136
AC:UC 5:1	166	161	166	150	147	151	133	133	131	117	123	129	111
AC:UC 2:1	166	161	150	150	147	133	133	133	131	117	103	118	111
AC:UC 1:1	147	129	129	135	116	116	116	106	103	91	103	80	91

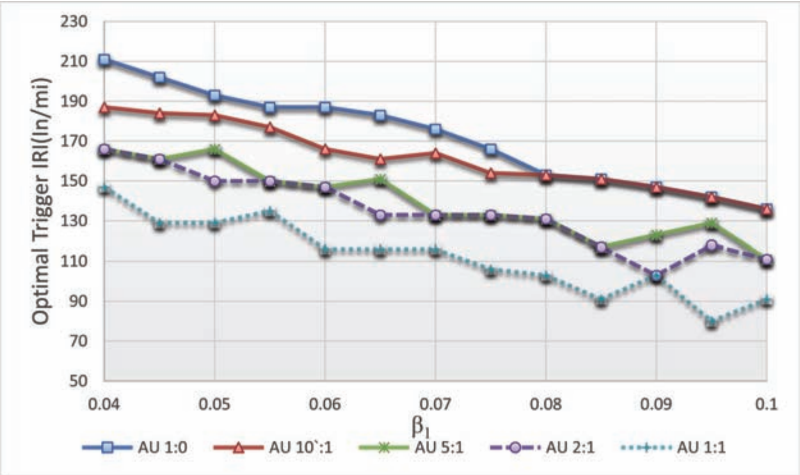


Figure 4.14 Optimal trigger IRI under different pre-treatment performance curves (HMA minor structural overlay, Interstate).

percentage decrease in cost-effectiveness, are presented in Figure 4.16(1)–(15), where a AC:UC ratio of 5:1 is used. For most of the treatments, the consequences of delay are not as severe as the consequences of applying the treatment earlier than the optimal timing, and for some of the treatments, the difference is not significant.

TABLE 4.21
Effect of Discount Rate (HMA Minor Structural Overlay, Interstate)

Interest Rate	**0.03**	**0.035**	**0.04**	**0.045**	**0.05**	**0.055**	**0.06**	**0.065**	**0.07**	**0.075**	**0.08**
	Optimal IRI Trigger										
AC:UC 1:0	187	187	195	195	195	203	211	211	211	211	211
AC:UC 10:1	180	180	180	187	187	187	187	187	187	203	203
AC:UC 5:1	166	166	166	166	166	166	166	166	166	180	180
AC:UC 2:1	147	147	147	147	147	147	166	166	166	166	166
AC:UC 1:1	147	147	147	147	147	147	147	147	147	147	147

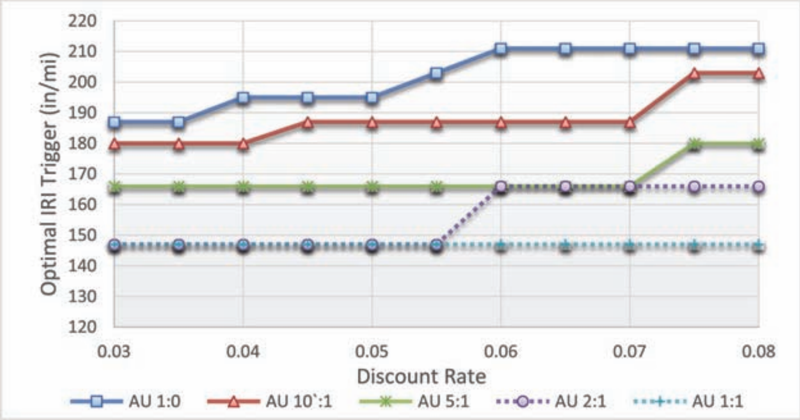


Figure 4.15 Optimal trigger IRI under different discount rates (HMA minor structural overlay, Interstate).

4.6 Long-Term M&R Scheduling

Besides identifying the optimal trigger condition for each type of treatment, another task of this study is to develop appropriate long-term M&R scheduling strategies. In the current study, this can be achieved by including multiple treatments during the pavement life cycle, and identifying the optimal trigger condition and corresponding year of treatment application for each treatment by repeating the same optimization process of finding the optimal trigger for a single treatment. The overall cost-effectiveness of each evaluated M&R strategy under the optimal timing were compared, and an appropriate M&R schedule was recommended for each family of pavement.

Instead of using the incremental costs and benefit for one individual treatment, the cost-effectiveness evaluation for long-term M&R scheduling used the overall costs and benefit for one M&R strategy (a sequence of multiple treatments). The agency costs and user costs during the work zones of M&R treatments were held. However, for the VOC during normal vehicle operations, instead of using the incremental VOC compared to the base case (80 in/mi), the total VOC (including the VOC incurred by roughness less than 80 in/mi) was used. The equation to calculate cost-effectiveness is shown below:

$$CE_i = \frac{Total AOC_{(i)}}{Overall EUAC_{(i)}}$$

where:

CE_i= Overall cost-effectiveness for candidate M&R strategy i.

