JOINT TRANSPORTATION
RESEARCH PROGRAM
INDIANA DEPARTMENT OF TRANSPORTATION
AND PURDUE UNIVERSITY

Effects of Bridge Surface and Pavement Maintenance Activities on Asset Rating

Tariq Usman Saeed, Yu Qiao, Sikai Chen, Saeed Alqadhi,
Zhibo Zhang, Samuel Labi, Kumares C. Sinha

SPR-4012 • Report Number: FHWA/IN/JTRP-2017/10 • DOI: 10.5703/1288284316573

RECOMMENDED CITATION

Saeed, T. U., Qiao, Y., Chen, S., Alqadhi, S., Zhang, Z., Labi, S., & Sinha, K. C. (2017). *Effects of bridge surface and pavement maintenance activities on asset rating* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2017/19). West Lafayette, IN: Purdue University. https://doi.org/10.5703/1288284316573

AUTHORS

Tariq Usman Saeed
Yu Qiao
Sikai Chen
Saeed Alqadhi
Zhibo Zhang
Graduate Research Assistants
Lyles School of Civil Engineering
Purdue University

Samuel Labi, PhD
Professor of Civil Engineering
Lyles School of Civil Engineering
Purdue University
(765) 494-5926
labi@purdue.edu
Corresponding Author

Kumares C. Sinha, PhD
Edgar B. and Hedwig M. Olson
Distinguished Professor of Civil Engineering
Lyles School of Civil Engineering
Purdue University
(765) 494-2211
sinha@purdue.edu
Corresponding Author

ACKNOWLEDGMENTS

The authors of this report acknowledge the valuable support and guidance provided by the members of the Study Advisory Committee: Scott Chandler, William Flora, Robert Montgomery, Tom Duncan, Samy Noureldin, and Chris Wheeler. The research team is also grateful to Jackeline Murillo Hoyos for carrying out the initial part of the analysis.

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: 978-1-62260-491-3

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/IN/JTRP-2018/19		

4. Title and Subtitle	5. Report Date
Effects of Bridge Surface & Pavement Maintenance Activities on Asset Rating	November 2017
	6. Performing Organization Code
7. Author(s) Tariq Usman Saeed, Yu Qiao, Sikai Chen, Saeed Al Qadhi, Zhibo Zhang, Samuel Labi, Kumares C. Sinha	8. Performing Organization Report No. FHWA/IN/JTRP-2018/19
9. Performing Organization Name and Address Joint Transportation Research Program Hall for Discovery and Learning Research (DLR), Suite 204 207 S. Martin Jischke Drive West Lafayette, IN 47907	10. Work Unit No.
	11. Contract or Grant No. SPR-4012
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

Treatment effectiveness modeling is essential for asset performance modeling and predictions, and ultimately, for effective performance monitoring and feedback and for evaluating and comparing alternative treatments. Asset managers use these models to determine the expected incremental change of asset condition resulting from a future application of a specific maintenance treatment. That way, the agency can update its asset performance curves in software simulation to reflect maintenance application at any future year and to identify the most cost-effective treatments. Asset managers also seek to identify the factors that influence treatment effectiveness, and to use cost and performance data to estimate the cost-effectiveness of these treatments.

This study provides and demonstrates a methodology to quantify the impact of INDOT’s standard maintenance treatments on state highway pavements and bridge deck surfaces, in terms of their condition ratings. Of the specific objectives, the first is to generate requisite reset values that INDOT’s asset manager can use in the agency’s PMS and BMS software packages. The second is to measure the longer-term effectiveness of specific maintenance treatments in terms of the extension to asset life. The third specific objective is to use this information to assess the cost-effectiveness of the treatments.

The research product from this project is a set of averages or models that represent the impacts (performance jump, post-treatment performance vs. age relationship, and cost) of each treatment type typically applied to INDOT’s assets. The performance impacts are expressed in terms of the requisite performance indicators. The performance jump models showed that the asset’s functional class and pre-treatment condition, and the treatment type were major significant predictors of the performance jump and post-treatment performance loss. The first deliverable from this project is the average (mean) impact for each treatment type under investigation. The second is the overall statistical description of the impact, namely, the minimum and maximum impact, and range and standard deviation of impact; a statistical model that predicts the impact as a function of asset and treatment attributes. The third is a set of charts that describe the sensitivity of the treatment impact to factors related to the asset or the treatment. The study also developed cost models for each of the pavement and bridge treatments and used these results to assess the long-term cost-effectiveness of the treatments.

17. Key Words	18. Distribution Statement
maintenance, effectiveness, treatment, cost-effectiveness, pavement, bridge	No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	61	

Form DOT F 1700.7 (8-69)

EXECUTIVE SUMMARY

EFFECTS OF BRIDGE SURFACE AND PAVEMENT MAINTENANCE ACTIVITIES ON ASSET RATING

Explicit statements of the efficacy of pavement and bridge treatments, in terms of the asset condition ratings and other performance indicators, is generally essential to asset performance monitoring and feedback and for evaluating and comparing alternative treatments. Also, in asset performance modeling and prediction, such effectiveness values are important because asset managers use them to determine the expected incremental change of asset condition resulting from a future application of a specific maintenance treatment. That way, the agency can update its asset performance curves in software simulation to reflect maintenance application at any future year and to identify the most cost-effective treatments.

In response to these needs, the Indiana Department of Transportation (INDOT) commissioned this study to synthesize the literature on how standard asset maintenance treatments have affected asset surface ratings; use INDOT asset performance data to quantify the effectiveness of such treatments in order to identify the factors that influence such effectiveness; and use cost and performance data to estimate the cost, effectiveness, and cost-effectiveness of these treatments. This report addresses these objectives.

The report presents a set of averages or models that represent the impacts (performance jump, post-treatment performance-vs.-age relationship, and cost) of each standard treatment type typically applied to INDOT's pavement and bridge assets. The performance impacts are expressed in terms of the requisite performance indicators. The performance jump models showed that the asset's functional class and pre-treatment condition and the treatment type are major significant predictors of the performance jump and post-treatment performance loss. The first deliverable from this project is the average (mean) impact for each treatment type under investigation. The second deliverable is the overall statistical description of the impact of each treatment, namely the minimum and maximum impact and the range and standard deviation of impact, as well as a statistical model that predicts the impact as a function of asset and treatment attributes. The third deliverable is a set of charts that describe the sensitivity of the treatment impact to factors related to the asset or the treatment. The report also presents the development of cost models for each of the pavement and bridge treatments and shows how these were used to assess the long-term cost-effectiveness of the treatments.

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1. INTRODUCTION

1.1 Study Background

From a general perspective, the Indiana Department of Transportation (INDOT)'s pavement and bridge managers continue to invest heavily in identifying and implementing cost-effective maintenance practices through the use of reliable and comprehensive Pavement Management System (PMS) and Bridge Management System (BMS). These Asset Management (AM) tools continue to help INDOT's pavement and bridge managers make more objective and defensible investment decisions towards keeping their assets in a state of good repair.

INDOT's dTIMS asset management packages—PMS and BMS—each involve three main components—data management, analysis and modeling, and program development. The Data Management component involves data collection, data storage and data integration. The PMS or BMS databases contain pavement and bridge inventory data, condition and history, traffic volumes and loads, climatic data, and contract and cost data. The availability of quality input data for these packages impacts the agency's ability to identify investment needs and evaluate competing investments. The Analysis and Modeling component, which uses data from the first component, involves measuring and modeling of the asset condition, making performance predictions, determining the effectiveness and costs of the maintenance, rehabilitation, and reconstruction (MR&R) treatments, evaluation of asset condition or remaining life before and after the MR&R treatment, and budgeting and programming. The Program Development component integrates the data and analysis components and uses decision making tools to identify/select assets that deserve some MR&R treatments, and prioritizing these candidate projects within available budgetary constraints.

This report addresses a part of the second component of asset management systems, specifically, the efficacy of asset maintenance treatments. Within this component, in the specific context of models on asset performance that the system user needs to input, there are two kinds of models: (a) asset performance-vs.-age models that are used to track the asset condition trends over time, correctly identifying their current condition, and forecasting their future condition. (b) treatment effectiveness models that are used to estimate the extent to which the asset performance "jumps" (or, resets) in response to a treatment, the extent to which the rate of deterioration is reduced, or the extent to which the asset life is increased due to the treatment.

1.2 Problem Statement

Explicit statements of the efficacy of INDOT's asset treatments, in terms of the asset condition ratings, deflection units and other performance indicators, is generally essential to effective performance monitoring and feedback (Flora, 2009) and for evaluating and comparing alternative interventions (Lavrenz, Murillo Hoyos, & Labi, 2015). These statements help answer questions such as: By how much is a bridge deck condition rating enhanced by deck overlay? How many additional years of life can be obtained by thin HMA overlay? Therefore, from a strategic perspective of asset management, it is useful to assess the effectiveness and cost-effectiveness of individual maintenance treatments as reliably as possible.

In asset performance modeling and predictions, reliable assessment of treatment effectiveness is important because asset managers use these effectiveness models to (i) predict the expected change in the asset condition resulting from a future application of a specific maintenance treatment. **That way, the agency's asset performance curves can be updated in the software simulation to account for maintenance application at future years, and** (ii) make decisions to select the best (most cost-effective) treatment at any given time.

These applications are consistent with one of INDOT's 2015–2016 goals, which is to "Take Care of What We Have." Under this goal, two of the four objectives are to "… maintain steady improvement in pavement and bridge quality" and to "… link strategy and operations to results." Also, two of INDOT's Key Performance Indicators (KPI) directly address the condition of highway assets: KPI#1: State-controlled roads in fair or better condition and KPI #2: State-owned and state-maintained bridges available for use as intended. Motivated in part by these existing and emerging targets related to highway asset performance measurement and evaluation in Indiana, INDOT's highway bridge and pavement managers expressed a need to quantify the impacts of various activities (or treatments) associated with the maintenance of their assets, in terms of the requisite asset ratings.

In response to this need, the present study was commissioned by INDOT, to carry out a synthesis of the literature on how asset maintenance actions have affected asset surface ratings, to use INDOT asset performance data to quantify the effectiveness of such treatments and to identify the factors that influence such effectiveness, and to use cost and performance data to estimate their cost-effectiveness.

1.3 Study Objectives and Scope

This study provides and demonstrates a methodology to quantify the overall impact of maintenance treatments on highway asset ratings. The first objective is to generate requisite reset values that INDOT's asset manager can use in the agency's PMS and BMS software packages (dTIMS-pavements and dTIMS-bridges, respectively). **These packages simulate sudden jumps in asset condition (due to prospective future treatments)** and the gradual deterioration thereafter. As such, the packages require the user to input the new value of asset condition just after a treatment is applied. The second objective is to provide information that will enable INDOT's asset manager to carry out ex poste evaluation of the effectiveness of past treatments or ex ante evaluation of proposed or prospective future treatments in terms of the performance jump or treatment life. The third objective is to use this information (coupled with cost data) to assess the **cost-effectiveness** of INDOT's standard maintenance treatments.

The study investigates two asset types (pavement and bridge surfaces) and considers standard treatments that INDOT typically applies to these assets. The initial list of treatments intended for study included crack sealing, chip sealing, patching, HMA overlays (for pavements); and deck patching, latex modified concrete overlay, and polymeric overlay (for bridges). Due to data limitations, only a subset of these treatments were investigated. In addition, the scope covers state highways only (excludes assets owned by local jurisdictions).

With regard to the performance indicators for the performance jump measurement, it was initially desired to use a wide range of indicators. However, for pavements and bridges, data on IRI only and NBI Rating, respectively, were available to the researchers. Nevertheless, the study framework is generic and can therefore be applied easily to any performance indicator.

1.4 Organization of this Report

This report starts with the background and problem statement for this research, followed by a description of the objectives and study approach. Chapter 2 presents the asset families and typical maintenance types. Chapter 3 reviews the state of the practice and the state-of-the-art methodologies for assessing the effect of asset treatments. The chapter also provides some examples of published effectiveness value for the various bridge and pavement surface treatments. Chapter 4 presents the overall methodology adopted in this study. Chapters 5 and 6 present the results of performance jump values, the sensitivity of the model outcomes, and cost-effectiveness analysis associated with the pavement and bridge treatments. These results were obtained using the methodology documented in Chapter 4. In Chapter 7, the report summarizes the study effort, makes recommendations, and highlights the benefits of the study results to the practice of pavement and bridge management.

2. ASSET FAMILIES AND TYPICAL MAINTENANCE TYPES

2.1 Pavement Families

The specific treatments for pavement maintenance and rehabilitation vary across the different pavement types. For this reason, it is useful to group pavement assets into families to limit not only the variation of the influential factors of treatment effectiveness but also any statistical interactions or correlations between any family-factor and other factors. Based on the topmost pavement surface material, the pavements in Indiana are categorized as concrete (rigid) and asphalt (flexible) pavements, with the latter dominating the former by far (Figure 2.1). Asphaltic pavements include composite pavements that have a flexible top layer.

It can be expected that for a given treatment type and pre-treatment pavement condition, the effectiveness of a maintenance treatment will differ across the functional classes. This may be because highway agencies design and construct Interstates to higher standards compared to non-NHS roads, and therefore the recuperative effect of maintenance treatments to these pavement and bridge surface material types and thicknesses can be expected to differ. In Indiana, the highest class of highways is the National Highway System, which was designated by legislation in 1995. This is a collection of roads based on their importance to the national economy and defense, and comprises a few state roads and US Roads and all Interstates. Higher class roads attract long-distance traffic with heavy-loads due to their high mobility, limited access, and superior pavement and geometric standards and quality. In this study, the road sections were placed in the following road classes: Interstates (INT), NHS Non-Interstate (NIN), and Non-NHS (NNN).

2.2 Characterizing the Pavement Surface Condition

A performance indicator represents, in quantitative or qualitative terms, the extent to which a distress manifests on the pavement surface. Generally, pavement performance can be categorized into surface roughness, surface distress, and structural condition (Haas, Hudson, & Zaniewski, 1994).

2.2.1 Pavement Surface Roughness

Roughness is a primary criterion by which road users judge the quality of a pavement and 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) and is directly related to the vehicle operation cost (Archondo-Callao & Faiz, 1994; Chesher & Harrison, 1987).

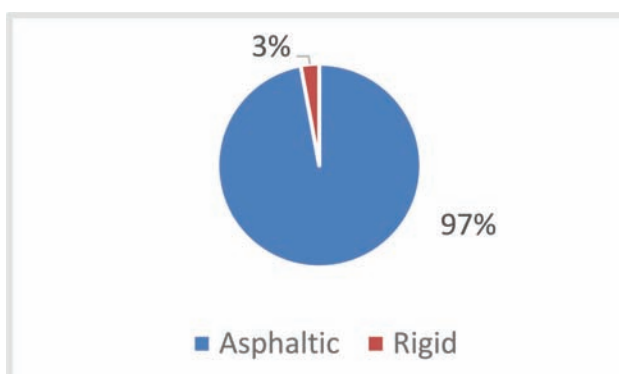


Figure 2.1 Distribution of major pavement surface types, Indiana State Highway Network (FHWA, 2016).

2.2.2 Pavement Surface Distress/Defects

Surface distress can be defined as any kind of damage observed on the pavement surface. Distress modes can be categorized into three groups (Paterson, 1987):

1. *Fracture*. This category contains all types of cracking (in flexible and rigid pavements), and spalling caused by excessive loading thermal changes, fatigue, slippage or contraction, moisture damage, and distortion. This category contains all forms of deformation, resulting from such things as rutting, corrugation, and shoving. For rigid pavements, the rut-shaped distortion is referred to as Wheel Path Wear (WPW).
2. *Disintegration*. This category contains raveling, stripping, and spalling, caused by aggregate degradation, loss of bonding, traffic abrasion, chemical reactivity, binder aging, or poor compaction.
3. *Surface distress*. This, to some extent, is related to surface roughness (more frequent and severe cracks, distortion and disintegration will, in the long term, lead to a rougher pavement) as well as structural integrity. Surface distress may be an indication of current or impending problems with the pavement structure). Each of these surface distresses can constitute a performance indicator for evaluating pavement condition. For example, rutting, as a performance indicator, has been used to evaluate pavement condition in several studies (Hall, Correa, & Simpson, 2002; Irfan, Khurshid, & Labi, 2009). However, given that a defective pavement typically exhibits multiple distresses at the same time, it may not be prudent to use only one distress type for purposes of evaluating the overall pavement condition.

2.2.3 Combined Indicators of Overall Pavement Performance

Pavement Condition Rating (PCR) is another commonly-used aggregate performance indicator for surface distress, and identifies pavement distress in terms of extent and severity. The PCR evaluation scale ranges from 100 (very good condition) to 0 (very poor condition). A number of highway agencies have established a distress index for each individual distress type, such as transverse crack index, while others have an index representing various combinations of distress type, extent and severity.

The calculation of combined indices, similar to that for PCR, requires the establishment of weights or priority factors among the various distress types. Pavements can be assigned a score that represents their overall condition based on measurements of roughness, surface distress, skid resistance and deflection. This quantifies a pavement's overall performance and can be used by pavement managers to identify optimal treatments and schedules, and to prioritize projects. The first combined-index pavement condition rating system, Present Serviceability Rating (PSR), was based on the AASHO Road Test. Various correlations have been developed between PSR and IRI (Al-Omari & Darter, 1994; Gulen, Woods, Weaver, & Anderson, 1994; Paterson, 1986).

2.3 Pavement Treatment Types

The pavement maintenance treatments typically implemented in Indiana are summarized in the Table 2.1.

2.3.1 Maintenance Treatments for Flexible Pavements

Figure 2.2 presents photos of some standard maintenance treatments for flexible pavements. A majority of the information in this section is taken from INDOT's design manual (INDOT, 2013a).

HMA overlay. As a preventive maintenance or maintenance treatment, HMA overlay has gained wide acceptance in the United States and abroad. Hot Mix Asphalt Overlay may be carried out with or without profile milling or as an inlay (replacing it with a new asphalt surface to the original surface elevation). Depending on the thickness, HMA overlay can be categorized as HMA Overlay PM, HMA Overlay Minor Structural (or Functional), and HMA Overlay Major Structural (or Structural). HMA overlays generally contribute very little to pavement structural capacity (Roberts et al., 1996). These surface treatments (up to 2 in thickness) are often intended to resolve problems associated with the pavement surface roughness, rutting, and surface cracking, improve ride quality, correct minor surface defects, improve safety characteristics such as skid resistance and drainage, enhance appearance and reduce road-tire noise.

TABLE 2.1
Pavement Maintenance Treatments (INDOT, 2013a)

Asphalt (Flexible) Surfaces	Portland Cement Concrete (Rigid) Surfaces
Crack Sealing/Routing and Filling	Crack Sealing/Filling
Fog Seal	PCCP Joint Resealing
Scrub Seal (Sand Seal)	Load Transfer Retrofit
Seal Coat (Chip Seal)	Cross-stitching
Flush Seal	PCCP Profiling (Diamond Grinding) Partial
Microsurfacing	Depth
Profile Milling	Patching Full-Depth
HMA Overlay, Preventive Maintenance	Undersealing
Ultra-thin Bonded Wearing Course (UBWC)	
HMA Minor Structural Overlay	

Figure 2.2 Illustration of flexible pavement surface treatments.
Sources:

a. http://old.post-gazette.com/pg/09173/979033-147.stm?cmpid=news.xml
b. https://www.fhwa.dot.gov/publications/focus/98mar/georgia.cfm
c. http://fp2.org/2012/10/09/thin-hma-overlay/
d. http://dpw.lacounty.gov/gmed/lacroads/treatmentslurryseal.aspx
e. https://www.fhwa.dot.gov/publications/focus/07sep/01.cfm
f. http://www.mnltap.umn.edu/publications/exchange/2017/March/opera/index.html

Microsurfacing. Microsurfacing comprises of the basic ingredients of well-graded fine aggregate emulsified asphalt, water, and mineral filler. This treatment repairs fair-to-moderate pavement surface defects, fills cracks and voids, and improves skid and abrasion resistance. Microsurfacing may not be suitable at high-volume and high-speed sections (Raza, 1994).

Crack sealing/routing and filling. Crack sealing/routing and filling is a preventive maintenance treatment that involves the placement of specialized materials into or above cracks on the pavement surface, to prevent the intrusion of incompressibles and water into the cracks. In Indiana, this activity is mostly carried out in-house (crews at the sub-districts) on force account.

Fog seal. Fog seal is a light (spray) application of a thin liquid oil (this is a diluted asphalt emulsion that sets slowly) to the surface of an old pavement. This is a relatively low-cost treatment that rejuvenates the oxidized pavement surface and can be applied to all road types to address raveling, mild oxidation, and to seal hairline cracks (Asphalt Institute, 1999) to keep water out of the pavement.

Seal coat (chip seal). Seal coat involves spraying of a thin layer of liquid asphalt followed by uniform spreading of coarse aggregate (chips). This is done to fill and seal cracks and raveled surfaces of old pavements, provide "an anti-glare surface during wet weather and an increased reflective surface for night driving, seal the pavement surface-minimizing the effects of aging, and to provide a highly skid-resistant surface, particularly on wet pavements" (INDOT, 2013a; WSDOT, n.d.). There are many types of seal coats in terms of the number of seal coat layers (for example, single, double, and triple seal coats), layer types, and materials (for example, geotextile seal and fiber-mat seal).