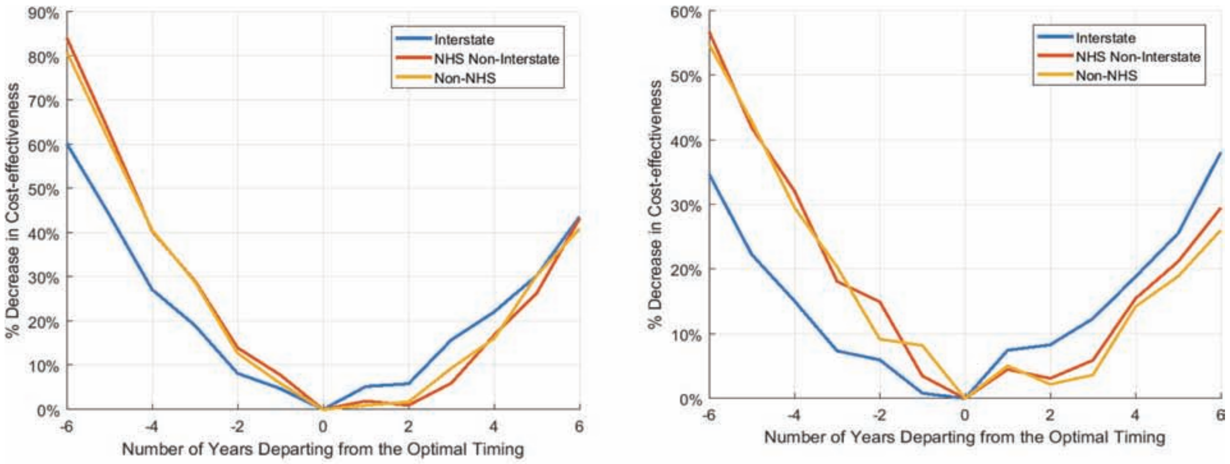
$Total\ AOC_{(i)}$ = Total area over the performance curve with candidate M&R strategy i. (including the area over the do nothing curve after last treatment)

$EUAC_{(i)}$ = Equivalent uniform annual cost converted from pavement life-cycle cost with candidate M&R strategy i.

To select the appropriate M&R strategy for a certain family of pavements:

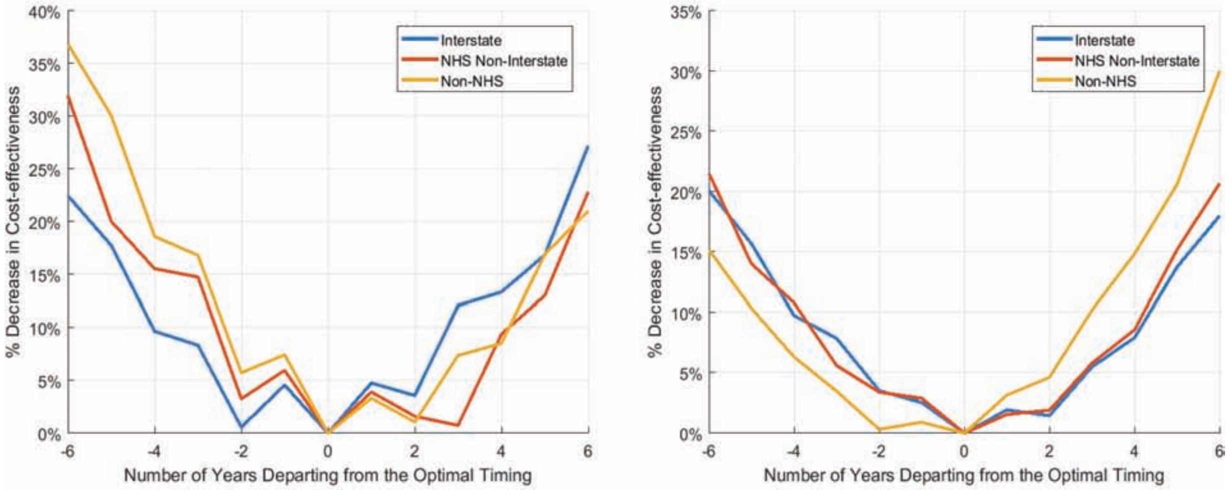
1. Propose a set of candidate M&R strategies, with pavement replacement as the last activity.
2. Apply the optimization method to identify the optimal trigger condition for each treatment, and for pavement replacement.
3. Obtain the overall cost and annualized total benefit.
4. Calculate the overall cost effectiveness (CE) using the equation above for each of the evaluated candidate M&R strategies.
5. Assign ranks to all candidate M&R strategies based on the CE Index.

Figure 4.17 presents two examples of long-term candidate M&R strategies for flexible pavements and rigid pavements on an Interstate. The analysis ended at the year of pavement replacement. The AOC (benefit area) is the area bounded by the red dashed lines and the performance curve from year 0 to the end of analysis year (the condition-based optimal time for pavement replacement). The optimal trigger IRI for each treatment was obtained (with AC:UC = 5:1 and IRI upper



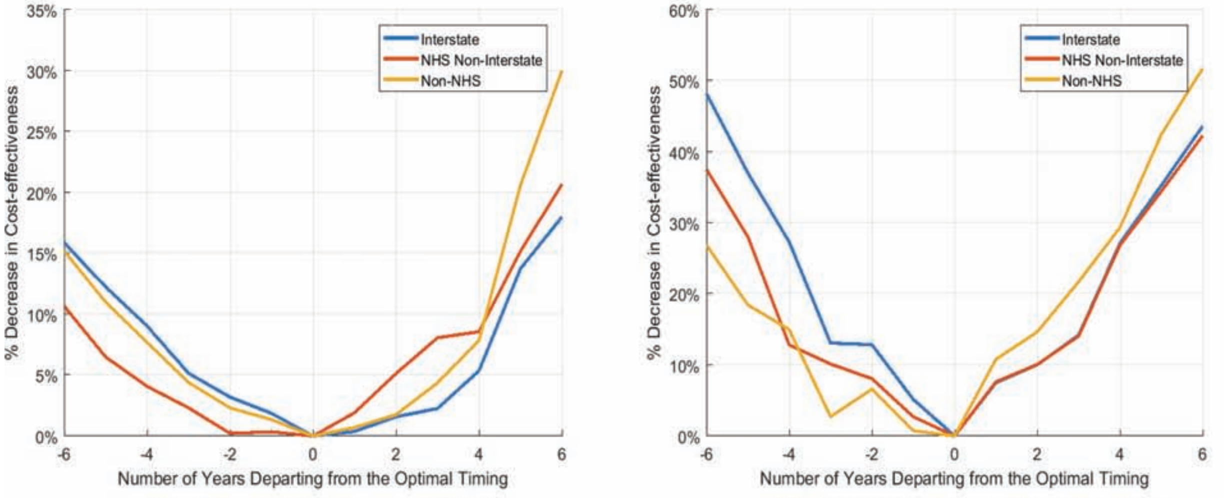
(1) Crack Sealing, HMA

(2) HMA Overlay, PM



(3) HMA Overlay, Minor Structural

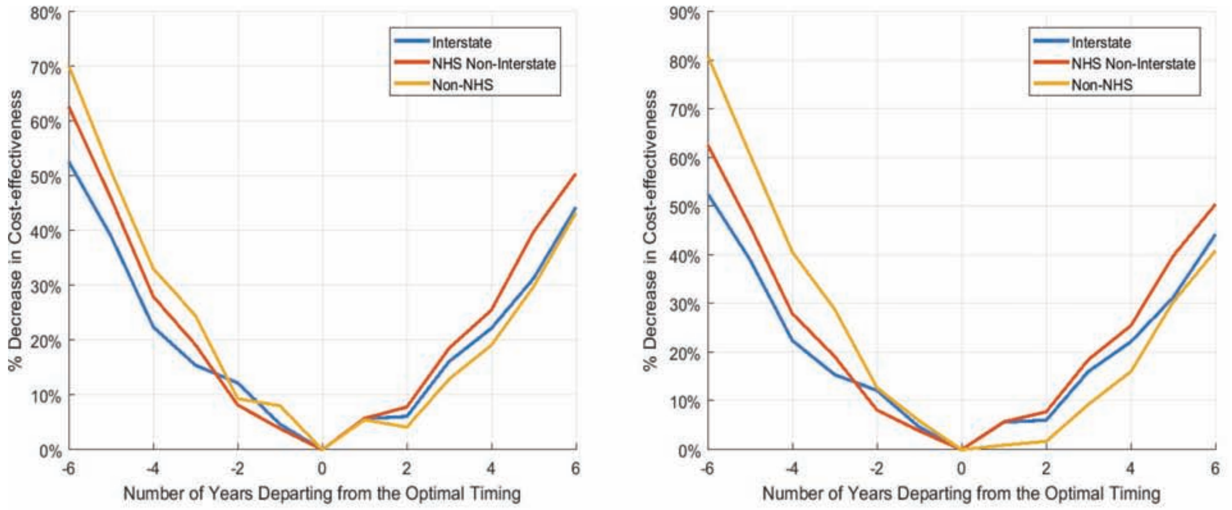
(4) HMA Overlay, Major Structural



(5) Pavement Replacement, HMA

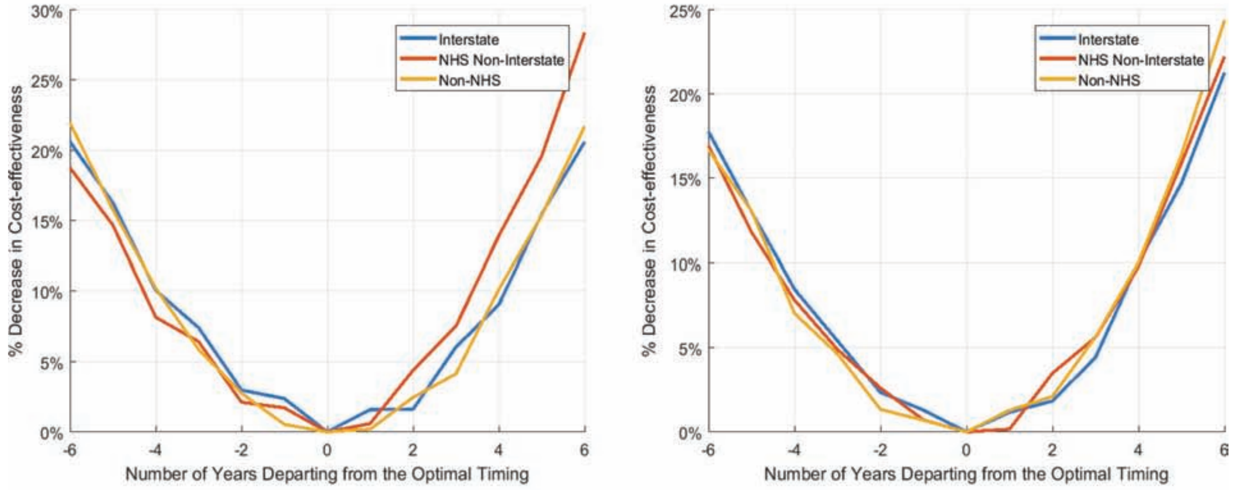
(6) PCCP Cleaning and Sealing Joints

Figure 4.16 Consequences of departure from optimal timing on Interstate, NHS Non-Interstate and Non-NHS roads.