Scrub seals (sand seals). Scrub seals are thin surface treatments that involve thin-layer spraying of asphalt emulsion, brooming the sprayed surface to direct the emulsion into the pavement cracks, followed by the immediate spread of a thin layer of fine aggregate, and brooming the pavement surface to scrub the emulsion and to direct the sand into any voids and cracks. Scrub seal is similar to sand seal, except that the latter does not involve brooming (INDOT, 2013a).

Fog seal or flush coat. Fog seal is a kind of seal coat that applies a fog seal coat to the surface of a chip sealed pavement. With regard to chip seals, a major failure mode, aggregate loss, exposes asphalt at the surface and causes bleeding. Fog seals reduce aggregate loss from the seal coat and restore the pavement color, thus enhances the visibility of pavement markings (INDOT, 2013a).

Profile milling. Profile milling removes the upper portion of the pavement surface to "correct the pavement profile or roughening the existing surface in preparation for a new thin HMA overlay" (INDOT, 2013a). Also known as asphalt scarification, this is used to roughen the pavement surface or to remove excessive crack sealant before placing a HMA overlay.

Ultra-thin bonded wearing course (UBWC). UBWC is a "gap-graded, ultrathin hot-mix asphalt mixture applied over a thick polymer-modified asphalt emulsion membrane." This membrane seals the existing pavement surface and provides a layer with high binder content at the interface between the existing pavement surface and the UBWC layer (INDOT, 2013a).

2.3.2 Maintenance Treatments for Rigid Pavements

Figure 2.3 presents images of standard maintenance treatments for rigid pavements. *Patching* is a common maintenance option for rigid pavements. Patches treat localized slab problems such as spalling, scaling (due to conditions including reactive aggregate distress and over-finishing the surface), corner breaks, joint deterioration, or punchouts. Partial depth patches restore defects within the top one-third of the slab depth. For slab damage that occur in the bottom two-third of the slab depth, full-depth patches are often applied. Any defective existing patches are replaced.

Crack sealing/filling. Crack sealing/filling of the PCCP pavement involves placement of specialized material into or on top of the crack. The intent is to prevent the entry of debris and moisture. Prior to the sealing, the cracks are cleaned and dried. In certain cases, the crack is routed prior to the sealing treatment.

PCCP joint resealing. Joint seal distresses often include "loss of bonding to the sidewall, cohesive failure, spalls, and torn or missing sealant" (INDOT, 2013a). These distresses can cause spalling of the joint wall, PCCP faulting, shattering of slab edges or even slab blowup. The process of sealing of joints includes sawing to remove old sealant and reshaping the joint seal reservoir, cleaning, and sealing in the PCCP joints.

Load transfer retrofit (LTR). This treatment, also referred to as "stitching" involves the installation of dowel bars across cracks or joints of the PCC pavements to re-establish the integrity of load transfer across a crack or joint. This treatment involves slot-cutting, placing new dowels or reinforcing bars in the slots, and cementing them. LTR is often carried out with undersealing and fault grinding. When used in conjunction with diamond grinding, the treatment restores the equality of adjacent slab elevations and therefore helps transfer wheel loads across successive slabs, thereby reducing the rate of the pavement deterioration (INDOT, 2013a).

Cross-stitching. Cross-stitching repairs and strengthens PCCP longitudinal joints and cracks (INDOT, 2013a). The treatment "uses deformed tie bars epoxied or grouted into holes drilled at an angle through non-working longitudinal cracks or joints." The cross-stitching tie bars prevent the crack from horizontal and vertical movement, and provides additional strength to the crack or joints.

PCCP profiling (diamond grinding). This treatment, which corrects faulting or roughness on concrete pavements, uses a diamond grinding machine to create a texturized pattern on the pavement surface—the machine grinds 0.2 in. to 0.25 in. off the concrete surface (INDOT, 2013a).

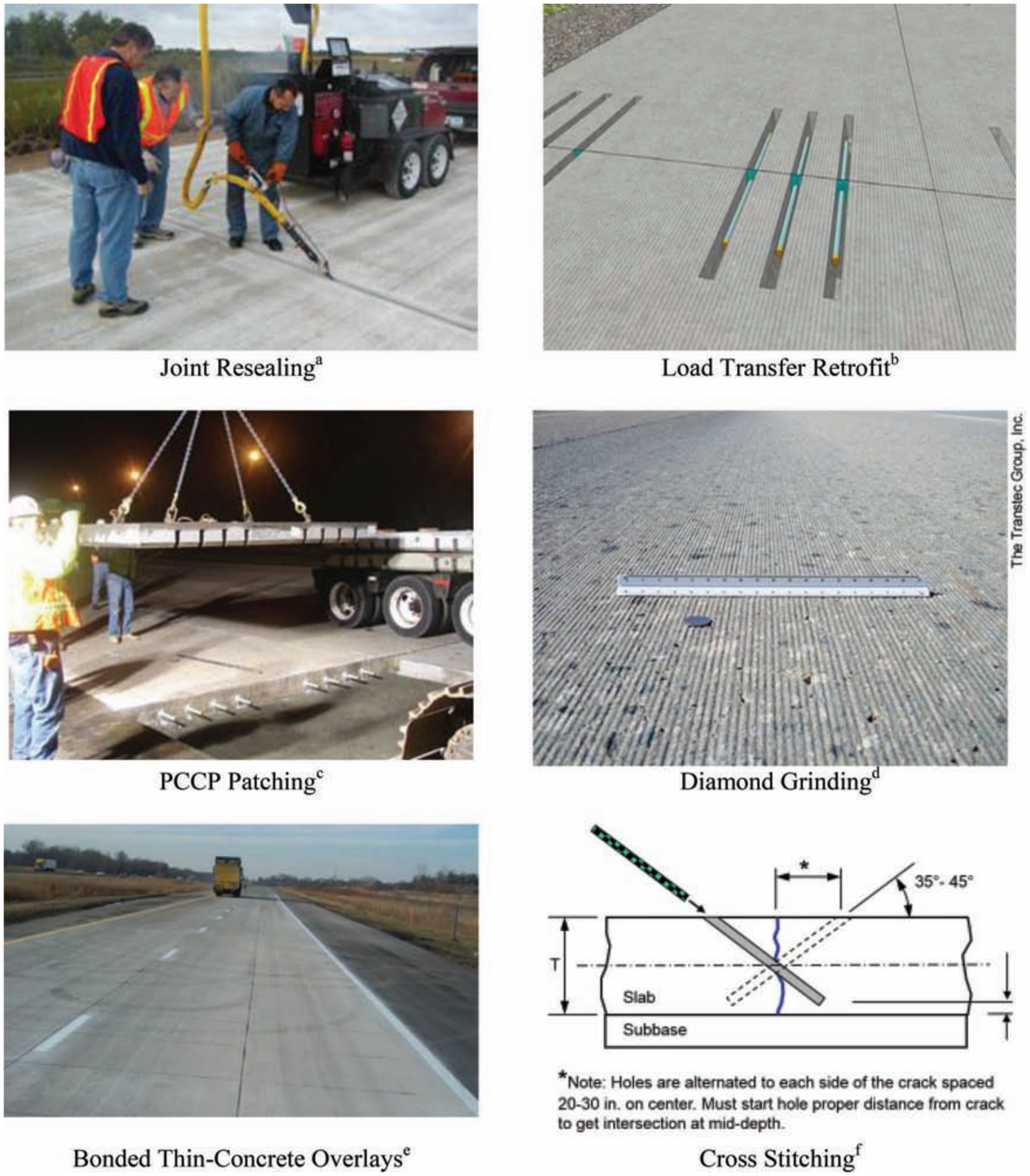


Figure 2.3 Illustration of rigid pavement surface treatments.
Sources:

a. http://www.dot.state.mn.us/mnroad/projects/PCC_Joint_Sealing/index.html
b. https://www.fhwa.dot.gov/publications/research/infrastructure/pavements/pccp/11065/003.cfm
c. https://www.fhwa.dot.gov/publications/focus/08oct/05.cfm
d. https://www.fhwa.dot.gov/publications/publicroads/14julaug/01.cfm
e. https://www.dot.state.mn.us/mnroad/projects/Whitetopping/index.html
f. http://wikipave.org/index.php?title=joint_sealing

Undersealing. Voids under PCC pavements cause faulting, corner breaks, pumping, and joint failure, and filling them (undersealing) can yield significant extension to PCCP life and improves rideability. This technique pumps cement grout or liquid asphalt under PCCP to flow into the voids beneath the pavement (INDOT, 2013a).

2.4 Bridge Families

Similar to the case for pavements, bridge deck maintenance practices are expected to vary by deck surface material type. Based on the topmost surface material, Indiana's bridge deck surfaces can generally be categorized as follows: those with a wearing course and those without a wearing course. Again, a given treatment may not fit both types of deck surface material. Therefore, grouping of bridge deck surfaces, for purposes of maintenance treatment selection or for *ex poste* evaluation, can be useful.

2.5 Characterizing the Bridge Deck Surface Condition

For purposes of this study, the bridge deck surface condition was characterized in terms of the National Bridge Inventory rating (FHWA, 1995). This is a universal scale for evaluating the deck condition on a 0–9 scale:

9 - Superior to present desirable criteria
8 - Equal to present desirable criteria
7 - Better than present minimum criteria
6 - Equal to present minimum criteria
5 - Somewhat better than minimum adequacy to tolerate being left in place as is
4 - Meets minimum tolerable limits to be left in place as is
3 - Basically intolerable requiring high priority of corrective action
2 - Basically intolerable requiring high priority of replacement
1 - This value of rating code not used
0 - Bridge closed

TABLE 2.2
Preventive and Corrective Treatments for Deck Surfaces (INDOT, 2014)

Treatment Role	Examples
Preventive Treatments	Cleaning/Flushing Bridge Decks Cleaning Joints Deck Sealing
Corrective Treatments	Deck Patching (shallow/deep) Joint Repair/Replacement Thin Deck Overlay (e.g. Polymeric Overlay) Latex Modified Concrete (LMC) Overlay Deck Crack Sealing

TABLE 2.3
Other Maintenance Techniques for Bridge Deck Surfaces (INDOT, 2013b)

Code	Technique
BD-1	Patching
BD-2	Epoxy Resin Injection
BD-3	Low Viscosity Sealant for Crack Repair
BD-4	Concrete Overlay
BD-5	Cathodic Protection
BD-6	Deck Drainage Improvements
BD-9	Joint Elimination
BD-10	Concrete Sealants
BD-11	Corrosion Inhibitors

2.6 Typical Bridge Deck Surface Treatments in Indiana

INDOT's Bridge and Culvert Preservation Initiative (BCPI) policy statement (INDOT, 2014) defines preventive maintenance as "specific activities that are scheduled on a fixed cycle that are intended to maintain a structure at its current level, and prevent or reduce deterioration" and corrective maintenance is defined as "specific activities that are condition driven, intended to correct defects and prevent or reduce deterioration." The typical bridge M&R treatments implemented in Indiana are summarized in Tables 2.2 and 2.3, based on information from the BCPI and the Indiana Design Manual, respectively. Tables 2.4 and 2.5 present INDOT's application warrants for pavement preventive and corrective treatments, respectively. Figure 2.4 illustrates some bridge deck surface treatments typically used in Indiana.

A major cause of bridge deck deterioration in Indiana is the accumulated winter-time application of pavement deicing chemicals. Often, such deterioration is manifest in the form of concrete scaling, cracking, and delamination, loss of bond between the rebars and the concrete deck, and corrosion of the steel reinforcement. To mitigate this problem, the top surfaces of Portland cement concrete decks are overlaid with protective wearing surfaces such as latex-modified concrete. Then, the deck is patched and any needed overlay is placed, finished, and cured (INDOT, 2004). The sections below, culled from the Indiana Design Manual (INDOT 2013b), describe some of the standard treatments.

Patching. Patching of the bridge deck appears to be one of the most common bridge deck repair activities in Indiana. In certain cases, this is followed by a modified

TABLE 2.4
Application Warrants for Preventive Treatments (INDOT, 2014)

Preventive Treatments	NBI Item No.	Threshold Condition Rating	Cycle (years)[2]
Cleaning/Flushing Bridge Decks	Item 58[1]	>4	1
Substr./Superstructure Washing	Item 59 & 60	>4	1
Cleaning Deck Drains	Item 58	>4	1
Cleaning/Lubricating Bearings	Item 59A	>4	1
Cleaning Joints	Item 58.15, 58.16, 58.16A&6B, 58.16C	>4	1
Deck Sealing	Item 58.01 & 58.02	>5	1

[1]Item No. refers to NBI Item number defined in FHWA (1995).
[2]Cycle refers to the frequency (in years) of implementing each preventive treatment.

TABLE 2.5
Application Warrants for Deck Surface Corrective Treatments (INDOT, 2014)

Corrective Treatments	NBI Item #	Threshold Condition Rating	Other Criteria
Deck Patching (shallow/deep)	58.01[1]	>4	D/SS[2] > 4; & Max 10% deck patching
Joint Repair/Replacement	58.16	<6	WS/D/SS > 4
Thin Deck Overlay (e.g., Polymeric)	58.01	>5	D/SS > 4; & Max 10% deck patching
Latex Modified Concrete (LMC) Overlay	58.01	>3	D/SS > 5; & Max 15% deck patching
Deck Crack Sealing	58.01	>5	D/SS > 5

[1]Item No. refers to NBI Item number defined in FHWA (1995).
[2]WS = Wearing Surface (58.01); D = Deck (58); SS = Superstructure (59) AND Substructure (60).

concrete overlay. Patching may be full-depth or partial-depth. In cases where removal of the unsound concrete yields deck cavities whose depth exceeds the level of the adjacent prepared deck surface, partial-depth patching is typically applied. On the other hand, where the unsound concrete is rather deep (in such cases, all the concrete within the area demarcated for patching is replaced), full-depth patching is typically applied. After removing the concrete, the resulting voids are cleared of all debris, foreign material, and loose concrete to yield a solid and firm surface to receive the new concrete. Before the actual patching operation, the exposed full- or partial-depth patch surfaces are typically inspected carefully to ensure that (i) all unsound concrete has been removed, edges have a vertical face of 1 inch (ii) there is no damage to the exposed rebar, (iii) a "minimum 1-inch clearance exists around the rebars (if the bond between existing concrete and reinforcing steel has been destroyed, or if over 50% of the rebar diameter is exposed for more than 12 inches) and holes thoroughly are cleaned out." Then an air compressor is used to clean out the cavity. Finally, epoxy adhesive is applied to all surfaces in the patch areas (INDOT, 2004) and the patching concrete is placed. Deck patching does not completely arrest the corrosion rate. It causes direct contact between new (uncontaminated) concrete and old (contaminated) concrete thus generating new corrosion activity in the area. It has been reported that repaired decks may exhibit significant corrosion 7 years after the treatment. Therefore, it has been recommended that deck patching should be considered a temporary solution only.

Concrete deck sealing. Deck sealing is applied to avoid the penetration of chloride ions from deicing products into the deck. Sealers are classified into two main groups: (a) penetrating sealers and (b) surface coatings. Penetrating sealers penetrate deeper into the concrete deck and include hydrophobic sealers (or water-repellants) and pore blockers. Penetrating sealers are applied early after deck construction (3–6 months) and before the deck is contaminated by chloride ions. The sealer is applied periodically.

Concrete deck crack sealing. Cracks serve as a direct conduit for chloride ion penetration into the concrete deck slab. Potential solutions for crack sealing include penetrating sealers, HMWM (high molecular weight methacrylate), and epoxy injection.

Latex-modified concrete (LMC) overlay. At INDOT, latex-modified bridge deck overlays have been used successfully for over 4 decades. The treatment is typically applied after deck patching. According to the guidelines, for an LMC overlay project to qualify as a candidate for preventive maintenance, each of the three bridge components (superstructure, deck, and substructure) must have a bridge inspection rating of 5 or higher and the need for partial depth patching must be less than 15%. If full-depth patching exceeds 35%, consideration should be given to deck replacement. LMC overlay is intended to protect the bridge deck for 15 $\pm$ 5 years (the large variation is due to the expected differences in the work quality, traffic loading, and level of salting during wintertime. Frosch, Kreger, and Strandquist (2013) stated that LMC overlays can provide a long service life and therefore are recommended for more critical bridges as both a preventive maintenance and a rehabilitation measure.

Polymeric overlay. This treatment applies an epoxy polymer with a special aggregate. For a bridge to qualify as a candidate for this treatment, each of the wearing surface and the 3 components (deck, superstructure and substructure) must have an inspection rating not less than 4. The treatment is often intended to last for 10 years. According to Frosch et al. (2013), thin polymer overlays are recommended for "situations where quick installations are required and where a thin protective system is needed." In addition, this treatment can be considered as a preventive treatment for new bridge decks.

New wearing surface. Deck overlay, such as provision of a wearing surface for the bridge deck, is a common treatment applied not only to correct minor defects but also to reduce imminent deterioration of the bridge deck. As such, this treatment can be considered as a preventive maintenance treatment. In this treatment, the bridge deck is first prepared to receive the concrete overlays by scarifying (breaking up the surface of) the entire deck or floor of the existing bridge) or milled to a depth of ¼ inch. Scarification helps provide a clean concrete surface for bonding with the new wearing

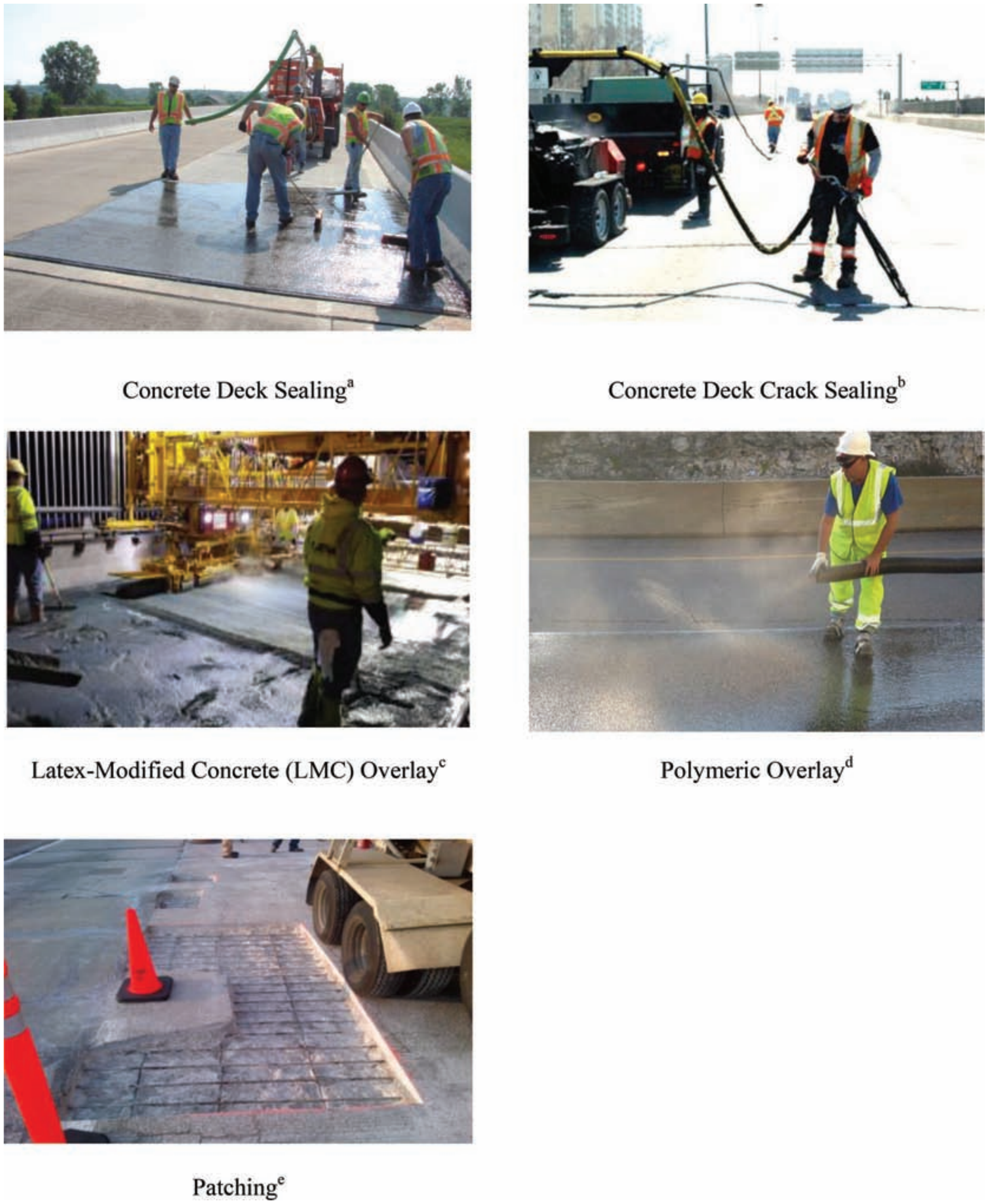


Figure 2.4 Illustration of bridge deck surface treatments.
Sources:

a. https://mdotwiki.state.mi.us/construction/index.php/712_-_bridge_rehabilitation,_concrete
b. https://mdotwiki.state.mi.us/construction/index.php/712_-_bridge_rehabilitation,_concrete
c. http://www.uppercanadaasphalt.com/services/crack-sealing-route-seal/
d. https://www.fhwa.dot.gov/innovation/innovator/issue61/issue61.cfm
e. Bowman & Moran, 2015

surface. After scarification, the next step is to identify the precise location of the deteriorated areas on the bridge deck. Then any unsound concrete and reinforcing steel are removed from such areas, the deck is sandblasted, and all dust and chips from exposed surfaces are cleaned with compressed air (INDOT, 2004). Concrete is placed at the areas deserving patching and finally, the deck is overlaid with the new wearing surface layer. At Indiana's neighboring state of Ohio, the preventive maintenance treatments for concrete overlay wearing surface are similar to those discussed for concrete decks. However, for asphalt concrete deck overlay, cracks are sealed with a flexible asphalt sealer (ASTM D3405, 1997). For low-volume asphaltic concrete bridge decks that have started to exhibit signs of weathering or surface raveling, chip sealing treatment is often applied. For high-volume roads, preventive maintenance treatments include milling and filling with asphaltic concrete (1-inch minimum thickness) or slurry seals.