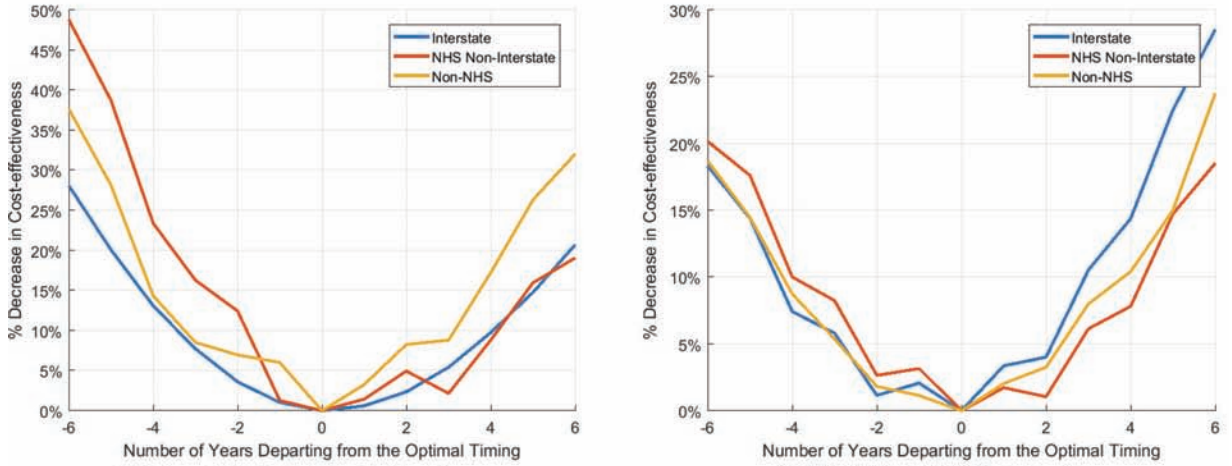
(7) Diamond Grinding

(8) Crack Sealing, PCC



(9) Crack & Seat PCCP & HMA Overlay

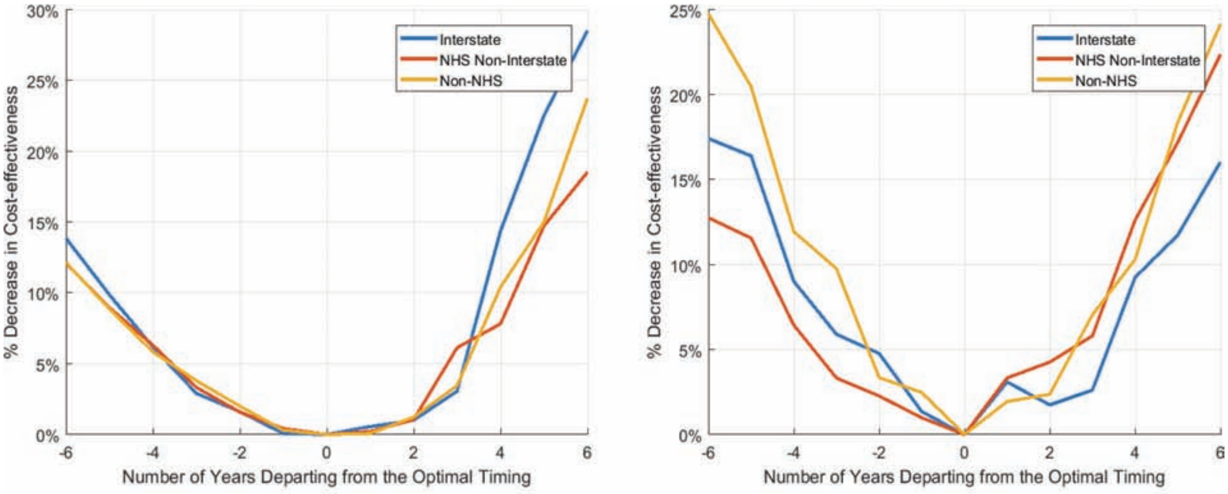
(10) Rubblize PCCP & HMA Overlay



(11) Repair PCCP & HMA Overlay

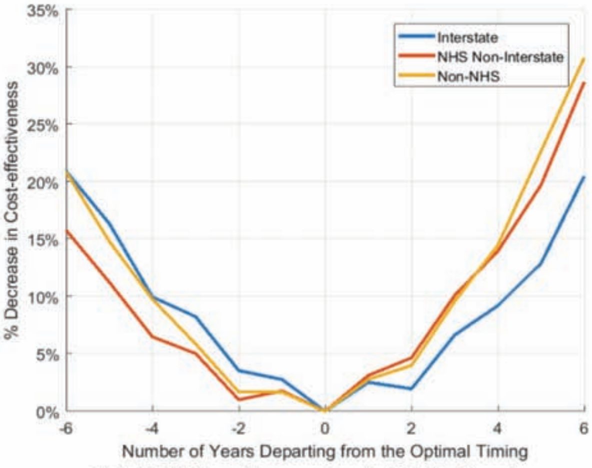
(12) PCCP on PCC Pavement

Figure 4.16 (Continued)



(13) Pavement Replacement, New PCC

(14) Crack & Seat Composite Pavement & HMA Overlay



(15) Rubblize Composite & HMA Overlay

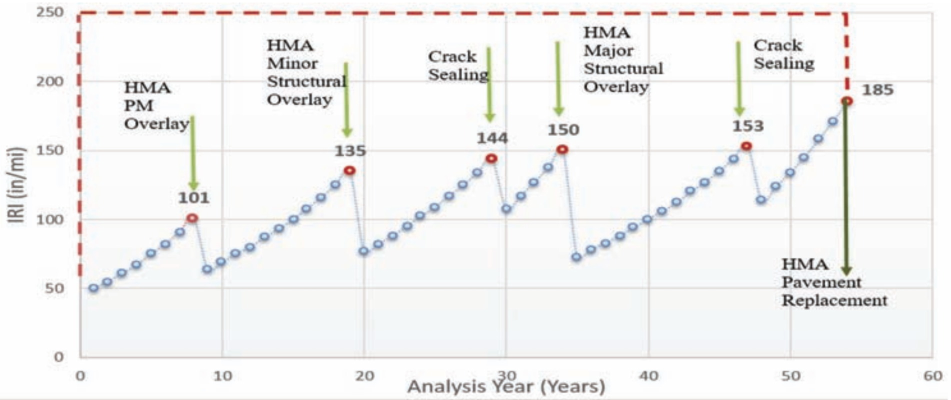
Figure 4.16 (Continued)

limit = 250 in/mi) through optimization and identified in Figures 4.10(a)–(b). The overall EUAC and AOC for the two examples were then calculated as shown in Table 4.22.