3. LITERATURE REVIEW

3.1 Introduction

A review of past studies helps establish some a-priori expectations regarding the effects of pavement and bridge surface treatments (on the condition rating of these assets) as well as the factors that influence such effectiveness. In the past ten years, prominent state and national research studies have been carried out to evaluate the effectiveness of pavement and bridge treatments. These include:

- The CDOT (Shuler, 2010) study used full-scale test sections to assess the long-term efficacy of pavement treatments under different environmental conditions. These included chip seals, crack sealing, and thin HMA overlays (for asphalt pavements) and cross-stitching, joint resealing, and micro-grinding (for concrete pavements).
- MACTEC Engineering and Consulting, Inc., California Pavement Preservation Center, and the Federal Highway Administration carried out performance evaluation of various preservation treatments at six states in the USA.
- The Center for Transportation Research and Implementation, Minnesota State University analyzed the expected longevity, pavement life extension, and cost-effectiveness of alternative pavement preservation treatments.
- Wang (2013), in his thesis, investigated the effectiveness of pavement preservation treatments (slurry seal, thin HMA overlay, crack seal, and chip seal) on mitigating multiple pavement distresses (fatigue, transverse, and longitudinal cracking, and rutting) and restoring pavement surface friction, using data from the Specific Pavement Studies-3 (SPS) experiments of the Long Term Pavement Performance (LTPP) program.
- Researchers at the University of Tennessee, Knoxville, evaluated the effectiveness and cost-effectiveness of asphalt pavement rehabilitations using LTPP data.
- Ram and Peshkin (2013) evaluated the costs and benefits of a number of preventive maintenance treatments used in Michigan DOT's CPM program. They defined "benefit" as the percent increase in performance over an untreated pavement performance curve. Using unit costs, the authors calculated the benefit-cost ratio of each treatment, and compared such cost-effectiveness of the treatments.

In the above-listed and other literature, various research papers and agency practice manuals have reported such effectiveness in the short term or long term. The list below presents the measures of effectiveness (MOEs) that have been identified or used in previous studies (Labi & Sinha, 2003; Lavrenz, Murillo-Hoyos & Labi, 2015).

Short term effects of surface treatments (Figure 3.1):

- Increase in the asset condition, measured as an instantaneous jump or the difference between the asset's post-treatment condition and its pre-treatment condition
- Delayed measurement (typically over 1 year) of the performance jump
- Reduction of the rate of the asset deterioration (that is, the difference between the pre-treatment and post-treatment rates of deterioration)

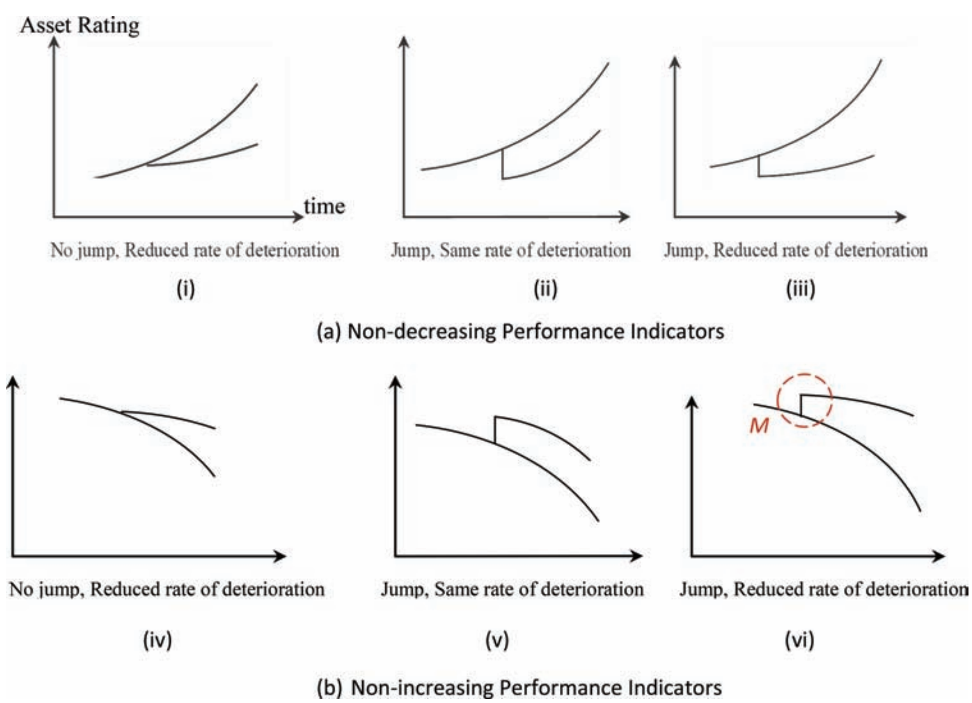


Figure 3.1 Short-term effects of surface treatments on asset rating—the different perspectives.

Long term effects of surface treatments (Figure 3.2):

- Effective life of the treatment (time that elapses before the same or higher level treatment is applied)
- Extension in the service life of the asset due to the treatment
- Average annual loss in performance in the post-treatment period
- Increase in the area bounded by the asset performance curve due to the treatment
- Reduction in the cost of the asset maintenance after the treatment
- Decrease in the likelihood that a specific distress will occur for the first time in a given period

This report focuses on increase in the asset condition or performance jump (a short-term measure of effectiveness) and the effective life of the treatment (long-term measure of effectiveness). With regard to the short-term measures of effectiveness only, the impacts of maintenance treatments on asset rating in the short term, may generally take one of three forms: (i) a reduction in the rate of deterioration subsequent to the treatment, (ii) a modest sudden jump in the asset condition rating (Lytton, 1987; Markow, 1991), or (iii) both (Mamlouk & Zaniewski, 1998) as illustrated below. INDOT has expressed a need to investigate effectiveness of their standard treatments from at least one of these perspectives.

3.2 Short-Term Impacts—The Three MOEs as Developed/Used in the Literature

Figure 3.3 presents a blown up section of Area M in Figure 3.1 (b)(iii) (due to some maintenance treatment) in a performance curve, and illustrates the Delayed Measurement of the Jump (DMJ) concept. Point A the asset condition at a specified time (say, 1 year) before the treatment. Point D is the asset condition just before treatment. Point F is the asset condition just after the treatment, while point E is the state of the asset a specified time after maintenance. C_i and t_i represent the condition of the asset and the year of the asset condition measurement, respectively, corresponding to point *i*.

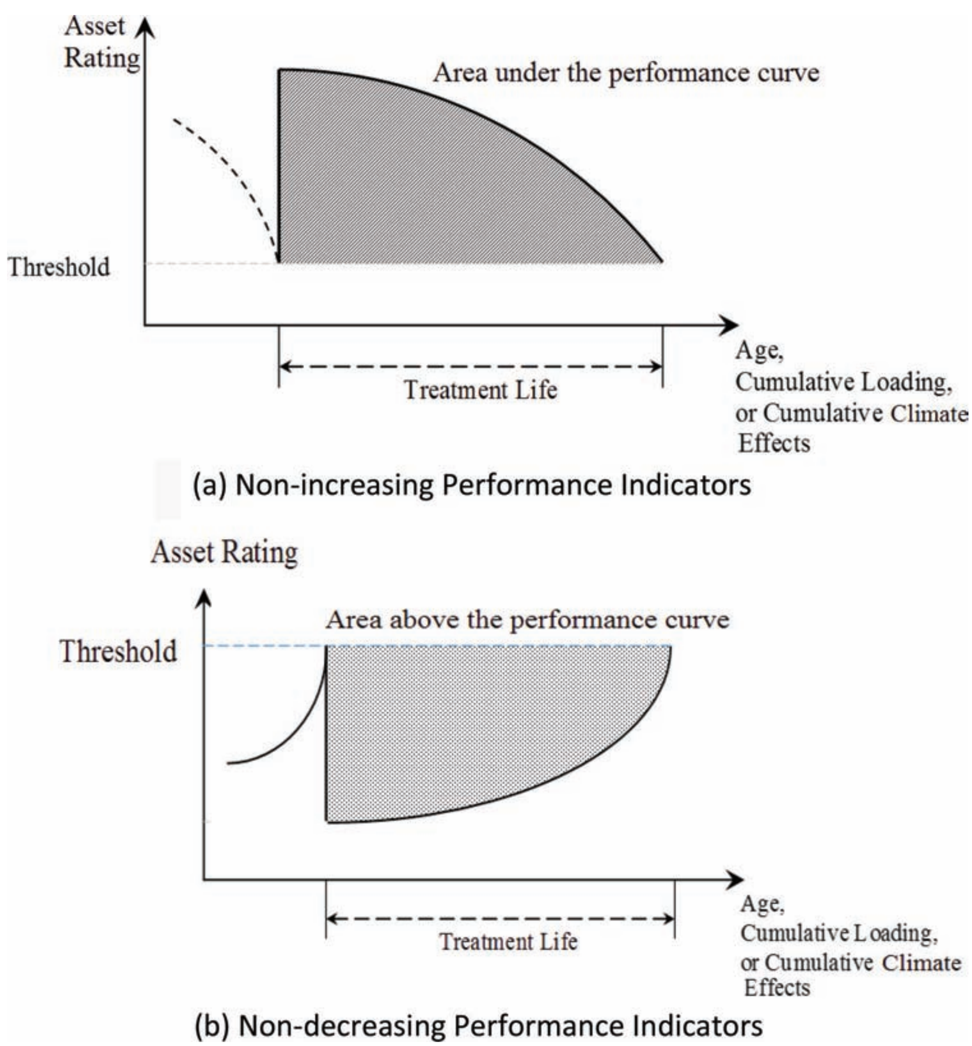


Figure 3.2 Long-term measures of the effect of surface treatments on asset rating.

3.2.1 Delayed Measurement of the Jump (DMJ)

Labi and Siha (2003) presented the three ways in which Delayed Measurement of the Jump has typically been computed in the literature (Figure 3.3):

1. Difference in deterioration 1-year before maintenance (A) and just after maintenance (F), as illustrated as ΔC_1 in the figure. This is $DMJ_{TYPE\ I}$.
2. Difference in deterioration just before maintenance (D) and 1-year after maintenance (E), as illustrated as ΔC_2 in the figure. This is $DMJ_{TYPE\ II}$.
3. Difference in deterioration 1-year before maintenance (A) and 1-year after maintenance (E), as illustrated as ΔC_3 in the figure. This is $DMJ_{TYPE\ III}$.

Each of these measures of DMJ tend to underestimate the maintenance effectiveness. If $DMJ_{TYPE\ I}$ is used to measure maintenance effectiveness, the asset condition just before maintenance is not considered and therefore the maintenance effectiveness in recovering the asset performance from point D to point Z is not captured. Therefore, using $DMJ_{TYPE\ I}$ leads to underestimation of the maintenance effectiveness. Similarly, $DMJ_{TYPE\ II}$ fails to consider the asset condition just after maintenance; thus, the maintenance effectiveness in recovering the asset condition from point W to point F is not accounted for. Thus, using $DMJ_{TYPE\ II}$ underestimates the maintenance effectiveness. $DMJ_{TYPE\ III}$ is associated with the highest level of underestimation; if this measure is used, the maintenance effectiveness is likely perceived to be negative, leading to the often erroneous conclusion that the maintenance treatment was not effective.

DMJ has been used to measure short-term maintenance effectiveness in past research. This has been used to determine the change in roughness (over a 1-year period) of pavements that received each of several types of routine maintenance (Fwa & Sinha, 1987). Models were developed to estimate PSI change as a function of the maintenance type and other factors. In addition, Sinha et al. (1988) estimated models to predict the effectiveness of maintenance (the change in pavement surface roughness) arising from a given amount of maintenance spending, for each climate zone. The change in roughness was calculated as:

$$RRN = (RN_{1985} - RN_{1984})/RN_{1984},$$

where RN = the roughness of a pavement section in a given year.

That study concluded that "for most treatments, roughness increases after treatment, regardless of maintenance expenditure level," which is unintuitive and was probably because the study had used DMJ to measure of the maintenance effectiveness.

Another DMJ measure, expressed as "change in roughness number," has also been used as a response variable in models that estimated the effectiveness of general maintenance and rehabilitation (Madanat & Mishalani, 1998). In addition, using data from Indiana, models utilizing the DMJ concept were developed by Li and Sinha (2000) to estimate change in IRI as a function of pavement attributes. The underestimation of maintenance effectiveness by using DMJ as a measure of effectiveness could be further exacerbated by not giving due cognizance to the relative timing between maintenance and deterioration measurement. Such omission may further lead to incorrect conclusions about maintenance effectiveness.

3.2.2 Performance Jump

Performance jump (PJ) is the instantaneous elevation in the pavement or bridge condition upon receiving maintenance (see ΔC_4 in Figure 3.3). This is computed using the deterioration values just-before and just-after maintenance. The concept of PJ or instantaneous increase in performance has often been the subject of discussion in pavement performance modeling (Lytton, 1987). PJ uses the just-before-treatment and just-after-treatment values of the pavement deterioration. Thus, PJ calculation does not suffer the bias associated with DMJ and represents a superior measure of short-term

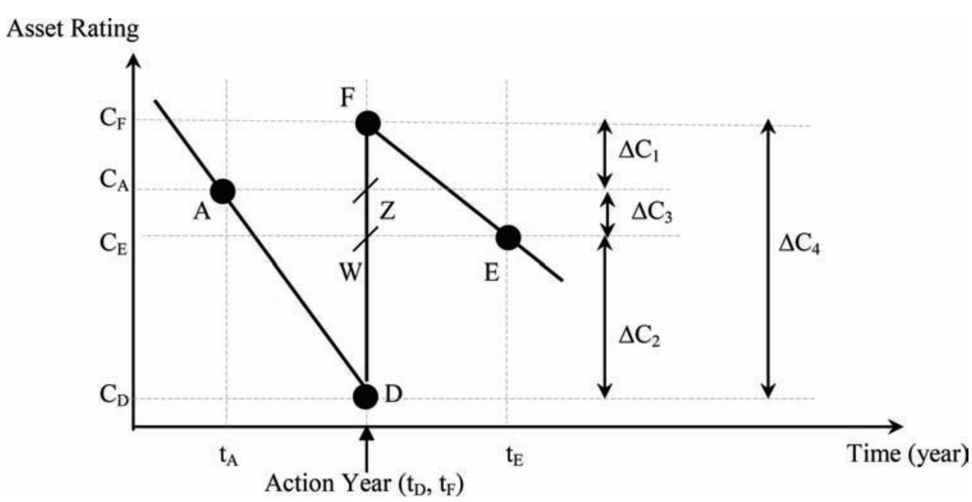


Figure 3.3 Blown-up of Area M illustrating the short-term effect of a treatment on asset rating.

effectiveness of maintenance Unfortunately, agencies typically do not carry out deterioration measurements just before and just after a treatment, it is often difficult to obtain data for PJ computation, and extrapolation of the performance curve from both directions to the point of maintenance is often necessary to estimate the asset's PJ due to treatment.

3.2.3 Deterioration Rate Reduction (DRR)

The deterioration rate reduction (Labi & Sinha, 2003) is defined as the difference in the slope of the deterioration curve before maintenance and after maintenance. The DRR concept involves the "slowing down" of asset deterioration with time or cumulative loading due to the application of maintenance. Therefore in the context of DRR, the effect of maintenance is to make a steep deterioration curve slope more gently. DRR can be calculated as the algebraic difference in the gradients of the asset deterioration curve before-maintenance and after-maintenance. A gentle slope following a steep slope is generally indicative of the application of maintenance.

This measure of treatment effectiveness has been mentioned in literature, albeit, mostly in a conceptual manner (Lytton, 1987; Markow, 1991; Markow et al., 1994) due to the difficulties associated with identifying and quantifying pavement deterioration rate and the reduction of the rate, and the few numerical analyses include the study by Labi and Sinha (2003). Older assets in poor condition suffer progressively increased rates of deterioration if denied maintenance, an observation that is supported by past research. On the other hand, new pavements in good condition may likely deteriorate at the same rate if they receive no maintenance (because they do not need it). These observations are founded on the shape of the typical asset performance curve (which shows little deterioration at the initial phases of the asset life but increasing deterioration rates as the asset ages. With lower level maintenance (such as shallow patching and crack sealing for pavements, for example) the asset is nevertheless expected to exhibit deterioration with time, however at a lower rate. As the intensity or level of asset repair increases, the deterioration curve takes on increasingly less negative gradients.

3.3 Discussion for All Three Measures of Effectiveness

Compared to that for capital improvements, maintenance effectiveness has been addressed in relatively fewer studies. For maintenance effectiveness studies, the concept of DMJ, and to a lesser extent, PJ has been widely used as the measure of effectiveness. As we have discussed in a previous section of this report, DMJ can lead to significant mis-estimation of effectiveness. In addition, it seems that past studies did not consider implicitly the relative timing between deterioration measurement and maintenance occurrence in a given reported year. Such oversight could be costly in estimating maintenance effectiveness regardless of which measure of effectiveness is used. Table 3.1 summarizes the various measures of short-term maintenance effectiveness (see also Figure 3.3).

3.4 Long-Term Impacts—MOEs as Developed/Used in the Literature

For some long-term effectiveness assessment techniques, the development of a performance curve (a single regression function developed using data from all of the similar asset types that received the treatment in question); or performance plot (performance vs. time for each individual asset) is a prerequisite. In such curves or plots, the ordinate is some time-related variable that is related to the asset condition; for example, years, or accumulated usage, loading, or climatic severity. Examples of the variables for climatic severity include

TABLE 3.1
Various Measures of Maintenance Effectiveness (Labi & Sinha, 2003)

Deterioration Reduction Measure	Computation	Synonyms/Descriptions	Comments	References
ΔC_1	$C_F - C_A$	Delayed Measurement of the Jump (DMJ) Decrease in Roughness Increase in PSI	Misses effectiveness denoted by ZD	(Li & Sinha, 2000)
ΔC_2	$C_E - C_D$	Same as for ΔC_2	Misses effectiveness denoted by WF	(Madanat et al., 1995)
ΔC_3	$C_A - C_E$	Same as for ΔC_2	Avoids critical timing issue. Likely to result in negative effectiveness	(Fwa & Sinha, 1987; Mohammad et al., 1997)
ΔC_4	$C_F - C_D$	Performance Jump (PJ) Instantaneous Deterioration Reduction Vertical Elevation in Condition	Ideal but data is often unavailable	(Colucci et al., 1985)
ΔRate	$(C_E - C_D) - (C_D - C_A)$	Deterioration Rate Reduction	Sometimes D is not known; Requires data over 3-year span	(Lytton, 1987; Markow, 1991, 1994)

precipitation, freeze index, freeze-thaw cycles, and temperature.

3.4.1 Increase in Average Performance of the Asset over the Treatment Life

This MOE can be calculated as the level of distress as an absolute value or relative to the level just before the treatment. To measure such effectiveness, the average infrastructure condition can be monitored over the treatment life using annual field measurements of the PI until the asset condition falls below a specified threshold (Figure 3.4). Alternatively, performance models can be developed using data from a collection of all the similar infrastructure that received the same treatment type and the developed models can be used to determine the average value of the ordinate (asset conditions) at each year of the treatment life.

The increase in the asset's average condition due to the treatment, ψ, can then be determined by computing the percentage change in the average condition of the asset relative to its pre-treatment condition.

$$\psi = 100 * \frac{\left(\frac{1}{t_T}(PI_0 + PI_1 + \ldots + PI_T) - PI_{INI}\right)}{PI_{INI}}$$

where PI_0 and PI_c represent the asset condition, in terms of the performance indicator, at the time just after the treatment and at the time when the asset condition reaches the threshold condition, respectively;

PI_i represents the asset condition at any intervening year, i, and t_T is the target period over which the post-treatment condition is being measured (often, this target is the treatment life);

$(PI_0 + PI_1 + \ldots + PI_T)/t_T$ is the average asset condition over the target period; and PI_{INI} = pre-treatment condition.

To determine the treatment life, the methods described in Section 3.4.2 below can be used.

In the highway management literature, variations of this MOE (the increase in average performance) have been used. For pavement infrastructure for example, Sharaf and Sinha (1984) and Hall, Darter, and Armaghani (1993) used this MOE to assess the impact of various pavement M&R treatments. In the case of highway bridges, Islam, Sonhanghpurwala, and Scannell (2002) studied the effectiveness of bridge corrosion inhibitors, based on the reductions in the overall corrosion rate relative to the control (untreated bridges) after a five-year period of observation. A similar study carried out for the FHWA by Islam et al. (2002) evaluated the long-term effectiveness of corrosion-protecting cathodic systems in reinforced concrete bridges relative to untreated (control) sections. Lee et al. (2004) used structural load capacity as the performance indicator to assess the efficacy of carbon-reinforced fiber polymer (CRFP) composites in rehabilitating the tension side of concrete bridge decks; the load capacities of the treated members were compared with (i) their pre-treatment load capacities and (ii) the load capacities of their untreated counterparts.

3.4.2 Estimated Life of the Maintenance Treatment

(a) Performance models (deterioration curves). Haider (2011) 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 $f_{post}(t) = \alpha_2 e^{\beta_2 t}$. Similarly, Lu and Tolliver (2012) developed models with the same exponential equation using LTPP data, the models were established for pavement in six different climatic zones measured by freeze-thaw and precipitation.

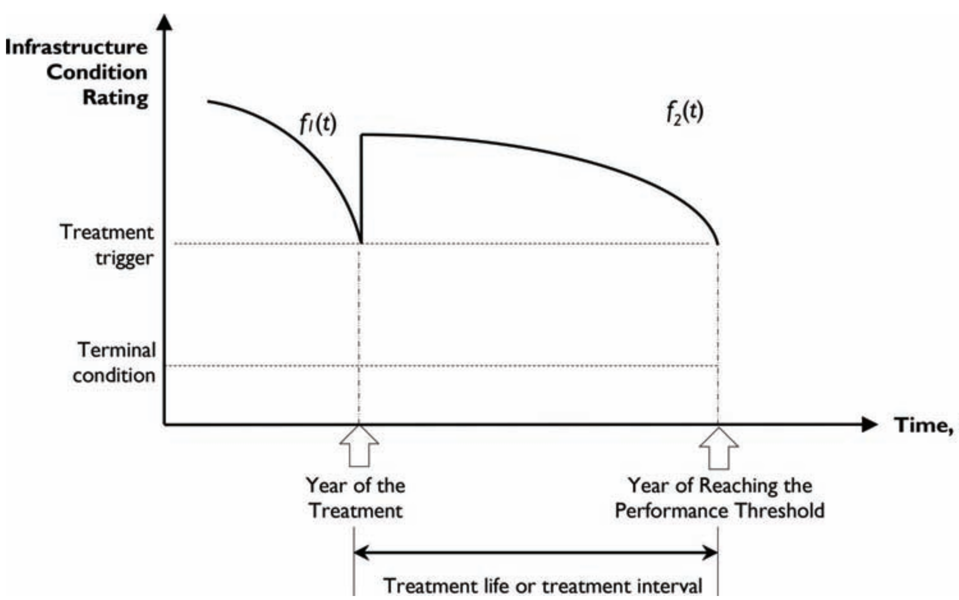


Figure 3.4 Increase in average performance of the infrastructure over the treatment life.

(b) Estimation of treatment life. The life of a maintenance treatment (also referred in some literature as the treatment service life or application interval), can be defined as the time taken for the performance (condition) of the treated asset to revert to some predefined condition threshold (see Figure 3.4). The condition is expressed in terms of a PI that the treatment was intended to address. The length of the treatment life depends on the asset condition, treatment intensity, agency policy on triggers, loading, climate; the treatment application interval depends not only on these factors but also on the funding availability.

Treatment life can be determined using (a) an age-based approach. This is a subtraction of calendar dates; this gives the number of years that have elapsed between the application of the treatment in question and that of the next treatment of similar or higher level, or (b) a condition-based approach. This is the measured or estimated time for the treated infrastructure to revert to a certain specified performance threshold. As we shall discuss subsequently, the age-based and condition-based approach for treatment effectiveness assessment may be described as disaggregate or aggregate depending on the data granularity.

In the practice and research literature, the concept of treatment life has been used widely as an MOE to assess the effectiveness of treatments applied to highway infrastructure (Geoffroy, 1996; Hall et al., 2002; Labi & Sinha, 2006; Mamlouk & Zaniewski, 1998; Raza, 1994). Kong and Frangopol (2003) assessed bridge treatment effectiveness in terms of the element life extension and the increase in bridge reliability. For pavement assets for example, Smith, Freeman, and Pendleton (1993) evaluated a number of M&R treatments using several performance indicators (individual measures of pavement distress such as roughness and skid resistance) and compared the treatments based on the time taken for the treated asset to reach the threshold level of the performance indicators. In a study of LTPP pavement sections, Khurshid, Irfan, and Labi (2011) determined that treatment life could be stated not only in years but also in terms of some accumulated traffic loading or climate severity; they also determined that aggregate MOEs provide a more reliable assessment of treatment effectiveness, compared to disaggregate measures. For example, Lounis, Martin-Perez, and Hunaidi (2001) assessed the effectiveness of various corrosion treatments in terms of bridge deck life extension.

3.4.3 Area under the Performance Curve Subsequent to the Treatment

Figure 3.5 depicts how to measure the long-term effectiveness when an asset that receives a treatment. Consider x, a time-related variable such as time (years), accumulated truck traffic, or accumulated climatic severity. Performance of the asset before and after the preservation treatment is denoted by $f_1(x)$ and $f_2(x)$. Many agencies have developed deterioration models, $f_2(x)$, for each asset type that has received some specific preservation treatment. As the figure suggests, it is rather easy to determine the service life (time taken for the performance indicator to reach a pre-specified threshold condition), given the performance curve $f_2(x)$. The values of each preservation treatment MOE (increased service life, increased average condition, and area-bounded-by-the-curve) can be determined using either (i) a single performance curve developed using data from all similar asset types that received the preservation treatment or (ii) manual plots for individual similar asset types that received the preservation treatment and using coordinate geometry or calculus to determine the MOE.

As explained in Labi & Sinha (2003), the area bounded by the performance curve and the threshold line embodies both effectiveness concepts of average performance of the asset after it has received the treatment and the service life (time taken for the asset to revert to the pre-treatment level of performance). As such, the "area bounded by the curve" may represent the most appropriate measure of long-term effectiveness. A simple approach for determining the area under the performance curve is to carry out field monitoring of performance indicator for several similar asset types that received the preservation treatment, plotting a graph of the condition measurements versus time, determining the area under the performance plot for each element, and finding the average of these areas. As an alternative, a single representative performance curve could be developed using the field data from all the assets that received that treatment, and then the area bounded by the performance curve, from year of the treatment to the year it reaches a specified threshold, could be determined using calculus or coordinate geometry (Labi & Sinha, 2003). As seen in Figure 3.5, for non-increasing performance indicators, the preservation treatment effectiveness is represented by the area bounded by the curve and the horizontal line projected from the threshold condition level (i.e., the area *under* the curve); for non-decreasing indicators, preservation treatment effectiveness is the area bounded by the curve and the horizontal line projected from the threshold condition level, that is, the area *over* the curve. Past researchers that used this concept include Geoffroy (1996), Kher and Cook (1985), Joseph (1992), Shahin, Kohn, Lytton, and McFarland (1985).

From Figure 3.5, the effectiveness of the treatment, in terms of the area bounded by the curve, can be expressed as:

(i) For non-decreasing performance indicators,

- Total area bounded by the performance curve

$$= 2 \times \left\{ (PJ \times t_c) - \int_0^{t_c} f(t)dt \right\}$$

- Total area bounded by the performance curve relative to a do-nothing scenario

$$= (PJ \times t_c) - \int_0^{t_c} f(t)dt$$

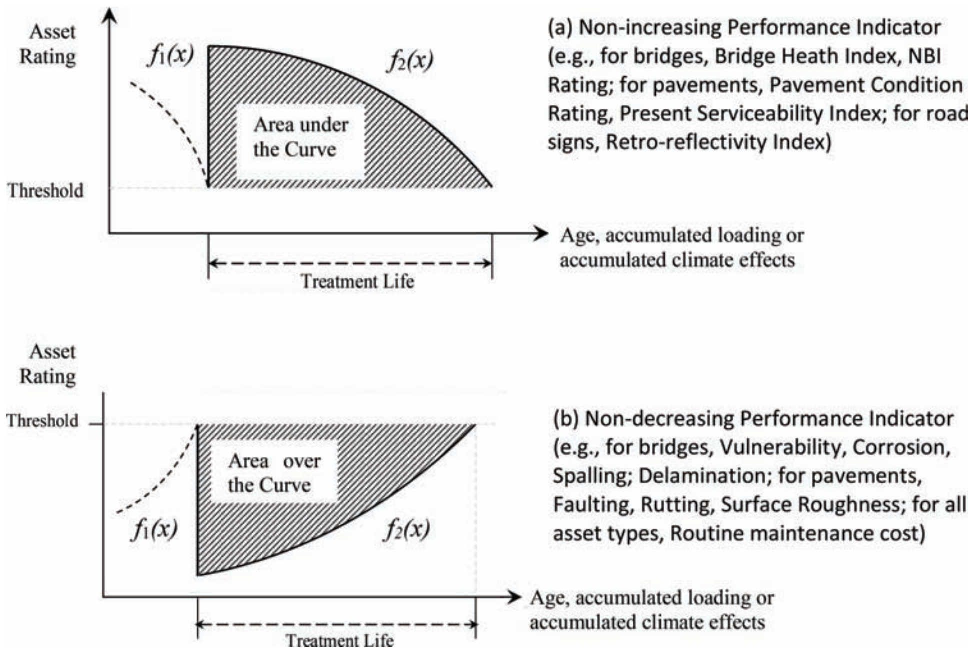


Figure 3.5 Graphical depiction of treatment life as a measure of long-term effectiveness of asset treatments.

(ii) For non-increasing performance indicators,

- Total area bounded by the performance curve

$$=2\times\left\{\int_0^{t_c} f(t)dt\right\}$$

- Total area bounded by the performance curve relative to a do-nothing scenario

$$=\int_0^{t_c} f(t)dt$$

where all symbols have their usual meanings as explained in earlier sections of the paper.

3.5 A Literature Review—Factors Affecting the Effectiveness of Asset Surface Maintenance

Al-Suleiman, Sinha, and Kuczek (1994) discussed the effects of pavement age and traffic on maintenance effectiveness. Morian, Gibson, and Epps (1998) concluded that the preparation of the pavement surface prior to overlay is generally a vital factor of the treatment effectiveness and that the pre-treatment condition significantly influences the subsequent performance of the pavement. The list below presents the factors that affect the jump in asset performance upon treatment. Wang (2013) analyzed LTPP data and determined that precipitation, freeze index, and pavement roughness showed significant correlation to the friction number.

From the literature, it is seen that the factors affecting performance jump due to surface maintenance treatments include:

- Weather at time of treatment
- Treatment intensity (for example, thickness)
- Quality of materials
- Pre-treatment condition of the asset
- Quality of workmanship

Also from the literature, it has been determined that the factors affecting treatment life due to surface maintenance treatments include:

- Pre-treatment condition of the asset
- Treatment intensity (for example, thickness)
- Traffic loading
- Climatic severity
- Quality of initial product (materials and workmanship)

3.6 Measured Effectiveness Values for Asset Treatments (from the Literature)

3.6.1 Bridges—Short-Term Effectiveness of Deck Surface Treatments

Relatively little research has been carried out to evaluate the effects of bridge MR&R treatment on bridge deterioration. Two considerations are:

a. Some major rehabilitation activities (such as deck overlay) may lead to a performance jump (for example, deck condition rating of 5 increases to 6 or 7);
b. Some minor rehabilitation or maintenance (such as deck patching) may not increase the condition significantly, but may lower the rate of the bridge deterioration.

In the literature, simplified estimations of treatment effectiveness (referred to as “recovering effects” in certain literature) are assumed. For example, Lee and Kim (2007) measured some “recovering effects” on a scale from 1 to 90 for different maintenance treatments on various distress types, primarily based on opinions of

TABLE 3.2
"Recovering Effect" Values for Various Maintenance Treatments (Lee & Kim, 2007)

	Damage Types							
Treatments	**Micro-crack**	**Moderate crack**	**Macro-crack**	**Rebar Corrosion**	**Punching/ Cavitation**	**Exfoliation/ Pothole**	**Leakage/ Efflorescence**	**Maximum Effect**
Surface repair	5	3	0	1	0	1	3	13
Mortar filling	3	4	5	2	1	2	4	21
Epoxy injection	3	5	3	1	2	2	0	16
Corrosion inhibiting	3	3	5	5	5	5	5	31

Note: Condition rating scale: 1–100.

TABLE 3.3
Average Improvement of Deck Condition Rating (NBI Scale) Subsequent to MR&R Actions Based on Survey Results (Hong & Hastak, 2007)

M&R Actions	**Improvement of Condition Rating**
Crack maintenance	0.48
Sealing	0.41
Scaling	0.81
Patching/spalling	0.79
Cathodic protection	0.58
Thin epoxy/polymer overlay	1.19
Latex modified concrete	3.17
Increased slab thickness and cover	1.86
Attaching additional girders	0.92
Concrete overlay or high density overlay	2.17

Note: Condition rating scale: 1–9.

TABLE 3.4
Maintenance Impacts in Terms of the Deterioration Degree (Liu et al., 1997)

Maintenance Method	**Deterioration Degree**	**Impact**
Routine maintenance	0.0–0.8	0.01
Repair	0.2–0.8	0.05
Rehabilitation	0.4–1.0	0.40
Replacement	0.6–1.0	0.90

bridge maintenance experts (Table 3.2). Hong and Hastak (2007) quantified the average increases in deck NBI condition rating after maintenance actions based on a survey of 28 highway agencies in the USA (Table 3.3). Possible limitations of their results include (1) bias of the individuals; (2) inconsistency across agencies; (3) exclusion of the pre-treatment condition as a possible factor of the effectiveness of the maintenance actions.

Liu, Hammond, and Itoh (1997) established some "impacts" of maintenance on the asset deterioration (Table 3.4). A "deterioration degree" was defined by the authors on a scale of 0 (new deck) to 1 (structural failure level). Four maintenance treatments were recommended by the authors to be applied corresponding to different deterioration degree ranges. In addition, Elbehairy, Elbeltagi, Hegazy, and Soudki (2006) estimated the impacts of MR&R treatment categories ("light, medium, and extensive") on the bridge deck condition rating (Table 3.5).

TABLE 3.5
Impact of Repair Option on Bridge Deck Condition (Elbehairy et al., 2006)

Condition Rating After Repair	**Condition Rating Before Repair**		
	3, 4	5, 6	7, 8
3, 4	Light	–	–
5, 6	Medium	Light	–
7, 8	Extensive	Medium	Light

The updated IBMS manual (Sinha, Labi, McCullouch, Bhargava, & Bai, 2009) presented information on the effectiveness of repair activities on the conditions of the deck, superstructure, substructure, wearing surface, and the component service life. While this serves as a useful reference, it was based on expert opinion and their results did account for the influence of the pre-treatment condition. In addition, some of the repair activities indicated, such as deck rehabilitation and superstructure rehabilitation, were not specific enough in detailing the type of work done.

3.6.2 Bridges—Long-Term Effectiveness of Deck Surface Treatments

Tables 3.6 to 3.13 present the long-term effectiveness of various types of deck surface treatments in terms of their expected life or application interval. These data are from different sources (FHWA, 2011; NYSDOT, 2008; ODOT, 2007; Sprinkel, Brown, & Thompson, 2005; Weyers, Prowell, Sprinkel, & Vorster, 1993). These are average values and ranges. The actual lives of these deck surface treatments will be different under different circumstances (location, work process or equipment, material, expertise of labor and supervision, condition at time of the treatment, and so on).

A JTRP report by Frosch et al. (2013) provided INDOT with an enhanced toolbox of bridge deck protective systems. The report recommended LMC overlays for bridge decks where more extensive damage is observed. In addition, because LMC overlays provide a long service life, the JTRP report recommended that treatment for more critical bridges as both a preventive maintenance and a rehabilitation measure. Where quick installation is required and where a thin protective system is needed, the JTRP report recommended the

TABLE 3.6
Effectiveness (Treatment Life) of Concrete Deck-Penetration Sealing Treatments

Researchers/Organization	Treatment Life (years)
Sherman et al. (1993), Texas DOT	5–7
Weyers et al. (1993), SHRP	5
Zemajtis and Weyers (1996), Virginia Tech	7
NYSDOT (2008)	4
Meggers (1998), Kansas DOT	8–11
Soriano (2002), South Dakota DOT	4–10
Sohanghpurwala (2006), NCHRP Report 558	5–7
Mamaghani et al. (2007), North Dakota DOT	5
Wenzlic (2007), Missouri DOT	3–10
Filice and Wong (2008), Alberta DOT	4
Krauss et al. (2009), NCHRP Project 20-07	5–10
Morse (2009), Illinois DOT	4–5

Source: Bowman and Moran (2015).

TABLE 3.7
Effectiveness of Deck Preventive Maintenance in Virginia

Activity	Frequency
Deck Washing	Yearly
Deck Sweeping	Yearly
Scheduled Replacement of Pourable Joint Seal	6 years
Scheduled Replacement of Compression Joint Seal	10 years
Scheduled Installation of Thin Epoxy Overlay	15 years
Scheduled Installation of Concrete Overlay	30 years

Source: Sprinkel et al. (2005).

use of thin polymer overlays. The report also discussed the use of polymer overlays as a suitable preventive maintenance treatment of new bridge decks. However, the report did not give any numerical thresholds or strategies regarding when or under what condition the overlays should be applied.

The Minnesota DOT (MnDOT) sought to (a) quantify the benefits of various bridge maintenance treatments in relation to remaining service life and bridge life-cycle costs and (b) know how maintenance treatments could be incorporated into deterioration models. As such, the agency commissioned CTC & Associates (2016) to conduct a literature search and a survey of domestic and international transportation agencies. The survey documented the types and frequencies of bridge maintenance activities, practices for quantifying the impact of bridge maintenance activities on deterioration, and how deterioration models could be used to measure the benefits of bridge maintenance (CTC & Associates, 2016). In a similar synthesis study in Indiana, Bowman and Moran (2015) provided a synthesis of the effectiveness (treatment life) of concrete deck-penetration sealing treatments nationwide.

3.6.3 Pavements—Short-Term Effectiveness of Surface Treatments

HMA minor structural overlays. A considerable number of studies have used experimental data to evaluate pavement surface treatment effectiveness in terms of the short-term effect on asset condition ratings. Figure 3.7 presents the short-term effectiveness of selected LTPP SPS pavement treatments in terms of the performance jump. Hall et al. (1993) described a comprehensive load-transfer restoration experiment where the performance of 14 different treatments for load transfer restoration on Interstate 10 in Florida was monitored and analyzed. Sawing and sealing, which involves sawing of a joint in the asphaltic concrete overlay directly above the existing PCC pavement joint and sealing with joint sealant material, was evaluated as part of a national experimental study (Kilareski & Bionda, 1997).

In addition, concrete pavement rehabilitation strategies at Pennsylvania's SPS-6 sections have been evaluated for their effectiveness (Morian, Coleman, Frith, Stoffels, & Dawood, 2003). Furthermore, a national study established service life ranges for different rigid pavement treatments and provided useful conclusions for the state of practice (Hall, Correa, Carpenter, & Elliott, 2001). Recently, a study used LTPP data to analyze the effectiveness of pavement maintenance options (Hall et al., 2002). Also, a revealing study recently reported on an initial evaluation of the performance of rehabilitation activities on jointed Portland cement concrete pavements under the LTPP SPS-6 experiment (Ambroz & Darter, 2005). Irfan, Khurshid, Flora, and Labi (2009) presented the short-term effectiveness of a number of maintenance treatments involving overlay (Figure 3.6).

Thin HMA overlay effectiveness. In a JTRP-funded research project (Labi & Sinha, 2003), higher performance jumps were found to be attributable to the condition of the pavement before the overlay treatment; the lower the pavement condition, the higher the performance jump. The performance jump model for thin

TABLE 3.8
Effectiveness of Bridge Deck Transverse Crack Repair

Treatment Type	Expected Life
Seal top surface with: HMWM	15 years
Seal top surface with: Gravity fed resin	10 years
Seal top surface with: Silane	5 years
Seal top surface with: Reactive silicate	5 years

Source: ODOT (2007).

TABLE 3.9
Effectiveness of Bridge Deck Crack Repair

Treatment Type	Expected Life
Seal with a silane sealer	5 years
Treat cracks with a high molecular weight Methacrylate	15 years
Treat cracks with reactive silicate solution	5 years
Treat cracks with gravity fed resin	10 years

Source: ODOT (2007).

TABLE 3.10
Effectiveness of Bridge Deck Surface Treatments (Expected Life or Application Interval)

Treatment	Expected Life or Application Frequency
Seal deck with a silane sealer	4–5 years
Mill, 1.25″ concrete overlay/inlay	15 years
Aggregate Popout Repair	5 years
Crack seal with a silane sealer	5 years
Crack treatment with methacrylate	15 years
Treat cracks with reactive silicate solution	5 years
Treat cracks with gravity fed resin	10 years
Pothole repair, sawcut and concrete patching	10 years
Pothole repair using HMA	3 years
Deck overlay, concrete (microsilica or latex modified)	15 years
Transverse crack: Seal top surface with HMWM	15 years
Transverse crack: Seal top surface with gravity fed resin	10 years
Transverse crack: Seal top surface with Silane	5 years
Transverse crack: Seal top surface with reactive silicate	5 years
Scheduled replacement of pourable joint seal[1]	6 years
Scheduled replacement of compression joint seal[1]	10 years
Scheduled installation of thin epoxy overlay[1]	15 years
Scheduled installation of concrete overlay[1]	30 years
Clean substructure	2 years
Replace wearing surface	12 years
Place membrane	12 years
Deck sealing	4 years
Deck overlay, thin bonded polymer system	10–15 years
Deck overlay, asphalt, with waterproof membrane	10–15 years
Deck overlay, rigid (e.g., silica fume, latex modified)	20–25 years
Deck Protection, Epoxy[2]	SS= 6–10 years; DS=10–14 years
Deck Protection, Methacrylate[2]	SS= 9–13 years; DS=13–17 years
Deck Protection, Urethane[2]	SS=10–14 years; DS=14–18 years

Sources: FHWA (2011); NYSDOT (2008); ODOT (2007); Sprinkel et al. (2005); Weyers et al. (1993).
Note: These are average values and ranges only. Actual treatment life will be different under different circumstances (location, work process or equipment, material, expertise of labor and supervision, condition at time of treatment, etc.).
[1]Application frequency (not service life).
[2]SS = Sea Spray/Splash; DS - Deicer Salt Runoff Water.