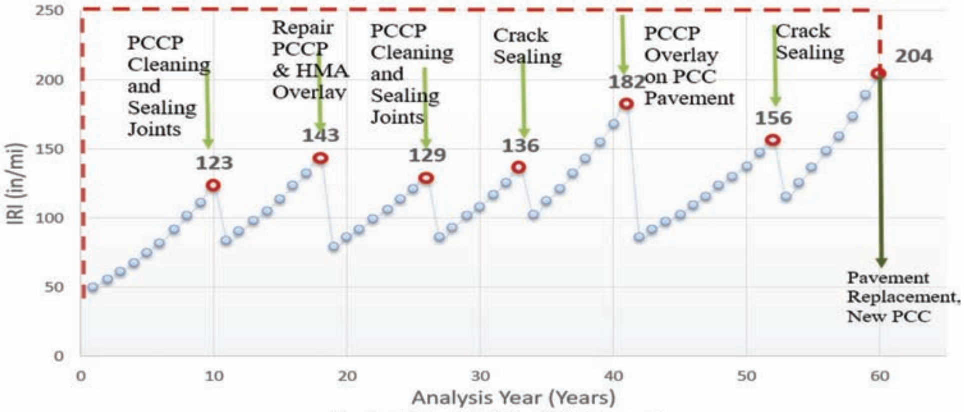
Various M&R strategies with different combinations and sequences of M&R treatments were evaluated separately for flexible and rigid pavements of different functional classes using the method discussed above. The AC:UC ratio of 5:1 was used in this analysis. The codes of all the treatments considered in this study are presented in Table 4.23.

Theoretically, one can add an unlimited number of M&R actions to the schedule based on the developed framework. However, in reality, the pavement must be replaced after a certain number of years. Therefore, some upper limits are set on the pavement service life in this study to ensure the applicability of the developed long-term M&R in the real life. The maximum service life for a pavement is assumed to be 45 years if only preventative maintenance is conducted, and 60 years if there is any rehabilitation work conducted during the pavement life.

The long-term M&R schedules analyzed in this study can be classified into three categories: (1) preventative maintenance (PM) only, (2) rehabilitation only, and (3) a combination of preventative maintenance and rehabilitation. Using the proposed framework, a variety of candidate M&R strategies were evaluated. Table 4.24 summarizes the types of M&R actions considered and the number of candidate M&R strategies evaluated under each of the three categories, for flexible and rigid pavements separately. A MATLAB program was developed to run the analysis. The optimal IRI trigger of each M&R action was identified for all the evaluated M&R strategies, and the candidates were then ranked according to their corresponding cost-effectiveness (CE) with service life (SL) as a constraint (less than 45 or 60 years). It was found that the evaluated M&R strategies from the third category generally have a higher cost-effectiveness than the M&R strategies from the



(a) Candidate M&R for Flexible Pavement



(b) Candidate M&R for Rigid Pavement

Figure 4.17 Illustration of optimal timing for one candidate M&R strategy.

TABLE 4.22
Results of Cost-Effectiveness for the Evaluated M&R Strategy

(a) Candidate M&R for Flexible Pavement	
EUAC (Agency Cost)	$897,409
EUAC (Work Zone User Cost)	$50,317
EUAC (VOC)	$3,575,808
Total EUAC (AC:UC=5:1)	$1,622,634
Total AOC	6674
CE Index (10^{-3})	4.113
Pavement Service Life	54
(b) Candidate M&R for Rigid Pavement	
Outcome	**Output**
EUAC (Agency Cost)	$1,132,248
EUAC (Work Zone User Cost)	$294,619
EUAC (VOC)	$3,629,539
Total EUAC (AC:UC=5:1)	$1,917,080
Total AOC	6807
CE Index (10^{-3})	3.551
Pavement Service Life	60

other two categories. Due to the limited space, results of only the top M&R strategies (in term of the cost-effectiveness) are provided under each category, presented in Table 4.25 and Table 4.26 for flexible and rigid pavements in different functional classes.

TABLE 4.23
M&R Treatments Code

Flexible Pavement	
Code	**Treatment Type**
CS	Crack Sealing, HMA
PM	HMA Overlay, Preventive Maintenance
MIS	HMA Overlay, Minor Structural
MAS	HMA Overlay, Major Structural
PR	HMA Pavement Replacement
Rigid Pavement	
Code	**Treatment Type**
PCSJ	PCCP Cleaning and Sealing Joints
CS	Crack Sealing, PCC
CSPHO	Crack & Seat PCCP & HMA Overlay
DG	Diamond Grinding
RPHO	Rubblize PCCP & HMA Overlay
PO	PCCP on PCC Pavement
RPHO	Repair PCCP & HMA Overlay
PR	Pavement Replacement, New PCC

4.7 Discussion and Limitations

The current study establishes a framework for determining the appropriate (condition-based) performance triggers for pavement maintenance, rehabilitation and

TABLE 4.24
Summary of the Evaluated Candidate M&R Strategies

	Flexible Pavement		Rigid Pavement	
Category of M&R strategy	**Types of M&R Work Considered**	**Number of Evaluated M&R Strategies**	**Types of M&R Work Considered**	**Number of Evaluated M&R Strategies**
Preventative Maintenance Only	CS, PM	50 for each functional class	PCSJ, CS, DG	100 for each functional class
Rehabilitation Only	MIS, MAS	50 for each functional class	CSPHO, RPHO, PO, RPHO	100 for each functional class
Combination of Preventative Maintenance and Rehabilitation	CS, PM, MIS, MAS	150 for each functional class	PCSJ, CS, DG, CSPHO, RPHO, PO, RPHO	300 for each functional class

replacement activities. Fourteen types of treatments were considered. Statistical models were developed in terms of performance jump due to M&R treatments, post-treatment performance, agency costs and user costs. An optimization approach was proposed to find the optimal trigger IRI that would maximize the cost-effectiveness of each type of treatment on different families of assets. The cost-effectiveness of an M&R treatment is defined as the area bounded by the performance curve divided by the life-cycle cost. This is a measurement of benefit that takes both pavement performance and service life into account. The life-cycle cost analysis incorporates both agency costs and user costs. Sensitivity analysis indicates that changing the relative weights of agency and user costs has a significant impact on the optimal trigger. As the AC:UC ratio increases, the optimal trigger IRI increases. The sensitivity analysis in terms of other important variables (e.g., traffic load, discount rate, IRI upper bound, and pre-treatment performance curve) are also provided. The results of sensitivity analysis show how the change in these factors can influence the optimal condition trigger results, providing asset managers with greater flexibility in making M&R decisions. The study also established a framework to find the optimal scheduling for multiple treatments and recommended appropriate long-term M&R strategies for flexible and rigid pavements of different functional classes.

Although the models and analysis presented in this paper were based on data from the state of Indiana, the general framework can be applied to other states or public agencies. The methodology can be applied to establish appropriate performance thresholds for other pavement treatments and for interventions on other highway assets (e.g. bridge, safety, mobility, etc.). The data-driven approach and results of this study can help agencies enhance their pavement M&R decisions in terms of the performance thresholds of each individual pavement treatment as well as long-term M&R scheduling. Some limitations of this paper should be mentioned. First, the optimal triggers established in this study only address surface roughness (IRI); other important performance indicators such as rutting, cracking are not considered in this study, due to data availability. For future studies, this framework can be modified and applied to find the optimal triggers in term of other performance indicators or combinations of several performance measurements. Second, a lack of quality data is a major challenge in the current study. The data trends indicated irregular patterns of pavement condition (increases in IRI when treatments were carried out or reductions in IRI where no treatment was carried out). The developed post-treatment performance models are therefore not very accurate. This caused some bias in the results for optimal triggers and long-term M&R strategies. In future studies, if more accurate and reliable pavement condition data becomes available, new models could be developed and the trigger results could be re-examined using the proposed framework. Future work in M&R schedule development could also address risk and uncertainty concepts as suggested by Piyatrapoomi and Kumar (2003).

This study is yet another step in INDOT's strides towards overall asset management of its highway infrastructure, for several reasons. Monitoring assets and making repair decisions is a key aspect of asset management (Adey, 2017; Taggart et al., 2017), and robust and strategic prescriptions of infrastructure rehabilitation and maintenance schedules can be developed only through reliable analysis of the cost and effectiveness/performance of candidate actions (Adey & Kielhauser, 2017; Moloney et al., 2017; Switzer & McNeil, 2004). This is important from a funding perspective, because transparent, rational, and comprehensive analysis that determines the optimal timing of M&R can help generate the traction that asset management leaders need to overcome institutional inertia or public reluctance to invest in infrastructure maintenance (Kellick, 2014).

TABLE 4.25
Optimal Results of the Top Candidate M&R Strategies for Flexible Pavement

(a) Preventative Maintenance Only

Top 3 Strategies	**Treatment Combinations**							
	Interstate						**SL**	**CE (10^{-3})**
Candidate 1	CS	PM	PM	PM	PM	PR		
Optimal $IRI_{Trigger}$	119	101	116	111	115	184	44	3.449
Candidate 2	PM	PM	PM	CS	CS	PR		
Optimal $IRI_{Trigger}$	108	105	119	141	136	198	41	3.085
Candidate 3	CS	PM	PM	PM	CS	PR		
Optimal $IRI_{Trigger}$	119	101	116	111	144	191	41	2.992
	NHS Non-Interstate						**SL**	**CE (10^{-3})**
Candidate 1	CS	PM	PM	PM	PM	PR		
Optimal $IRI_{Trigger}$	119	108	128	125	132	186	40	3.497
Candidate 2	CS	PM	PM	PM	CS	PR		
Optimal $IRI_{Trigger}$	119	108	128	125	132	190	39	3.375
Candidate 3	CS	PM	PM	PM	CS	PR		
Optimal $IRI_{Trigger}$	119	108	128	125	132	190	39	3.375
	Non-NHS						**SL**	**CE (10^{-3})**
Candidate 1	CS	CS	PM	PM	PM	PR		
Optimal $IRI_{Trigger}$	119	133	112	126	110	193	45	5.154
Candidate 2	CS	PM	PM	PM	CS	PR		
Optimal $IRI_{Trigger}$	119	122	125	118	141	176	44	4.978
Candidate 3	CS	CS	CS	PM	PM	PR		
Optimal $IRI_{Trigger}$	119	133	132	121	124	197	44	4.882

(b) Rehabilitation Only

Top 3 Strategies	**Treatment Combinations**							
	Interstate						**SL**	**CE (10^{-3})**
Candidate 1	MIS	MIS	MIS	MIS	MAS	PR		
Optimal $IRI_{Trigger}$	108	135	134	134	154	197	60	4.669
Candidate 2	MIS	MIS	MIS	MAS	MIS	PR		
Optimal $IRI_{Trigger}$	108	135	134	154	137	192	59	4.652
Candidate 3	MIS	MIS	MAS	MIS	MIS	PR		
Optimal $IRI_{Trigger}$	108	135	155	137	118	188	58	4.512
	NHS Non-Interstate						**SL**	**CE (10^{-3})**
Candidate 1								
Optimal $IRI_{Trigger}$	MIS	MIS	MIS	MAS	MIS	PR	55	5.554
Candidate 2	98	127	127	157	148	185		
Optimal $IRI_{Trigger}$	MIS	MIS	MAS	MIS	MIS	PR	55	5.355
Candidate 3	98	127	157	148	130	183		
Optimal $IRI_{Trigger}$	MIS	MAS	MIS	MIS	MIS	PR	55	5.161
	Non-NHS						**SL**	**CE (10^{-3})**
Candidate 1	MIS	MIS	MIS	MIS	MIS	PR		
Optimal $IRI_{Trigger}$	119	145	131	143	150	190	56	7.271
Candidate 2	MIS	MIS	MIS	MAS	MIS	PR		
Optimal $IRI_{Trigger}$	119	145	131	164	146	187	58	7.050
Candidate 3	MIS	MIS	MAS	MIS	MIS	PR		
Optimal $IRI_{Trigger}$	119	145	151	148	143	185	58	6.725