TABLE 3.11
Crack Repair Effectiveness

Treatment Type	Expected Life
Seal with a silane sealer	5 years
Treat cracks with a high molecular weight Methacrylate	15 years
Treat cracks with reactive silicate solution	5 years
Treat cracks with gravity fed resin	10 years

Source: ODOT (2007).

TABLE 3.12
Effectiveness of Scaling Repair

Treatment Type	Expected Life
Seal with a silane sealer	5 years
Mill surface and place 1 1/4″ concrete overlay/inlay (if scaling is severe; more than 1/2″ deep)	15 years

Source: ODOT (2007).

TABLE 3.13
Bridge Deck Treatment Service Lives

Treatment Type	Service Life (years)	Source
Latex Modified Concrete overlays	20	Sprinkel (1993)
	15	INDOT (2013)
Polymeric Overlays	15	INDOT (2013)
	(10–15)	MIDOT (2011)
Deck patching	(3–10)	MIDOT (2011)
Deck crack sealing	7	Sprinkel (1993)
	3	Hagen (1995)
	(1–4)	MIDOT (2011)

HMA overlay effectiveness model was as follows (Figure 3.7):

$$PJ = \frac{71.63}{42.01 + (10^{-5.11} \times 97.17^{PTC})}$$

PJ = Performance jump experienced by a pavement section after receiving the treatment, in PSI units.

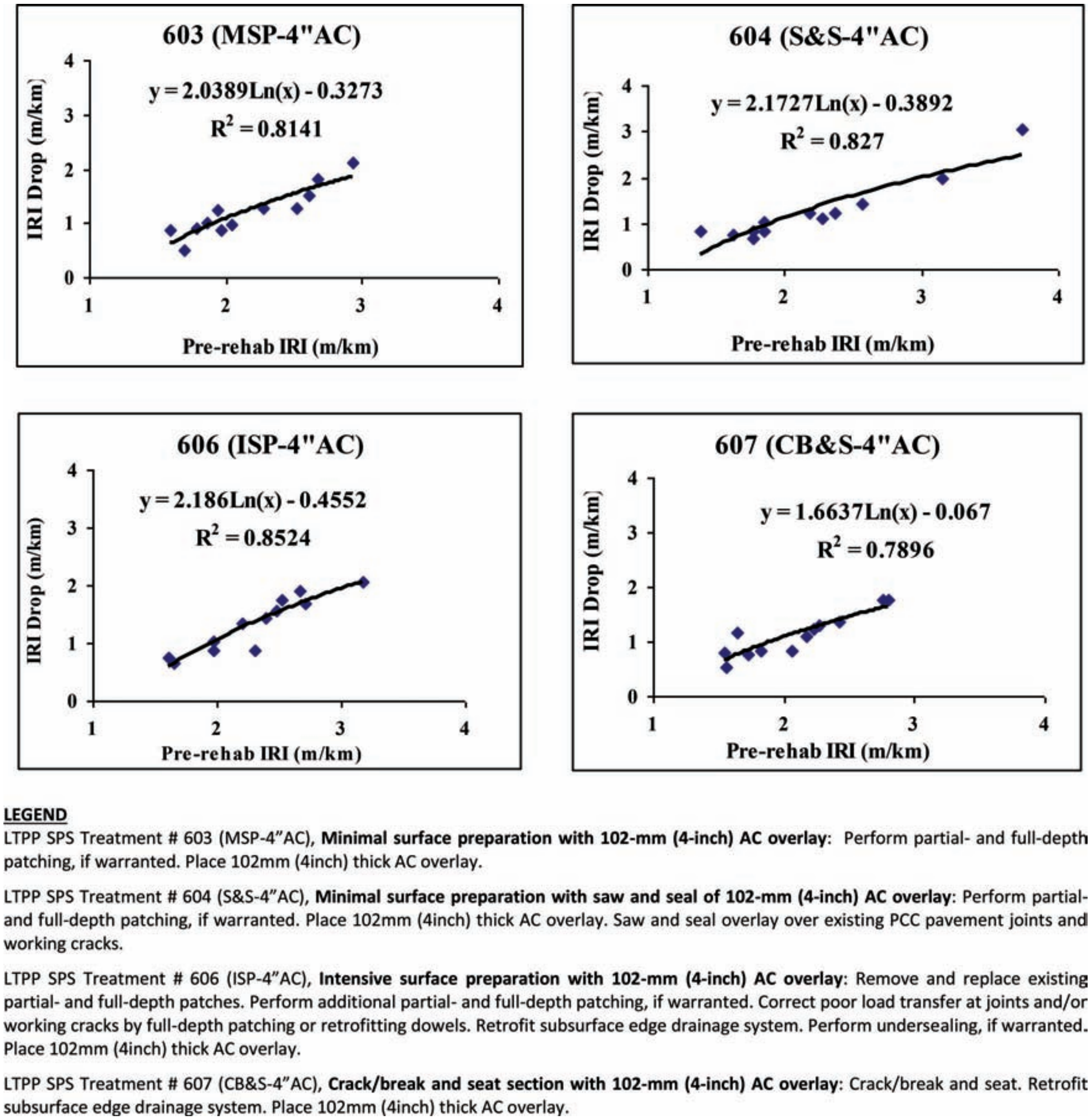


Figure 3.6 Short-term effectiveness of HMA minor structural overlays (Irfan, Khurshid, Labi & Flora, 2009).

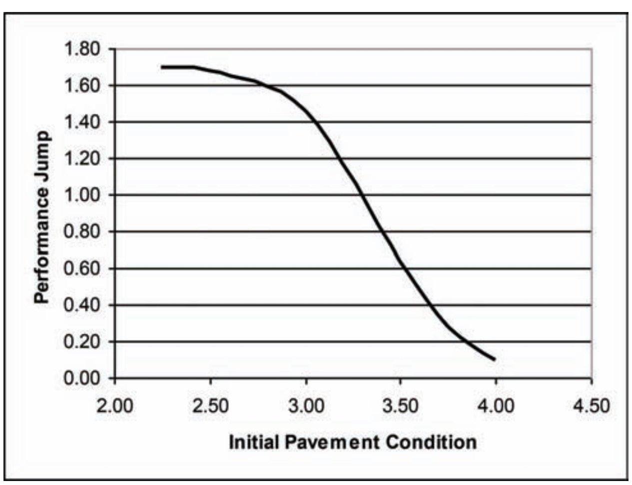


Figure 3.7 Model for predicting thin HMA overlay treatment effectiveness in PSI units (Labi & Sinha, 2003).

PTC is the pre-treatment or the "initial" condition in PSI units.

The shape of the curve for thin overlay effectiveness is S-shaped (Figure 3.7), indicating that the performance jump changes in a variable fashion with the pre-treatment condition. The curve begins with a "slow" phase (where the change in performance jump is small when the pavement is in poor condition), indicating that a poor-condition pavement benefits little from the overlay treatment. Also, for pavements in fair condition, the change in the performance jump is significant for a small change in the pavement condition. At the third phase of the curve a small change in pavement condition yields very little incremental benefit, obviously because there is relatively "little room for improvement" for pavements in that condition (Labi & Sinha, 2003). The 2001 JTRP study's findings for thin HMA overlay effectiveness appear to be consistent with those of previous research. In Mississippi, Rajagopal and George (1991) found that surface treated pavements experience 20–40% jump in condition (in terms of PCR) after treatment, and that lower condition of the pavement at time of treatment was associated with higher jumps in pavement condition.

Microsurfacing effectiveness. Microsurfacing involves laying of a bituminous mixture over the entire surface of a pavement. Rolling of the laid material is not required, as the mixture includes a hardening additive. The 2001 JTRP study (Labi & Sinha, 2003) found that the treatment yields a PSI jump of 0.76, with a standard deviation of 0.25.

Crack sealing. Crack sealing involves the placement of sealing material into surface cracks and aims to protect the underlying pavement materials from wetting and subsequent strength loss and pumping. A previous JTRP study (Labi & Sinha, 2003) modeled the reduction in the rate of pavement deterioration due to crack sealing. Table 3.14 presents the descriptive statistics of the crack sealing effectiveness data used in that study.

The Deterioration Rate Reduction (DRR, in PSI/yr) experienced by a crack-sealed pavement section is:

Pavements in poor condition:

If $CSI/PTC < 0.395$, $DRR = 0$

If $CSI/PTC \geq 0.395$, $DRR = 0.2952 - 0.5932 * 0.1698^{CSI/PTC}$

Pavements in fair condition:

If $CSI/PTC < 0.395$, $DRR = 0$

If $CSI/PTC \geq 0.395$, $DRR = 0.25810.4532 * 0.2313^{CSI/PTC}$

CSI = crack sealing intensity in \$100/lane-mile; PTC = the pre-treatment condition in PSI units

The above models show that for a given level of pavement condition, increasing the level of crack sealing treatment results in a lower value of the exponential term (because C is a fraction between 0 and 1) and consequently a reduced value of the negative term (B is negative), leading to a reduced DRR. The models also show that for a given level of pavement cracking condition, there is a limit of the benefits of crack sealing, as the curve appears to level off after a point. Also, for a given level of maintenance, a lower initial pavement condition leads to higher values of the exponential term and ultimately, higher DRR. This suggests that pavements in relatively poor condition (badly cracked) stand to benefit more by a given level of crack sealing treatment expenditure compared to those in relatively fair condition (lightly cracked). An important assumption is that a pavement in poor initial condition (as reflected in a low PSI value) is in that condition mainly because of the defect for which the treatment in question (in this case, crack sealing) is carried out. This assumption is made good by the fact that the pavements selected for modeling of crack sealing effectiveness were those that received only crack sealing and no other treatment at time of maintenance. A plot of the two crack sealing effectiveness models, using the fitted values of the response variable, is shown in Figure 3.8. Using this model the DRR afforded by crack sealing on a given pavement can be determined, if the pavement condition before treatment and the cost expended per lane-mile of treatment, are known.

Chip sealing. A thin coat of aggregates and binder is typically spread over flexible pavements (often, low-volume non-Interstates) to keep them in motorable condition and to defer major maintenance such as thin overlay or rehabilitation. Chip seals heal surface cracks and raveled surfaces and are used far more widely compared to sand sealing. A previous JTRP study (Labi & Sinha, 2003) analyzed the effectiveness of chip seals in terms of the immediate jump in PSI due to the treatment. Table 3.15 presents the descriptive statistics of the relevant variables.

The performance jump, PJ, experienced by a pavement section (that received only chip sealing) is:

$$PJ = 0.7971 \times \mathrm{EXP}^{-(PTC - 3.1482)^2}$$

where PTC = pre-treatment condition, in PSI units.

This bell-shaped model form was chosen because compared to other model forms considered it provided the closest fit to the available data, and also because it made it possible for the results to be interpreted from an engineering viewpoint. The model is illustrated in Figure 3.9.

The model suggests that pavements in relatively good condition (high PSI value) are associated with lower performance jump upon chip sealing, while those in relatively poor condition (low PSI values) have higher jumps in performance (see arc QR in Figure 3.9). However, the bell–shaped nature of the effectiveness function

TABLE 3.14
Crack Sealing Effectiveness–Descriptive Statistics

	Crack Sealing Expenditure (\$100s per lane-mile)	Initial Pavement Condition (PSI)	Performance Jump (PSI)
Maximum	13.42	4.20	0.21
Minimum	0.98	1.91	0.00
Mean	2.63	2.93	0.09
Standard Deviation	1.03	1.79	0.06
Coefficient of Variation	39%	62%	66%

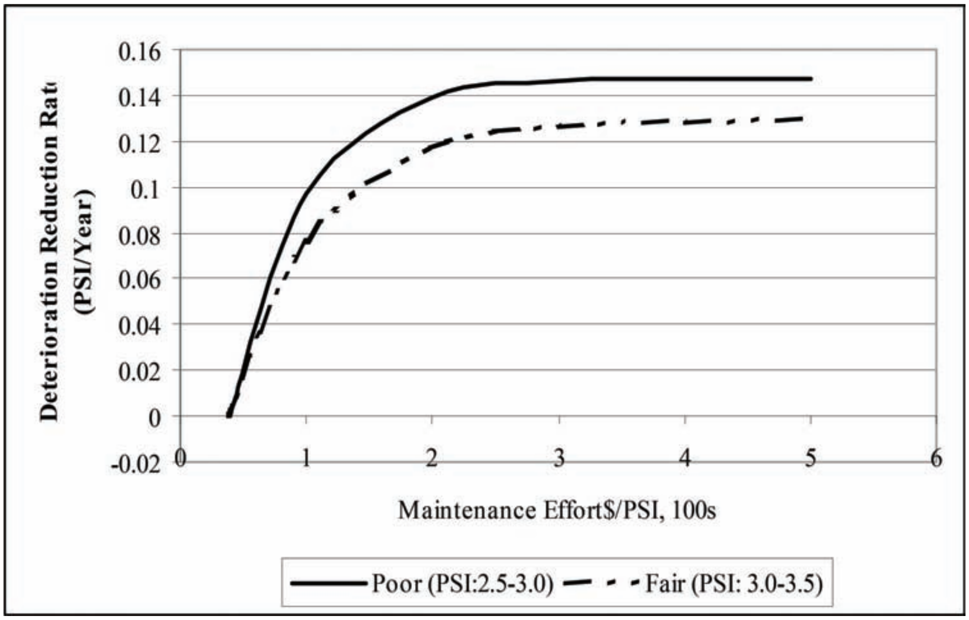


Figure 3.8 Crack sealing effectiveness for cracked pavements in poor or fair condition.

TABLE 3.15
Descriptive Statistics for Chip Sealing Effectiveness

Statistic	Initial Pavement Condition (PSI units)	Performance Jump (PSI units)
Maximum	3.92	0.83
Minimum	2.53	0.14
Mean	3.44	0.44
Standard Deviation	0.39	0.19
Coefficient of Variation	11.25%	42.48%

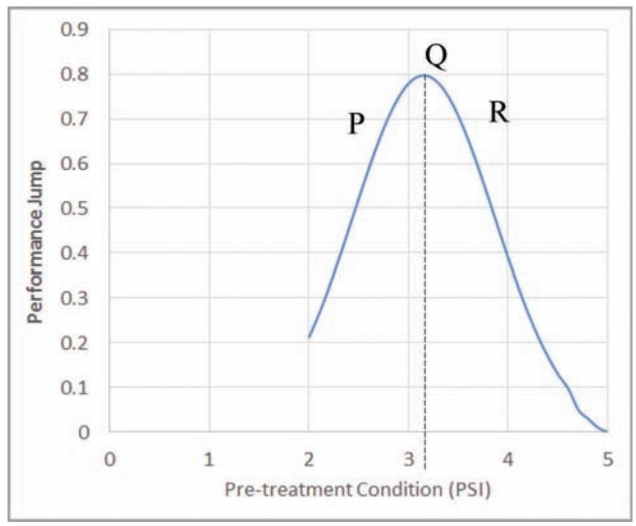


Figure 3.9 Effectiveness model chip sealing.

indicates that for pavements in very poor condition (very low PSI values), performance jump due to chip sealing increases with increasing initial pavement condition, as suggested by the arc PQ in the figure. This suggests that there exists a certain optimum level of pavement condition for which chip sealing effectiveness is a maximum. From the figure, this optimum value is 3.2 PSI units, and the corresponding maximum value is 0.8 PSI units. As no performance jump is possible by chip sealing a pavement in perfect condition, the effectiveness curve is extrapolated to meet the abscissa axis at PSI = 5.

The findings for chip sealing effectiveness appear similar to past research efforts. Using pavement condition rating (PCR) as the unit of performance jump measurement, a study in Mississippi found that surface treated pavements experience a 19–44% jump in performance after treatment (Rajagopal & George, 1991). That study also found that the lower the condition of the pavement before treatment, the higher the performance jump, which is consistent with the current findings (see arc QR in Figure 3.9). However that study did not provide an indication of diminishing performance jump as pavement condition decreases beyond a certain point (see arc PQ in Figure 3.9). The Supplemental Maintenance Effectiveness Research Program (SMERP) carried out in Texas in 1997 found that the condition of a pavement was a major determinant of the effectiveness of chip sealing treatment that is administered to the pavement (Syed, Freeman, & Smith, 1998). In contrast to the findings of the Mississippi study, the SMERP study found that pavements in good and fair initial condition outperformed those in poor initial condition, which appears consistent with the line PQ on Figure 3.9, but the study did not state the range of pavement conditions over which this observation was made. Al-Mansour and Sinha (1994) determined that the gain in PSI due to chip sealing was found to increase as pre-treatment pavement condition increases; this is reflected in the line PQ in Figure 3.8. This is consistent with the

SMERP study (Syed et al., 1998). However, the range of PSI's for pavements considered by these studies obviously did not go far enough to reveal the trend indicated by arc QR in the figure.

Ultra-thin bonded wearing course (UBWC). UBWC is a thin (0.375–0.75 inches) gap-graded modified HMA layer placed on a polymer-modified emulsified asphalt membrane in a single pass. Invented in France in 1986 and used in the US since 1992, UBWC provides a surface with excellent macro texture qualities, good aggregate retention, and excellent bonding of the very thin surfacing to the underlying pavement (Hanson, 2001). It has been used to correct surface distresses such as raveling or minor cracking, or to restore surface characteristics such as friction and smoothness. UBWC has also been found useful in reducing tire splash on rainy days as well as tire noise. Published experimental project reports and inspections of recently completed projects in many locations indicate good performance of the UBWC. In Minnesota, UBWC has been used to extend the longevity of both hot mix asphalt (HMA) and Portland cement concrete (PCC) pavements. Based on North Carolina's experience with UBWC on poor-quality jointed Portland cement concrete, a life of 6 to 10 years is attainable (Corley-Lay & Mastin, 2007). The NC study found that the ultrathin bonded overlays resulted in a "dramatic bump" in the pavement condition ratings (PCRs); the rate of decline of the PCR after resurfacing with UBWC is 0.8–3.0 points/year. Li et al. (2013) evaluated the surface properties of UBWC pavements based on surface friction, and surface macrotexture, and found that UBWC is "capable of providing sufficient and consistent skidding resistance to allow quick opening to traffic. The study concluded that UBWC can provide sound, durable surface friction, but requires highly polish-resistant aggregates." Ji, Nantung, and Tompkins (2015) investigated the functional and structural benefits of UBWC applications using the Pavement Condition Rating (PCR), Structural Number (SN), and International Roughness Index (IRI) for in situ performance evaluation on UBWC and the four control sections (SR-58, SR-69, SR-68, and SR-145). They found that UBWC generally addresses pavement distresses and can extend pavement life and is cost-effective if it provides more than 3.6 years of service life.

3.6.4 Pavements—Long-Term Effectiveness of Surface Treatments

The Michigan Department of Transportation (MDOT) is generally recognized as a leader in the United States in developing and implementing PM programs. Daleiden et al. (1994), Perera and Kohn (1999), Hall et al. (2002), Perera and Kohn (2006), Ahmed (2009), and Carvalho, Ayres, Shirazi, Selezneva, and Darter (2011) evaluated the effectiveness of flexible pavement treatments using data from LTPP program SPS-5 test sections. Ahmed et al. (2010) found that (a) the treatments involving 5-inch overlays demonstrated higher effectiveness (in terms of the estimated treatment life) compared to those involving 2-inch overlays by 47% on average, and (b) the rate of pavement deterioration after the treatment in the long-term is significantly influenced by the pre-treatment condition. Table 3.16 presents the effectiveness of various pavement maintenance in terms of treatment life. Table 3.17 presents the initial effect of SPS-3 maintenance treatments on IRI and rutting (Morian, Epps, & Gibson, 1997; Morian et al., 1998), and Table 3.18

TABLE 3.16
Pavement Maintenance Treatment Service Lives

Treatment Type	Service Life (years)	Source
Crack sealing	2.2	(Feighan et al., 1986)
	(3–5)	(Brown, 1988)
	(6-8)	(Morian et al., 1997)
	3	(INDOT, 2013a)
Chip sealing	(1–6)	(Shuler, 1984)
	4	(Feighan et al., 1986)
	(3–6)	(Parker, 1993)
	(4–7)	(Raza, 1994)
	(6–10)	(Morian et al., 1997)
	4	(INDOT, 2013a)
Slurry Seal	(1–6)	(Shuler, 1984)
	(3–6)	(Brown, 1988)
	(7–10)	(Morian et al., 1997)
Microsurfacing	(4–6)	(Shuler, 1984)
	(5–7)	(Raza, 1994)
	7	(Irfan, 2010)
	6	(Bilal, 2010)
	8	(INDOT, 2013a)
HMA overlay, PM	<6	(Shuler, 1984)
	8	(Joseph, 1992)
	(8–11)	(Raza, 1994)
	(6–11)	(Morian et al., 1997)
	9	(INDOT, 2013a)
HMA overlay Minor Structural	12	(Irfan, 2010)
	15	(INDOT, 2013a)
HMA overlay 4–5 in (Structural)	11	(Irfan, 2010)
	18	(INDOT, 2013a)
Asphalt pavement patching	(1–3)	(Johnson, 2000)
PCCP Patching	10	(Irfan, 2010)
	8	(Ahmed, 2012)
Diamond Grinding	(16–17)	(Caltrans, 2005)
	14	(Caltrans, 2008)
Repair PCCP & HMA Overlay	14	(Irfan, 2010)
	15	(Ahmed, 2012)
Load Transfer Restoration (Dowel Bar Retrofit)	15	(Pierce et al., 2003)
	(10–15)	(Gulden & Brown, 1983, 1985)
	(8–15)	(Caltrans, 2008)

shows the long-term effect of SPS-3 maintenance treatments on IRI and Rutting (Morian et al., 1997). In addition, Table 3.19 and Table 3.20 present the pavement condition at the pre- and post-rehabilitation stages, for pavements in LTPP's SPS-5 and SPS-6 experiments (Morian et al., 1997). Table 3.21 presents the effectiveness of pavement maintenance in terms of treatment life, reported by various authors. Table 3.22 presents the optimum time for applying selected treatments on flexible pavements (Hicks, Seeds, & Peshkin, 2000) and Table 3.23 presents the treatment application thresholds for flexible and composite pavements at MDOT (2000). In Chapter 52 of the INDOT Design Manual, typical performance lives of various treatments, when applied to different types of pavements, are defined, as shown in Table 3.24.

Wang (2013) analyzed LTPP data and determined that "chip seals have little effectiveness in rutting prevention; slurry seals demonstrate effectiveness in longitudinal cracking; crack seals show effectiveness in fatigue cracking." They also investigated the effectiveness of preservation treatments on surface friction. They also found that slurry seal yields a substantially higher friction number compared to the control section. The influence of various factors on the long-term loss of pavement friction, was also analyzed, and freeze index, precipitation, and pavement roughness were found to exhibit significant correlation to the friction number.

TABLE 3.17
Initial Effect of SPS-3 Maintenance Treatments on IRI and Rutting (Morian et al., 1997)

Treatment Type	IRI Drop, m/km (Std Dev)	Rutting Drop, mm (Std Dev)
Crack sealing	0.036 (0.111)	0.3 (2.9)
Chip sealing	0.064 (0.118)	1 (3.2)
Slurry Seal	0.044 (0.222)	0.0 (2.8)
Thin HMA overlay	0.191 (0.531)	0.1 (6.5)

TABLE 3.18
Long-Term Effect of SPS-3 Maintenance Treatments on IRI and Rutting (Morian et al., 1997)

Treatment Type	IRI (control versus treatment), m/km	Rutting (control versus treatment), mm
Crack sealing	0.02	1.2
Chip sealing	0.07	1.3
Slurry Seal	0.02	0.7
Thin HMA overlay	0.32	6.7

TABLE 3.19
Pavement Condition Pre- and Post-Rehabilitation, SPS-5 (Morian et al., 1998)

	Pre-Treatment		Post-Treatment	
SPS-5 Treatments	**IRI (m/km)**	**PSI (0-5 scale)**	**IRI (m/km)**	**PSI (0-5 scale)**
SPS-501: Control	1.40	3.46	1.47	3.38
SPS-502: 2-in overlay, recycled mix, minimal prep	1.83	3.03	1.01	3.94
SPS-503: 5-in overlay, recycled mix, minimal prep	1.76	3.10	0.94	4.04
SPS-504: 5-in overlay, virgin mix, minimal prep	1.76	3.10	0.96	4.01
SPS-505: 2-in overlay, virgin mix, minimal prep	1.58	3.27	0.93	4.05
SPS-506: 2-in overlay, virgin mix, intensive prep	1.51	3.34	0.93	4.05
SPS-507: 5-in overlay, virgin mix, intensive prep	1.68	3.17	0.96	4.01
SPS-508: 5-in overlay, recycled mix, intensive prep	1.59	3.26	0.89	4.11
SPS-509: 2-in overlay, recycled mix, intensive prep	1.79	3.07	0.96	4.01

TABLE 3.20
Pavement Condition Pre- and Post-Rehabilitation, SPS-6 (Morian et al., 2003)

	Pre-Treatment		Post-Treatment	
SPS-6 Treatments	**IRI (m/km)**	**PSI (0-5 scale)**	**IRI (m/km)**	**PSI (0-5 scale)**
SPS-601: Control	2.39	2.97	2.54	2.82
SPS-602: Non-overlay minimal repair	2.26	3.12	1.82	3.63
SPS-603: 4-in overlay with minimal preparation	2.15	3.20	0.98	4.49
SPS-604: 4-in saw-and-seal overlay, min. prep	2.20	3.20	1.00	4.47
SPS-605: Non-overlay intensive repair	2.40	3.02	1.36	4.10
SPS-606: 4-in overlay with intensive preparation	2.27	3.09	1.00	4.47
SPS-607: 4-in overlay with crack/break-and-seat	2.08	3.27	1.08	4.38

TABLE 3.21
Effectiveness of Pavement Maintenance in Terms of Treatment Life

Treatment	Description	Effectiveness
Saw & seal HMA Overlay	Saw and seal reflection joints locations in HMA-PCC composite pavement	8 years (NYSDOT, 1992) 12.4 years (Morian et al., 2003)
HMA Minor Structural Overlay[1]	A non-structural treatment that involves placing hot asphaltic concrete overlay approx. 2-4 inches thickness	11–14 years, Int., 13–17 years, non-Int. (Bardaka et al., 2014)[2] 6–15 years, avg. 8 years, (Irfan, Khurshid, Labi, & Flora, 2009)
PCCP Patching[1]	A treatment that repairs existing damaged slabs or exiting repaired patches that have deteriorated	8 years (Hall, Correa, Carpenter, & Elliott, 2001) 5–15 years (Khurshid, Irfan & Labi, 2011)

[1]Treatment effectiveness generally depends on existing pavement strength, pre-treatment preparation of pavement surface, post-treatment traffic volume and climate severity, treatment intensity (overlay thickness).
[2]Is a function of pre-treatment condition).

TABLE 3.22
Optimum Time for Applying Selected Treatments on Flexible Pavements (Hicks et al., 2000)

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

TABLE 3.23
Flexible and Composite Pavement Treatment Thresholds (MDOT, 2000)

Treatment	Pavement Surface Material Type	Life Extension (Years)
Surface Treatment Non-Structural Bituminous Overlay	Flexible Composite	5–10 4–9
Surface Milling With Non-Structural Bituminous Overlay	Flexible Composite	3–6 (Single Seal) 4–7 (Double Seal) 3–6 Double Seal
Chip Seal	Flexible Composite	3–5 (Single Course) 4–6 (Multiple Course) NA
Microsurfacing	Flexible Composite	Up to 3 Up to 3
Crack Sealing and Crack Filling	Flexible Composite	Up to 3 Up to 3
Ultra-Thin Bituminous Overlay	Flexible Composite	3–5 3–5

TABLE 3.24
Treatment 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	6
Chip Seal	4
Asphalt Crack Sealing	3

4. METHODOLOGY FOR THE ANALYSIS

4.1 Data Collection and Collation

4.1.1 Pavements

The study involved data collection and collation from different sources and preparation of input data for developing asset performance. The data sources include road inventory data, bridge condition data, pavement condition data and contract data, etc. There are over 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 and 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 classes: 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 inspected annually on Interstate routes, and every two years on NHS Non-Interstate and Non-NHS highways. The treatment-specific performance jump post-treatment effects models were developed using the merged dataset assembled from the condition data and contract data. The contract data in the INDOT database contained contracts that were carried out before 2006. The dataset includes contract number, contract starting and ending date, contract location, type of pavement work, contract cost and fiscal year.

4.1.2 Bridges

The study used data primarily from the National Bridge Inventory (NBI) database. The NBI data are cross-sectional and include bridge information from 1992 to 2014. The bridge components are inspected on a 2-year cycle and during inspections, condition ratings are assigned to each component. The reference data included the highway class, milepost, and the coordinates (longitude and latitude). Contract data were obtained from the SPMS database. Data from the two sources were merged.

4.2 General Procedure for Assessing Maintenance Effectiveness

The three basic sequential issues associated with the evaluation of maintenance treatment effectiveness are as follows (Sinha & Labi, in press):

(a) How should effectiveness be measured, and what performance indicator should be used to measure such effectiveness?
(b) On what grounds can the treatment or schedule be deemed effective?
(c) If the maintenance treatment or schedule is found to be effective, (i) what is the probability distribution of such effectiveness, and (ii) how could such effectiveness be modeled as a function of attributes of the asset, treatment, and the environment?

Therefore, the steps for effectiveness evaluation can be represented as shown in Figure 4.1. The material presented below is culled from Sinha & Labi (in press).

4.2.1 Step 1: How should the "maintenance effect" be measured?

For purposes of this study, at least two measures of effectiveness were considered: performance jump (short-term) and treatment life (long-term). For each asset that received a given treatment, the performance jump was measured using the methodology described in Section 3.2.2 of Chapter 3, and the treatment life was measured using the methodology described in Section 3.3.2 of Chapter 3.

4.2.2 Step 2: Which performance indicator should be used to measure such impact?

Treatments to bridge surfaces or pavements are applied with the intention of addressing at least one specific distress. As such, the effectiveness of such treatments should be evaluated only in terms of the defects or

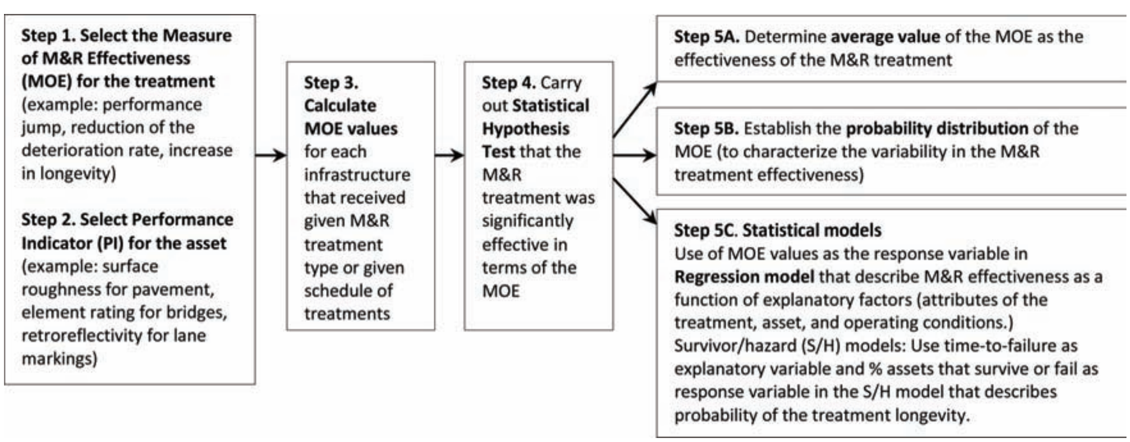


Figure 4.1 Steps for assessing the short- or long-term effectiveness of asset surface maintenance treatments.

distresses it is meant to address. At this step, therefore, the appropriate short term (performance jump) PIs were identified for pavements and bridges separately, for example, International Roughness Index (IRI), rutting, and cracking index for pavements; NBI index for bridges surface, and standard treatments for each of these two asset types.

4.2.3 Step 3: Calculate MOE values for each asset that received the treatment

The MOE value, in terms of the selected performance indicator, is determined for each asset that received the treatment under investigation. Therefore, in this step, average values of the short-term effectiveness (PJ) and the long-term effectiveness (treatment life) were derived for each type of treatment at each instance of application to an asset. In addition, probability distributions were establish to ascertain the statistical nature of the PJ and service life observations, for example, shape of the distribution, variance, and so on.

4.2.4 Step 4: Carry out test of hypothesis to ascertain whether the treatment was effective.

This step of the analysis uses the MOE values (in terms of the selected PI) to evaluate whether the treatment was significantly effective from a statistical viewpoint, The null hypothesis (that the mean MOE value is statistically equal to zero (that is, the treatment was not effective)) is tested against the alternate hypothesis (that the mean exceeds zero (that is, the treatment was effective)), at the specified level of confidence.

As the reported values of the performance indicators (and consequently, MOE values) are average values taken across a typically large number of assets, the distribution of the MOE values can be considered as a statistical sampling distribution of means. Based on this assumption, the null hypothesis (H_0) and alternate hypothesis (H_A) for the treatment effectiveness, in terms of the selected MOE and PI, can be formulated as follows:

$$H_0: \mu_{MOE} \leq 0 \text{ (the treatment was not effective)}$$

$$H_A: \mu_{MOE} > 0 \text{(the treatment was effective)}$$

This is a 1-sided hypothesis test with the "rejection region" in the upper tail. For example, assuming a normal distribution of the means of the entire population and 95% level of confidence, **the critical value of the test statistic** is given by: $Z_\alpha = Z_{0.05} = 1.645$.

The **calculated value of the test statistic** is given by: $Z^* = (\mu_{MOE} - 0)/(\sigma/\sqrt{n})$, where σ is the standard deviation, and n is the sample size (number of instances of the treatment application), μ_{MOE} is the mean value of the measure of effectiveness in terms of the performance indicator.

Figure 4.2 illustrates the region for rejecting the null hypothesis: If the calculated value of the test statistic

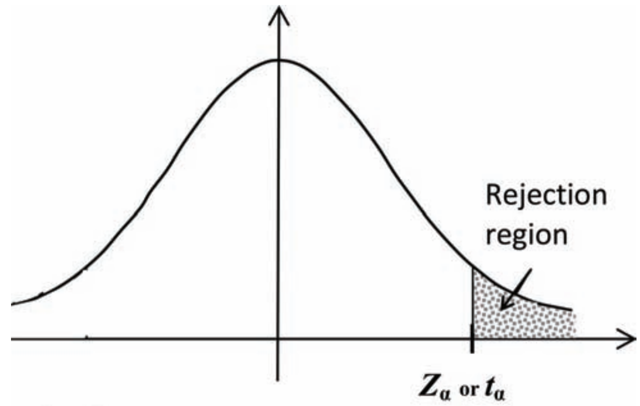


Figure 4.2 Region for rejecting the null hypotheses that the treatment was effective—illustration.

(t_C or Z_C) exceeds the critical value of the test statistic (t_α or Z_α) then the former falls in the null-hypothesis rejection region, thus suggesting that the treatments yielded MOEs that were significantly greater than zero and therefore the treatment was effective at that confidence level. On the other hand, if the calculated value of the test statistic does not exceed the critical value of the test statistic, then the former does not fall in the hypothesis rejection region, thus implying that there is no evidence to suggest that the treatment yielded MOEs that were significantly greater than zero and therefore, it cannot be concluded that the treatment was effective at that confidence level (Sinha and Labi, in print).

4.2.5 Step 5: Statistical Modeling of Treatment Effectiveness

Step 5A. In this step, the average value of the measure of effectiveness is calculated using the field data regarding asset condition before and after the specific instance of each treatment.

Step 5B. In this step, the probability distribution is established using the field data desired values of the measures of effectiveness. From the probability distribution and plot, the shape of the distribution and its parameters are determined.

Step 5C

(i) Was the treatment effective?
After confirming the effectiveness of the maintenance treatment in Step 3 (Section 4.2.3), the next step is to use the multiple values of the MOEs to make a broader statement about the effectiveness of the treatment. This can be done using at least one of three primary forms: a **simple average value,** a **probability distribution,** or **statistical model**. This step is needed because there was significant variation in the maintenance effects data (that is, the performance jumps), and it was hypothesized that some of the variation could be explained better if other explanatory factors were accounted for. Such accounting took the form of developing a model

for the treatment effectiveness as a function of attributes of the treatment, the asset, and the operating environment. Using data from the pavement sections and bridges in Indiana, the study demonstrated how the impacts were measured, for each of the standard treatments. Using statistical hypothesis testing, the study ascertained whether the impacts of each treatment type were considered significant. For example, does thin HMA overlay (treatment type) significantly reduce rutting (performance indicator) in terms of performance jump (MOE)?

(ii) Which significant factors affect the effectiveness of the treatment?
It is sought not only to use a regression model to predict the treatment effectiveness as a function of explanatory factors but also to determine whether each factor influences significantly the treatment effectiveness at a given level of confidence. For each factor, this may be done by testing the null hypothesis that the explanatory factor is not significant (its coefficient is statistically equal to zero) versus the alternate hypothesis that the explanatory factor is significant (its coefficient is statistically not equal to zero), at the specified level of statistical significance. This can be formulated as follows:

$$H_0: \beta_{Xi} = 0 \text{ (the explanatory factor has no effect on the treatment effectiveness)}$$

$$H_A: \beta_{Xi} \neq 0 \text{ (the explanatory factor has an effect on the treatment effectiveness)}$$

This is a 2-sided hypothesis test with the "rejection region" in both lower and upper tails. For example, assuming a normal distribution of the means of the entire population and 95% level of confidence, the critical value of the test statistic is given by: $Z_{\alpha/2} = Z_{0.025}$.

The calculated value of the test statistic is given by: $Z^* = (\beta_{X,\ MEAN} - 0)/(\sigma/\sqrt{n})$, where σ is the standard deviation, and n is the sample size (number of observations), $\beta_{X,\ MEAN}$ is the mean value of the coefficient of the explanatory factor.

Figure 4.3 illustrates the regions for rejecting the null hypothesis: If the calculated value of the test statistic (t_C or Z_C) exceeds the critical value of the test statistic

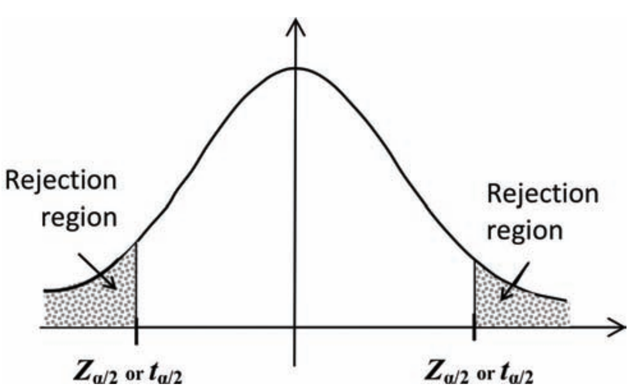


Figure 4.3 Region for rejecting the null hypotheses that a given explanatory variable is a significant factor of treatment effectiveness.

($t_{\alpha/2}$ or $Z_{\alpha/2}$) then the former falls in the null-hypothesis rejection region, thus suggesting that the coefficient of the explanatory variable is significantly different than zero and therefore the explanatory factor has an effect on the treatment effectiveness at that confidence level. On the other hand, if the calculated value of the test statistic does not exceed the critical value of the test statistic, then the former does not fall in the hypothesis rejection region, thus implying that there is no evidence to suggest that the coefficient of the explanatory variable is significantly different than zero and therefore, it cannot be concluded that the explanatory factor has an effect on the treatment effectiveness at the given level of confidence.

(iii) Sensitivity analysis
This step assessed, for each treatment, the sensitivity of its effectiveness with respect to changes in the significant explanatory factors identified at Step 3. This result can help in policy formulation regarding the application of each treatment.

(iv) Cost-effectiveness analysis
This step assessed, for each treatment, the cost, and the cost-effectiveness. Comparisons were then made across the treatment types and functional classes.

4.3 Application of the Methodology to Pavements

4.3.1 Modeling the Pavement Performance Jump

The general form of the treatment-specific performance jump model is:

$$\text{Performance Jump, PJ} = f(X)$$

where PJ = Performance jump (IRI (in/mi)) at the time of treatment application; X = vector of variables representing the factors that affect performance jump.

Performance jump models were developed for each treatment type and for each pavement family. Performance jump is defined in the current study as the improvement in the pavement condition rating (reduction in IRI) after a pavement treatment is carried out. Performance (IRI) jump is often related to the IRI before the treatment: the higher the IRI before the treatment, the greater the IRI jump will typically be.

The jump models were investigated for various treatments in the current study with IRI as the dependent variable and pretreatment IRI as the independent variable, using the following functional forms:

$$\text{Linear form: } IRI\ Jump = \beta_0 + \beta_1 * Pre-treatment\ IRI$$

$$\text{Logarithm form: } IRI\ Jump = \beta_0 + \beta_1 * ln\ (Pre-treatment\ IRI)$$

For rehabilitation and replacement (functional and structural overlay) treatments, the logarithm form was adopted in developing jump models, whereas linear functional form was used for jump models of preventive maintenance (PM overlay, patching, etc.). The main difference between these two functional forms is that when the condition is poor (high IRI value), the estimated IRI jump is higher than the actual jump in the linear model than it is in the logarithm model. Typically, preventive maintenance treatment such as HMA thin 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 pretreatment IRI increases, the logarithm functional form is capable of capturing this pattern. The performance jump model results for different treatments and pavement families are presented in the results sections of this report.

5. RESULTS AND DISCUSSION—BRIDGES

5.1 Bridge Deck Surface Treatments—Performance Jump

The following sections discuss the performance jump effects earned from LMC overlay and polymeric overlay, two common treatments at INDOT.