TABLE 4.25
(Continued)

(c) Combination of Preventative Maintenance and Rehabilitation

Top 5 Strategies	Treatment Combinations										
	Interstate									**SL**	**CE (10^{-3})**
Candidate 1	PM	CS	MIS	CS	PM	CS	PM	CS	PR		
$\text{IRI}_{\text{Trigger}}$	108	116	156	143	117	139	128	138	184	59	4.652
Candidate 2	PM	CS	CS	PM	MIS	CS	PM	CS	PR		
$\text{IRI}_{\text{Trigger}}$	108	116	136	112	134	143	117	139	185	60	4.647
Candidate 3	PM	CS	PM	CS	PM	CS	MIS	CS	PR		
$\text{IRI}_{\text{Trigger}}$	108	116	126	139	141	138	156	153	185	60	4.635
Candidate 4	PM	CS	CS	MIS	PM	CS	PM	CS	PR		
$\text{IRI}_{\text{Trigger}}$	108	116	136	121	117	139	141	138	184	59	4.606
Candidate 5	PM	MIS	PM	MAS	PM	CS	PR				
$\text{IRI}_{\text{Trigger}}$	108	116	118	151	127	138	184			58	4.553
	NHS Non-Interstate									**SL**	**CE (10^{-3})**
Candidate 1	PM	CS	MIS	CS	MIS	CS	PM	CS	PR		
$\text{IRI}_{\text{Trigger}}$	108	138	131	139	112	136	120	138	181	60	5.763
Candidate 2	CS	PM	MIS	CS	PM	MAS	PM	PR			
$\text{IRI}_{\text{Trigger}}$	119	128	138	125	121	161	133	187		60	5.464
Candidate 3	CS	PM	CS	CS	PM	MIS	PM	CS	PR		
$\text{IRI}_{\text{Trigger}}$	119	128	138	131	136	125	135	141	185	58	5.447
Candidate 4	CS	PM	CS	CS	PM	MIS	CS	PM	PR		
$\text{IRI}_{\text{Trigger}}$	119	128	138	131	136	125	126	122	188	58	5.433
Candidate 5	CS	PM	MIS	PM	CS	MAS	CS	PR			
$\text{IRI}_{\text{Trigger}}$	119	128	138	134	140	169	144	188		60	5.419
	Non-NHS									**SL**	**CE (10^{-3})**
Candidate 1	PM	CS	MIS	CS	MIS	CS	PM	CS	PR		
$\text{IRI}_{\text{Trigger}}$	108	123	131	133	143	140	117	140	190	59	7.682
Candidate 2	PM	CS	PM	CS	MIS	CS	CS	PM	PR		
$\text{IRI}_{\text{Trigger}}$	108	123	121	133	143	140	137	115	185	60	7.396
Candidate 3	PM	CS	PM	CS	PM	CS	MIS	CS	PR		
$\text{IRI}_{\text{Trigger}}$	108	123	121	133	112	135	145	131	181	60	7.282
Candidate 4	CS	CS	PM	CS	PM	CS	MIS	CS	PR		
$\text{IRI}_{\text{Trigger}}$	119	133	112	135	123	145	141	139	205	60	7.282
Candidate 5	PM	CS	CS	MIS	CS	CS	MAS	CS	PR		
$\text{IRI}_{\text{Trigger}}$	108	123	131	131	133	132	142	152	187	60	6.782

TABLE 4.26

Optimal Results of the Top Candidate M&R Strategies for Rigid Pavement

(a) Preventative Maintenance Only

Top 3 Strategies	Treatment Combinations								
	Interstate							**SL**	**CE (10^{-3})**
Candidate 1	CS	PCSJ	PCSJ	PCSJ	CS	PCSJ	RPHO		
$IRI_{Trigger}$	123	127	132	133	137	151	212	45	2.300
Candidate 2	CS	PCSJ	PCSJ	CS	PCSJ	PCSJ	RPHO		
$IRI_{Trigger}$	123	127	132	137	151	134	210	45	2.292
Candidate 3	CS	PCSJ	CS	PCSJ	PCSJ	PCSJ	RPHO		
$IRI_{Trigger}$	123	132	137	151	134	133	209	45	2.290
	NHS Non-Interstate							**SL**	**CE (10^{-3})**
Candidate 1	PCSJ	PCSJ	PCSJ	CS	PCSJ	PCSJ	RPHO		
$IRI_{Trigger}$	123	142	144	145	145	146	232	45	2.512
Candidate 2	PCSJ	PCSJ	PCSJ	PCSJ	PCSJ	CS	RPHO		
$IRI_{Trigger}$	123	142	144	145	146	136	244	45	2.506
Candidate 3	PCSJ	PCSJ	CS	PCSJ	PCSJ	PCSJ	RPHO		
$IRI_{Trigger}$	123	142	155	141	143	145	230	45	2.497
	Non-NHS							**SL**	**CE (10^{-3})**
Candidate 1	PCSJ	CS	PCSJ	PCSJ	PCSJ	PCSJ	RPHO		
$IRI_{Trigger}$	123	153	145	146	147	148	201	43	2.802
Candidate 2	CS	PCSJ	PCSJ	PCSJ	PCSJ	CS	RPHO		
$IRI_{Trigger}$	138	143	145	146	147	159	224	43	2.797
Candidate 3	CS	PCSJ	PCSJ	PCSJ	CS	PCSJ	RPHO		
$IRI_{Trigger}$	138	143	145	146	158	137	222	43	2.774