5.1.1 Performance Jump due to Bridge Latex-Modified Concrete (LMC) Overlay Treatment

(a) Background. As stated in Indiana's Design Manual (INDOT, 2013a, 2013b), a 1¾ inch thick LMC overlay is placed after 1/4 inch of the deck is removed, producing a net 1½-inch grade increase. A 1/4 inch layer of the original top layer of the deck is replaced (the bottom part remains the same), LMC overlays are intended to improve the deck condition rating.

The values of post-treatment condition, pre-treatment condition, and performance jump were summarized using data from three databases: (a) NBI (this provides deck condition rating data annually), (b) SPMS (this provides the time of LMC overlay implementation, and (c) Wearing surface condition data sets. The thresholds at which LMC overlays were carried out represented historical practice.

Figure 5.1 presents the distribution of deck condition rating changes resulting from LMC overlays. The pre-hyphen and post-hyphen digits represent the pre-treatment and post-treatment conditions, respectively, of the deck. The most frequent combinations are 7-7, 6-7, 6-6, 5-7, and 6-8. For certain observations, the deck condition does not seem to improve after the deck received the LMC overlay, for example, 5-5, 6-6, and 7-7. This could be because changes in the wearing course may not always translate into changes in the overall deck condition.

(b) Testing the Statistical Significance of the Measured Jumps in Deck Surface Performance (adapted from Sinha & Labi, in press). In this step, average values of the PJ were derived for each bridge deck that received the Latex-Modified Concrete (LMC) Overlay treatment. In addition, the mean and variance of the PJs were calculated. This step assesses whether the treatment was significantly effective from a statistical viewpoint, based on the MOE (performance jump) that is expressed terms of the selected PI (NBI rating). This was done by testing the null hypothesis that the mean performance jump is statistically equal to zero (the LMC treatment was not effective) versus the alternate hypothesis that the mean exceeds zero (the LMC treatment was effective), at the specified level of statistical significance (95%). As the measured PJs are average values taken across hundreds of bridge decks, the distribution of the PJ values can be considered as a statistical sampling distribution of means. Based on this assumption, the null hypothesis (H_0) and

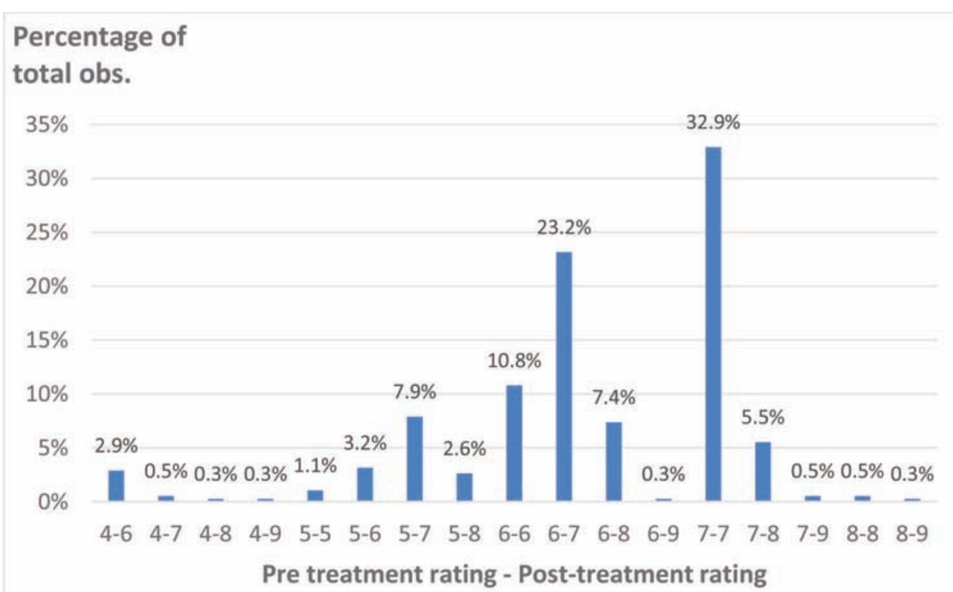


Figure 5.1 Distribution of deck condition changes (pre- and post-LMC overlay).

alternate hypothesis (H_A) for the treatment effectiveness, in terms of the selected MOE and PI, can be formulated as follows:

H_0: $\mu_{PJ} \leq 0$ (the LMC treatment was not effective)

H_A: $\mu_{PJ} > 0$ (the LMC treatment was effective)

This is a 1-sided hypothesis test with the "rejection region" in the upper tail. For example, assuming a normal distribution of the means of the entire population and 95% level of confidence, **the critical value of the test statistic** is given by: $Z_\alpha = Z_{0.05} = 1.645$.

The **calculated value of the test statistic** is given by: $Z^* = (\mu_{PJ} - 0)/(\sigma/\sqrt{n})$, where σ is the standard deviation, and *n* is the sample size (number of instances of the treatment application), μ_{PJ} is the mean value of the measure of effectiveness in terms of the performance indicator.

From the data, the z-value is calculated as:

$$z = \frac{\bar{X} - \mu}{\sigma/\sqrt{n}} = \frac{0.82105 - 0}{0.90123/\sqrt{380}} = 17.7593$$

(the corresponding p-value < 0.0001)

For 99% confidence interval ($\alpha = 0.01$), the critical value $z^* = 2.33 < 17.7593 = z$.

The calculated value of the test statistic does not exceed the critical value of the test statistic. The former falls in the hypothesis rejection region, thus implying that there is evidence to suggest that the LMC treatment yielded performance jumps that were significantly greater than zero and therefore, it can be concluded that the treatment was effective at that confidence level. (See Figure 5.2.)

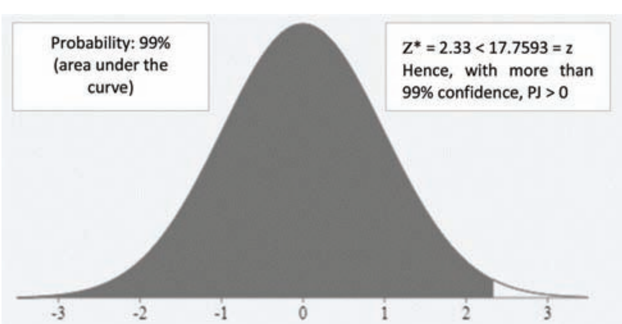


Figure 5.2 Region for rejecting the null hypotheses in Step 4—illustration.

(c) Developing a Model to Predict the Jump in Performance

Part 1. Preliminary Analysis. In order to identify the nature of relationship between the dependent variable and all the explanatory variables that were hypothesized to influence performance jump, a preliminary assessment was carried out by developing a correlation matrix and other statistical diagnostics (scatter plots, and descriptive statistics), see Tables 5.1 through 5.3.

As can be seen in the correlation matrix, the correlation of deck area with letting amount is significant which means that these two variables cannot be used as explanatory variables in the same model. The same explanation applies to other variables in the table. Different functional forms of age (linear, exponential, polynomial) in relation to performance jump were also investigated.

Part 2. Statistical Modeling. The best model was realized when the independent variable was transformed to its natural logarithm. Two alternative models were developed.

Model with pre-treatment condition as the only independent variable. The model developed using pre-treatment condition only as the independent variable is:

$$PJ_{Deck} = 8.312 - 4.164 \times \ln\,(Pre-treatment\ Deck\ Condition)$$

where PJ_{Deck} is the performance jump of the deck condition due to the LMC overlay, and ln(*Pre – treatment Deck Condition*) is natural logarithm of the deck condition prior to the implementation of the LMC overlay, where *Pre – treatment Deck Condition* ε{4,5,6,7,8}. Table 5.3 presents the details of the model estimation, and Figure 5.4 illustrates the model plot.

The model results suggest that the condition of the bridge deck prior to the treatment is statistically significant (p-value almost zero) and the sign of the parameter is negative. This indicates that the higher the pre-treatment deck condition, the smaller the jump in the deck condition subsequent to the treatment (see Figure 5.3).

Model with pre-treatment condition and deck area as the independent variables. The model developed using pre-treatment condition and deck area as the independent variables is:

$$PJ_{Deck} = 8.417 - 4.186 \times \ln(Pre_{treatment}\ Deck\ Condition)$$

$$-0.74(Deck\ Area)$$

where PJ_{Dec}, and *Pre_treatment Deck Condition* are as defined previously. *Deck Area* is the total area of the deck in 1000's of m^2. Table 5.4 presents the details of the model estimation.

The model results suggest that the condition of the bridge deck prior to the treatment is statistically significant with a negative sign of the parameter. This indicates that the higher the pre-treatment deck condition, the smaller the jump in the deck condition subsequent to the treatment. Also, the *Deck Area* is statistically significant with a negative parameter; this suggests that LMC applied to smaller decks generally yield higher performance jumps compared to the same treatment applied to larger decks. This is a rather curious observation.

(d) Discussion. In this report, we document the impact of the LMC overlay on the deck condition. It will be useful to investigate, if data were available, the

TABLE 5.1
Descriptive Statistics of Potentially Influential Variables: LMC Performance Jump

Variable	Mean	Std Dev	Minimum	Maximum
Deck_area (m^2)	917.64	836.19	99.56	6,460
Func_Class	7.5220994	4.571477	1	19
Deck_Age	34.2928177	12.1729186	15	98
Letting_Amount	433,078.83	367,710.08	0	3,128,082
Overlay Intensity (Unit Cost, $/$m^2$)	634.28	490.06	0	3776.68
Finish Date	2002	N.A.	1995	2010
NBI Rating before the overlay	6.19	0.83	4	8
NBI Rating after the overlay	6.98	0.66	5	9
Performance Jump	0.79	0.90	0	5

TABLE 5.2
Correlation Matrix for the Factors that Potentially Affect LMC Effectiveness

Pearson Correlation Coefficients, N = 358 Prob > |r| under H0: Rho=0					
	Deck_area	**PTDC**	**Deck_Age**	**Finish_Date**	**Letting_Amount**
Deck_area	1.00000	-0.05835	-0.13632	0.00171	0.54085
		0.2682	0.0094	0.9742	<.0001
Pre_Treatment Deck Condition (PTDC) or NBI Rating before the overlay	-0.05835	1.00000	-0.10096	-0.30196	-0.11614
	0.2682		0.0550	<.0001	0.0271
Deck_Age	-0.13632	-0.10096	1.00000	0.05944	0.04803
	0.0094	0.0550		0.2593	0.3622
Finish_Date	0.00171	-0.30196	0.05944	1.00000	0.03215
	0.9742	<.0001	0.2593		0.5420
Letting_Amount	0.54085	-0.11614	0.04803	0.03215	1.00000
	<.0001	0.0271	0.3622	0.5420	

TABLE 5.3
Performance Jump Model I—Results

Regression Statistics				
R Square	0.5546			
Adjusted R Square	0.5454			
Observations	358			
	Coefficients	**Standard Error**	**t Stat**	**p-value**
Intercept	8.312	0.367	22.66	<0.001
LN(Pre Deck)	-4.164	0.201	-20.72	<0.001
Deck area (1000 m^2)	8.312	0.367	22.66	<0.001

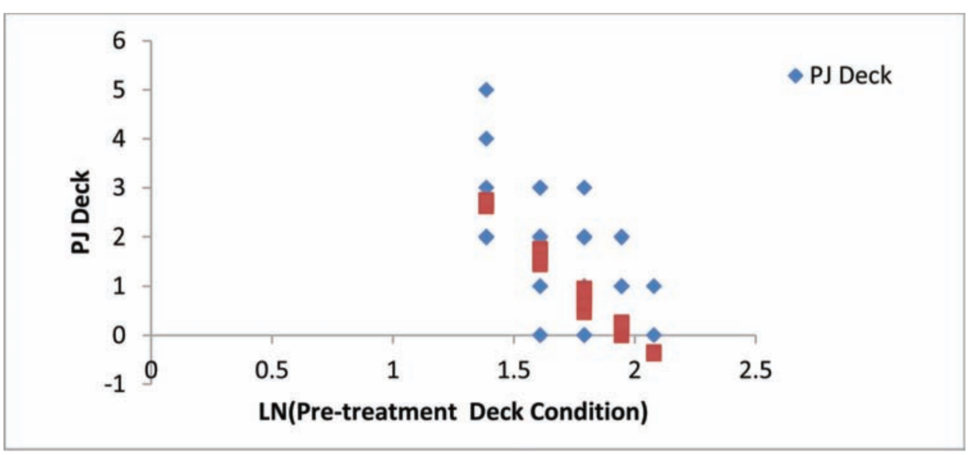


Figure 5.3 Relationship between deck performance jump and pre-treatment condition.

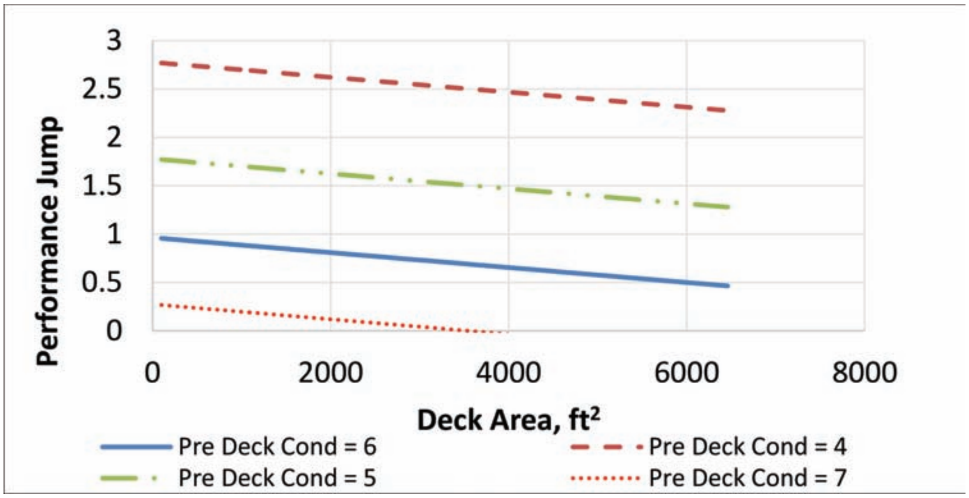


Figure 5.4 Relationship between deck performance jump and deck area, for different levels of pre-treatment condition.

TABLE 5.4
Performance Jump Model II—Results (Figure 5.4)

Regression Statistics				
R Square	0.5525			
Adjusted R Square	0.5499			
Observations	358			
	Coefficients	**Standard Error**	**t Stat**	**p-value**
Intercept	8.417	0.368	22.86	<0.001
LN(Pre-treatment Deck Condition)	-4.186	0.200	-20.90	<0.001
Deck area (1000s m^2)	-0.000074	0.000034	-2.15	0.032

impact on the deck wearing surface condition. This is because the warrants for LMC application are based not on the deck condition but the wearing surface condition. Figure 5.5 presents the distribution of the wearing surface conditions at which LMC overlay has been applied in the past. The figure shows that most LMC overlays were carried out when the wearing surface condition rating was 5, and nearly 25% were carried out at a condition rating of 6.

5.1.2 Performance Jump due to Bridge Polymeric Overlay Treatment

Polymeric overlay (or polymer overlay) has not been used much by INDOT until recently. For this reason, there were inadequate observations in the database, precluding the development of statistical models. INDOT maintains that a polymeric overlay does not improve the deck condition per se, but deck patching and other surface repair work prior to the overlay could lead to moderate increases in the deck condition.

Given the rather few observations, the polymeric overlay trigger values (regarding the wearing surface condition) can be 5, 6, 7, or 8. The effectiveness of the treatment (in terms of the change in deck condition) were assessed as follows (coded as "pretreatment rating – post treatment rating – relative frequency"): 8-8 (13%), 7-8 (9%), 7-7 (30%), 6-7 (21%), 6-6 (18%), and 5-6 (9%). With regard to the post-treatment condition of the deck wearing surface, it is assumed (similar to the case for LMC overlays) that the wearing surface condition returns to 9 after a polymeric overlay. In future research, it will be needed to verify this assumption using actual field observations.

5.2 Bridge Deck Surface Treatments—Post-Treatment Performance-vs.-Age Trend and Treatment Life

Deterioration rates are expected to be reduced by the treatments as the overlay protects the deck by providing a non-permeable "sacrificial" layer that prevents water and chlorides from penetrating to the reinforcing steel in the deck (Indiana Design Manual (INDOT, 2013a, 2013b).

5.2.1 Latex-Modified Concrete (LMC) Overlay

For this treatment, the post-treatment deck performance uses the same deterioration curves as shown in previous section. However, the post-treatment deterioration

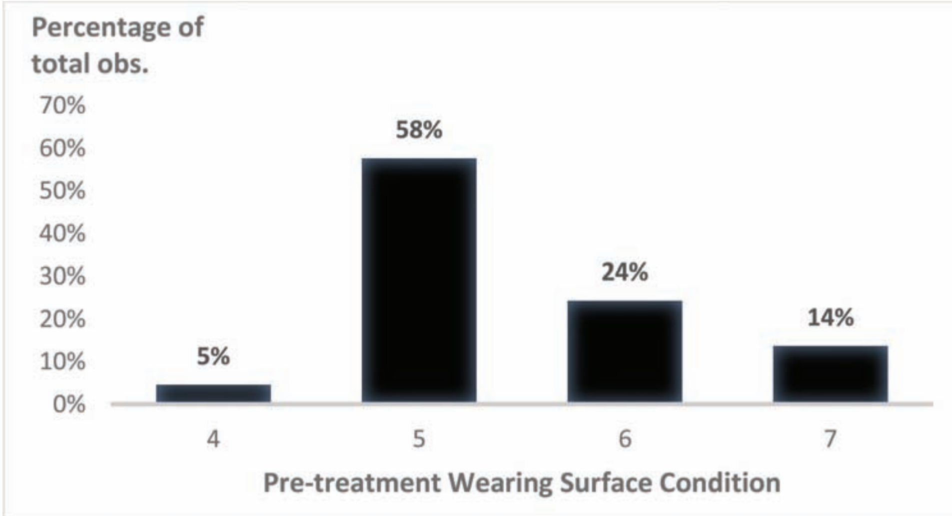


Figure 5.5 Distribution of pre-LMC overlay wearing surface condition (triggers).

restarts from an elevated condition level that is estimated using the performance jump model developed in this study. This method does not reflect the decrease in the deterioration rates, but provides an alternative way to measure the deck service life extension. According to the Indiana Design Manual (INDOT, 2013a, 2013b), LMC overlays typically provide deck protection for 15 $\pm$ 5 years. The post-treatment condition of the deck wearing surface is estimated using models that account for the pre-treatment condition of the deck. For example, for a pre-treatment deck condition of 5, when the LMC overlay is carried out, the post-treatment condition of the wearing surface would be determined using 5 as the model input for that variable. This is found to lead to faster post-treatment deterioration compared with the pre-treatment deck conditions of 7 to 9.

5.2.2 Polymeric Overlay

The effect of this treatment on the deck life extension was estimated based on very few observations. For each bridge deck that received the treatment, the post-treatment deck condition for each year after the treatment was tracked. Other bridges that have similar characteristics (highway district, functional class, ADT, truck percentage, etc.) to that bridge but did not receive the treatment, were identified using the NBI database. The average number of years that each bridge stayed in a certain condition was determined (for example, condition 8 for t_1 years, 7 for t_2 years, 6 for t_3 years). These were averaged and compared with the life of similar decks that had received a polymeric overlay. It was determined, within the sample size constraints, that the polymeric overlay provides a 5–8 years extension of the deck service life, and that this extension is influenced by the pre-treatment deck condition. According to the Indiana Design Manual (INDOT, 2013a, 2013b), polymeric overlays offer an average service life of approximately 10 years.

5.3 Bridge Treatments—Costs

Cost models were estimated using data from the SPMS database. This database contains contract information over the period spanning 1994 to 2010. The Site Manager database contains detailed data on contract pay item costs, from 2009 to 2012. The costs that occur in different years were converted into their equivalent constant dollars of year 2010, using the National Highway Construction Cost Index (NHCCI).

5.3.1 LMC Overlay Cost

The reported cost of LMC overlay represents not only for the LMC wearing surface but also hydro-demolition and deck patching and asphalt wedging of the approach roadway (because LMC overlays raise the bridge driving surface). These are preparatory or accompanying work activities for this type of overlay). For this reason, the LMC overlay unit cost is likely to be affected by the pre-treatment deck condition because a higher level of preparatory work will likely be required when the LMC overlay is to be placed on a deck in poorer condition. Besides, the unit cost of construction work is often influenced by scale economies. In this case, specifically, the greater the deck area (overlay area) is, the lower the unit cost is likely to be. The cost model developed for LMC overlays is:

$$\begin{aligned} &LMC\ Unit\ Cost\ \left(\$/\mathrm{ft}^2\right) = \\ &\qquad 9.48 - 11.14(\mathrm{Pre-\ treatment\ Condition}) \\ &\qquad - 0.66(\ln(Deck\_Area)) \end{aligned}$$

Figure 5.6 presents the LMC Overlay unit cost models. The signs of the variables are intuitive. Specifically, higher pre-treatment deck condition and larger deck area are associated with lower unit cost. The LMC overlay unit cost sample mean is \$62.81/ft^2, and the sample standard deviation is \$44.47/ft^2, which reflects a large variation in the data.