(b) Rehabilitation Only

Top 3 Strategies	Treatment Combinations						
	Interstate					**SL**	**CE (10^{-3})**
Candidate 1	RPHO	PO	RPHO	PO	RPHO		
$IRI_{Trigger}$	166	175	190	176	218	60	3.866
Candidate 2	PO	PO	RPHO	PO	RPHO		
$IRI_{Trigger}$	136	155	177	176	218	59	3.327
Candidate 3	PO	CSPHO	PO	CSPHO	RPHO		
$IRI_{Trigger}$	136	166	167	173	219	58	2.776
	NHS Non-Interstate					**SL**	**CE (10^{-3})**
Candidate 1	RPHO	RPHO	RPHO	RPHO	RPHO		
$IRI_{Trigger}$	123	183	184	185	250	56	4.858
Candidate 2	RPHO	RPHO	PO	RPHO	RPHO		
$IRI_{Trigger}$	123	183	163	151	248	55	4.341
Candidate 3	PO	RPHO	RPHO	PO	RPHO		
$IRI_{Trigger}$	123	157	186	164	245	58	4.206
	Non-NHS					**SL**	**CE (10^{-3})**
Candidate 1	RPHO	PO	RPHO	RPHO	RPHO		
$IRI_{Trigger}$	123	153	156	185	250	53	4.525
Candidate 2	PO	RPHO	RPHO	PO	RPHO		
$IRI_{Trigger}$	123	157	186	164	245	54	4.432
Candidate 3	RPHO	RPHO	CSPHO	RPHO	RPHO		
$IRI_{Trigger}$	136	167	178	163	225	53	4.306

TABLE 4.26
(Continued)

(c) Combination of Preventative Maintenance and Rehabilitation

Top 5 Strategies	Treatments Combinations										
				Interstate						**SL**	**CE (10^{-3})**
Cand. 1	PCSJ	RPHO	PCSJ	PCSJ	PO	CS	CS	RPHO			
$IRI_{Trigger}$	119	156	147	129	136	135	121	213		60	3.865
Cand. 2	CS	PCSJ	RPHO	CS	PCSJ	PO	CS	RPHO			
$IRI_{Trigger}$	119	129	185	156	126	156	145	208		60	3.670
Cand. 3	PCSJ	CS	PCSJ	RPHO	PCSJ	CS	CS	CS	RPHO		
$IRI_{Trigger}$	119	140	135	177	147	139	124	123	215	60	3.595
Cand. 4	PCSJ	RPHO	PCSJ	CS	PO	CS	CS	RPHO			
$IRI_{Trigger}$	119	156	147	139	145	149	131	208		59	3.555
Cand. 5	PCSJ	CS	PCSJ	CS	PCSJ	CS	RPHO	CS	RPHO		
$IRI_{Trigger}$	119	140	135	130	117	139	185	156	204	60	3.549
				NHS Non-Interstate						**SL**	**CE (10^{-3})**
Cand. 1	CS	PCSJ	RPHO	CS	PCSJ	PO	PCSJ	RPHO			
$IRI_{Trigger}$	111	131	159	145	137	151	165	236		59	4.022
Cand. 2	CS	PCSJ	RPHO	CS	PCSJ	PO	CS	RPHO			
$IRI_{Trigger}$	111	131	159	145	137	151	165	242		58	3.973
Cand. 3	CS	PCSJ	RPHO	CS	PCSJ	RPHO	PCSJ	RPHO			
$IRI_{Trigger}$	111	131	159	145	137	151	163	234		56	3.946
Candi 4	PCSJ	RPHO	PCSJ	PCSJ	RPHO	CS	CS	RPHO			
$IRI_{Trigger}$	123	165	158	144	169	149	140	230		57	3.914
Cand. 5	PCSJ	PCSJ	RPHO	CS	PCSJ	RPHO	CS	RPHO			
$IRI_{Trigger}$	123	142	168	158	140	166	168	246		58	3.905
				Non-NHS						**SL**	**CE (10^{-3})**
Cand. 1	CS	PCSJ	RPHO	CS	PCSJ	PO	PCSJ	RPHO			
$IRI_{Trigger}$	125	143	168	149	140	142	156	209		57	4.547
Cand. 2	CS	PCSJ	RPHO	CS	PCSJ	RPHO	CS	RPHO			
$IRI_{Trigger}$	125	143	168	149	140	166	178	226		56	4.546
Cand. 3	PCSJ	RPHO	PCSJ	CS	RPHO	PCSJ	CS	RPHO			
$IRI_{Trigger}$	123	153	163	160	150	162	159	207		54	4.403
Cand. 4	PCSJ	PCSJ	RPHO	CS	PCSJ	PO	CS	RPHO			
$IRI_{Trigger}$	123	142	168	149	144	145	169	200		56	4.331
Cand. 5	CS	PCSJ	RPHO	CS	PCSJ	CSPHO	PCSJ	RPHO			
$IRI_{Trigger}$	150	143	168	149	140	142	161	199		56	4.216

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On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,600 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at: http://docs.lib.purdue.edu/jtrp

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The recommended citation for this publication is:

Qiao, Y., Fricker, J. D., Labi, S., & Sinha, K. C. (2017). *Strategic scheduling of infrastructure repair and maintenance: Volume 3—Developing condition-based triggers for pavement maintenance, rehabilitation, and replacement treatments* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2017/14). West Lafayette, IN: Purdue University. https://doi.org/10.5703/1288284316513