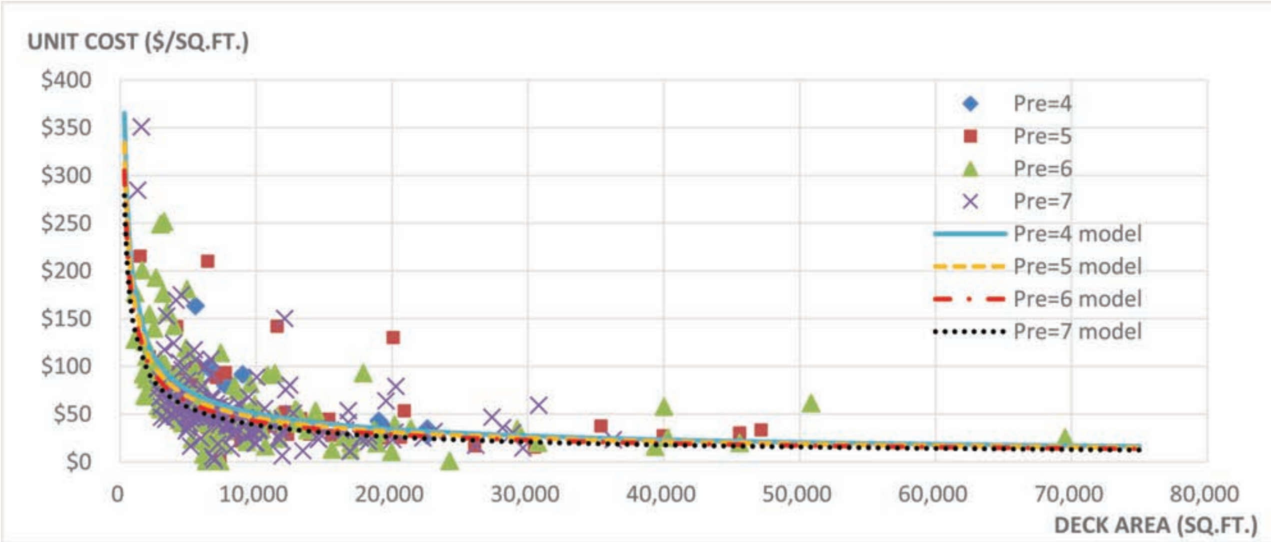


Figure 5.6 LMC overlay unit cost models.

5.3.2 Polymeric Overlay Unit Cost Model

Due to the rather limited number of polymeric overlay contracts, a reliable cost model could not be developed. Therefore, this report uses a polymeric overlay cost model provided by INDOT:

$$POC\ (\$) = 1.05[16.8(Deck\_Area) + 35{,}000]$$

where *DeckArea* is the total deck area (ft^2) (assumed to be equal to the area of the polymeric overlay, $35,000 is the estimated maintenance of traffic (MoT) cost, *POC* is the polymeric overlay contract cost, and 1.05 is a multiplier established by INDOT. The corresponding unit cost function (Figure 5.7) is indicative of the presence of scale economies.

$$POC\ Unit\ Cost\ \left(\$/\text{ft}^2\right) = 1.05\ [16.8 + (35000/Deck\_Area)]$$

5.3.3 Cost Model for Partial Depth Patching of Deck Surface

From forty-two (42) observations, the average unit cost of partial-depth patching based on the contract data in INDOT's Site Manager database is $34.46/ft^2 in 2010 constant dollars (the standard deviation was $47.25/ft^2). A statistical model was developed to describe the unit cost of partial depth patching of bridge decks, as follows:

$$Partial\!-\!Depth\ Deck\ Patching\ Unit\ Cost\ \left(\$/\text{ft}^2\right) =$$
$$99.54 - 11.14\ \ln(Deck\_Area)]$$

For the full-depth deck patching cost model, the patching area was found to be statistically insignificant. Therefore, only the average unit cost was determined: $48.56/ft^2 in 2010 constant dollars, with $68.13/ft^2

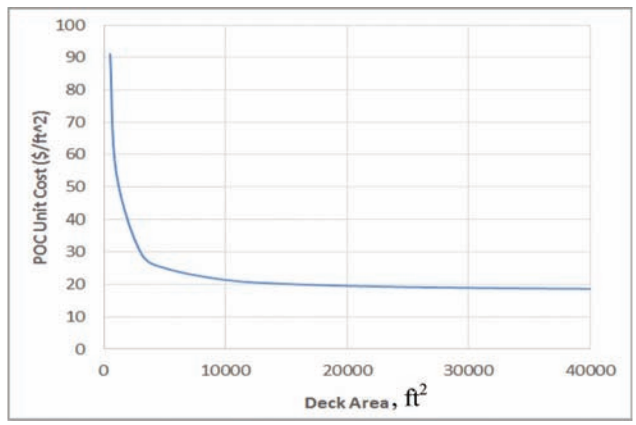


Figure 5.7 POC unit cost model.

standard deviation. The model plot is presented in Figure 5.8.

5.4 Cost-Effectiveness of the Bridge Deck Surface Treatments

Figure 5.9 presents the cost-effectiveness of the bridge deck surface treatments. This is done using two different measures of cost-effectiveness. Type I is the change in the asset rating per treatment intensity ($/m^2). For Type I, a treatment that yields a bigger change in asset rating for a given intensity, is considered more cost effective. Type II is the treatment intensity ($/m^2) that is needed to yield a given change in the asset rating per treatment intensity. For Type II, a treatment for which a smaller intensity is needed to yield a unit change in asset condition is considered more cost effective. Type II is the reciprocal of Type I. Both charts in the figure suggest that from the perspective of performance jump, polymeric overlay is the

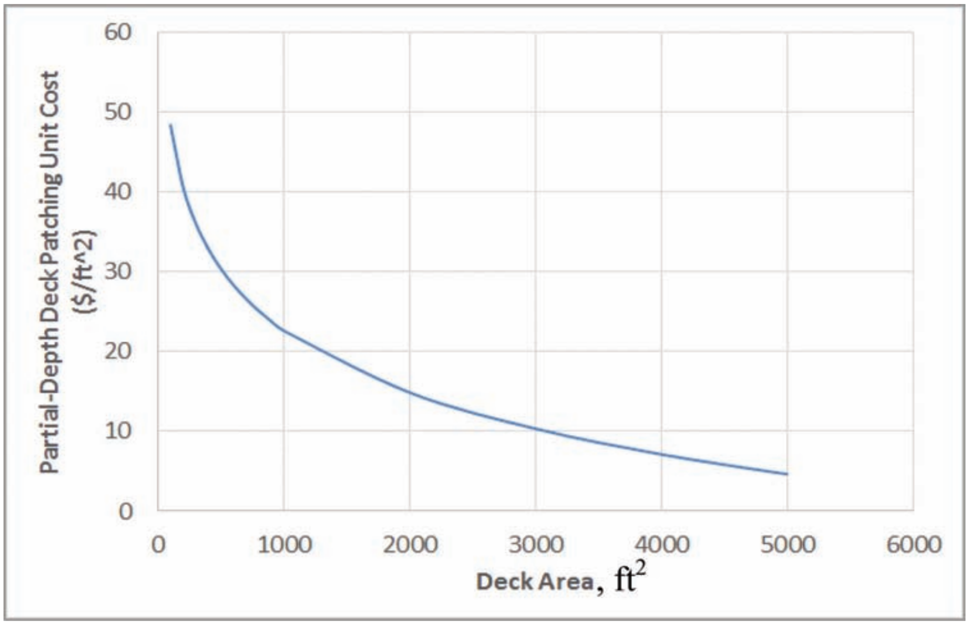
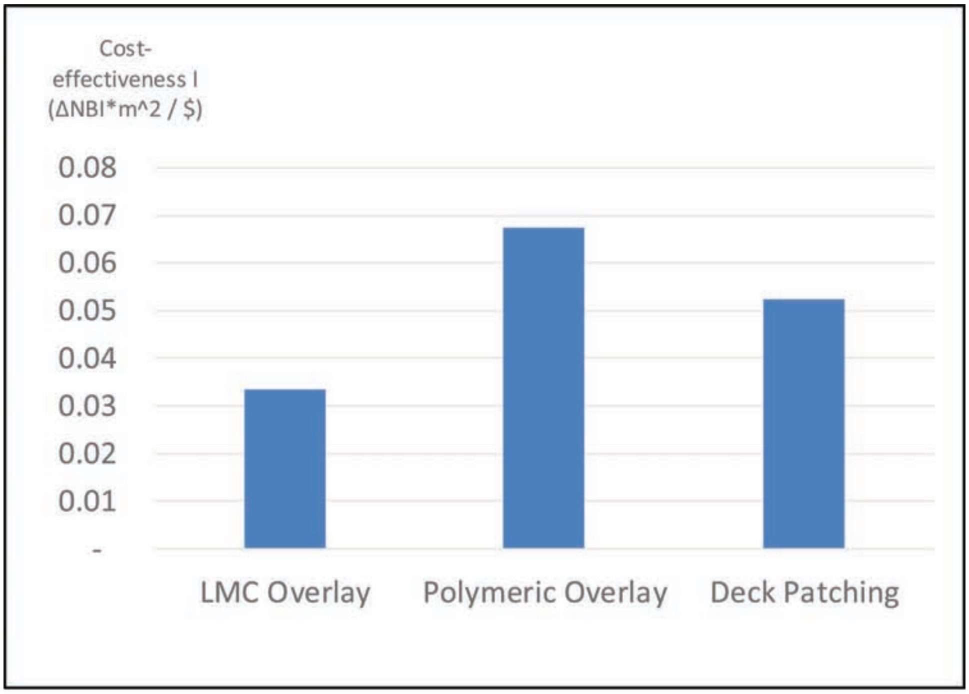


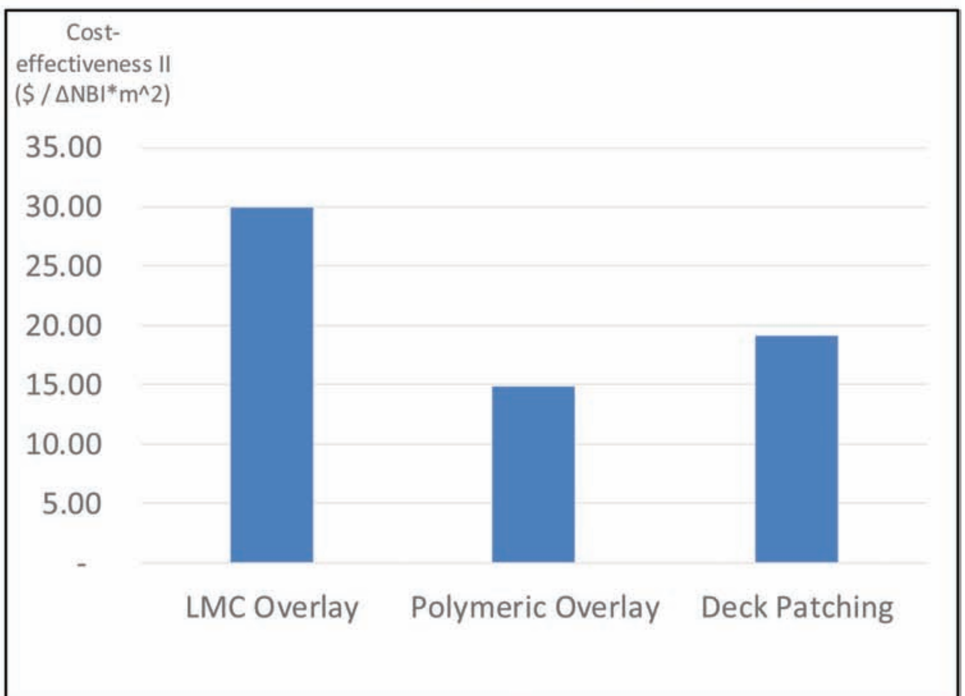
Figure 5.8 Unit cost model for partial-depth patching.

most cost-effective treatment, followed by deck patching and LMC overlay. However, two points must be borne in mind:

- The surface defects that warrant these treatments may be different, therefore it may not be a prudent exercise to make a direct comparison of their relative cost-effectiveness.
- The cost effectiveness computations are based on a short-term measure of effectiveness (performance jump). It may be better to compare them based on their cost-effectiveness in the longer term, for example, the treatment life (years) per treatment intensity ($/m^2).



(a) Cost-effectiveness I (ΔNBI per $\$/m^2$)



(b) Cost-effectiveness II: ($\$/m^2$ per Unit Change in NBI)

Figure 5.9 Cost-effectiveness comparison of three bridge deck surface treatments.

6. RESULTS AND DISCUSSION—PAVEMENTS

6.1 Performance Jump

6.1.1 Testing the Statistical Significance of the Measured Jumps in Pavement Surface Performance

Using the methodology explained in Chapter 4 of this report, the jumps in pavement surface performance due to each treatment type was tested for their statistical significance. We present the results of these hypothesis tests I Table 6.1 but we present only a single result below (for thin HMA overlay treatments at flexible-pavement Interstates).

For flexible Interstate Thin HMA Overlay treatments data, the z-value is calculated as:

$$z = \frac{\bar{X} - \mu}{\sigma/\sqrt{n}} = \frac{62.85 - 0}{25.50/\sqrt{133}}$$

$$= 28.4244 \text{ (the corresponding p-value} < 0.0001)$$

For 99% confidence interval ($\alpha = 0.05$), the critical value $z^* = 2.88 < 28.4244 = z$.

The calculated value of the test statistic does not exceed the critical value of the test statistic (Figure 6.1). The former falls in the hypothesis rejection region, thus implying that there is evidence to suggest that the thin HMA overlay treatment yielded performance jumps that were significantly greater than zero and therefore, it can be concluded that the Thin HMA Overlay treatment at flexible Interstates were effective at 95% confidence level. The analysis was repeated for each of the three pavement treatments, and for each treatment, and at each of the three functional classes of pavements that received the treatment. The results are tabulated below (Table 6.1).

6.1.2 Developing a Model to Predict the Jump in Performance and Hypothesis Testing of the Influence of the Explanatory Factors—Indiana Data

Model Development. A statistical model was developed to predict the performance jump and to measure the magnitude and direction of the effect of the various explanatory factors (variables) on the performance jump. The regression technique was applied to estimate the model. The functional form is given in the equation below:

$$PJ = \alpha + \boldsymbol{\beta}(\boldsymbol{X})$$

where PJ = Performance jump or IRI Drop at the time of application for treatment; α = Constant term, and $\boldsymbol{\beta}$ = parameter estimate for each explanatory variable; $\boldsymbol{X}$ is a vector of explanatory variables.

Influence of the Factors. The values of the variables are taken across a large number of pavement sections; therefore, the distribution of the PJ values can be

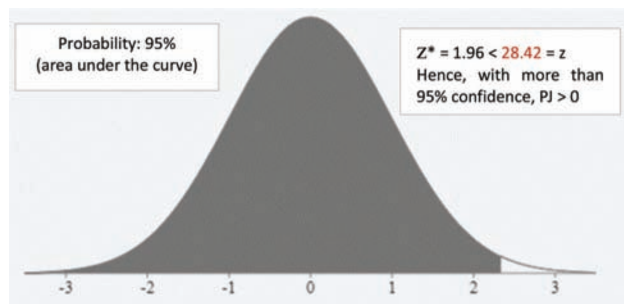


Figure 6.1 Rejecting the null hypotheses regarding treatment effectiveness, flexible Interstate pavements, thin HMA overlay.

TABLE 6.1
Performance Jump of Treatments at Various Functional Classes—Results of Hypothesis Tests

Treatment	Functional Class	Results of Hypothesis Test	Remarks[1]
HMA Overlay, PM	Flexible Interstates	Reject the null	Treatment was effective
	Flexible Non-Interstate NHS	Reject the null	Treatment was effective
	Flexible Non-NHS	Reject the null	Treatment was effective
Microsurfacing	Flexible Interstates	Reject the null	Treatment was effective
	Flexible Non-Interstate NHS	Reject the null	Treatment was effective
	Flexible Non-NHS	Reject the null	Treatment was effective
HMA Minor Structural Overlay	Flexible Interstates	Reject the null	Treatment was effective
	Flexible Non-Interstate NHS	Reject the null	Treatment was effective
	Flexible Non-NHS	Reject the null	Treatment was effective
PCC Repair & HMA overlay	Rigid pavements, all classes	Reject the null	Treatment was effective
PCC overlay of PCCP	Rigid pavements, all classes	Reject the null	Treatment was effective
PCCP Patching	Rigid pavements, all classes	Reject the null	Treatment was effective

[1]Effectiveness here refers to the performance jump.

TABLE 6.2
Performance Jump (IRI Drop) Models—Flexible Interstate Pavement Maintenance Treatments

Treatment Type	Model Variable	Coefficient Value	t-statistic	Model Statistics	Average Pre-treatment IRI (in/mi)	Average IRI Drop (in/mi)
HMA overlay, PM	Constant	–265.25	–11.413	$R^2 = 0.73$	121.83	71.14
	PTC[1]	70.332	18.034			
Microsurfacing[2]	Constant	–284.55	–7.68	$R^2 = 0.81$	114.84	58.81
	PTC[1]	72.38	9.26			
HMA Minor Structural Overlay	Constant	–244.08	–5.919	$R^2 = 0.80$	129.44	77.42
	PTC[1]	66.10	7.791			

[1]PTC = pre-treatment condition of the pavement (IRI in in/mi).
[2]The microsurfacing model is same for all functional classes because it was developed using data from all the classes.

TABLE 6.3
Performance Jump Model—Flexible Non-NHS Pavement Maintenance Treatments

Treatment Type	Model Variable	Coefficient Value	t-statistic	Model Statistics	Average Pre-treatment IRI (in/mi)	Average IRI Drop (in/mi)
HMA overlay, PM	Constant	–262.18	–6.217	$R^2 = 0.73$	122. 23	62.59
	PTC[1]	66.54	7.154			
Microsurfacing[2]	Constant	–284.55	–7.68	$R^2 = 0.81$	114.84	58.81
	PTC[1]	72.38	9.26			
HMA Minor Structural Overlay	Constant	–222.57	–6.45	$R^2 = 0.74$	141.22	85.04
	PTC[1]	59.988	8.33			

[1]PTC = pre-treatment condition of the pavement (IRI in in/mi).
[2]The microsurfacing model was developed using data from all functional classes.

considered as a statistical sampling distribution of means. Therefore, for each variable, the strength of its influence of the performance jump was investigated by testing the null hypothesis that the mean value of the variable's coefficient is statistically equal to zero (the variable is not a significant factor of the performance jump) versus the alternate hypothesis that the mean exceeds zero (the variable is a significant factor of the performance jump), at the specified level of significance.

H_0: $\beta_{Xi} = 0$ (the variable is not a significant factor of the performance jump)

H_A: $\beta_{Xi} \neq 0$ (the variable is a significant factor of the performance jump)

This is a 2-sided hypothesis test with the "rejection region" in the upper tail. For example, assuming a normal distribution of the means of the entire population and 95% level of confidence, **the critical value of the test statistic** is given by: $Z_{\alpha/2} = Z_{0.025} = 1.96$. The **calculated value of the test statistic** is given by: $Z^* = (\beta_{EF} - 0)/(\sigma/\sqrt{n})$, where σ is the standard deviation, and n is the sample size (number of instances of the treatment application), β_{EF} is the mean value of the measure of effectiveness in terms of the performance indicator. Using the above test, there was only one variable that was found significant in the developed model—the pre-treatment condition of the pavement. For this variable, it was determined that the calculated value of the test statistic exceeded the critical value of the test statistic thus the former falls in the null-hypothesis rejection region. This suggests that the coefficient of the variable representing the pre-treatment condition of the pavement, is significantly greater than zero and therefore the variable is an influential factor of the performance jump.

Tables 6.2 through 6.5 present the performance jump models for each treatment. The selected variables were found to be statistically significant at the given level of confidence, and models exhibit a good fit. The results suggest that pavements in poor pre-treatment condition exhibit larger jumps in performance after receiving a treatment, compared to those in fair-good pre-treatment condition.

6.1.3 Developing a Model to Predict the Jump in Performance—LTPP Data

The performance jump modeling was repeated using data for the LTPP wet-freeze region (which includes Indiana). The results are presented in Table 6.6.

$$PJ = \beta_0 + \beta_1 \times [\ln(PTC)]$$

TABLE 6.4
Performance Jump (IRI Drop) Model—Flexible NHS Non-Interstate Pavement Maintenance Treatments

Treatment Type	Model Variable	Coefficient Value	t-statistic	Model Statistics	Average Pre-treatment Performance (in/mi)	Average IRI drop (in/mi)
HMA overlay, PM	Constant	–265.31	–5.241	R^2 = 0.69	109.89	56.62
	PTC[1]	68.54	8.544			
Microsurfacing[2]	Constant	–284.55	–7.68	R^2 = 0.81	114.84	58.81
	PTC[1]	72.38	9.26			
HMA Minor Structural Overlay	Constant	–315.54	–3.457	R^2 = 0.71	138.5	76.04
	PTC[1]	78.77	7.51			

[1]PTC = pre-treatment condition of the pavement (IRI in in/mi).
[2]The microsurfacing model was developed using data from all functional classes.

TABLE 6.5
Performance Jump (IRI Drop) Model—Rigid Pavement Maintenance Treatments (All Functional Classes)

Treatment Type	Model Variable	Coefficient Value	t-statistic	Model Statistics	Pre-treatment Performance (in/mi)	Average IRI drop (in/mi)
PCCP Patching[2]	Constant	–341.88	–7.141	R^2 = 0.62	113.51	49.14
	PTC[1]	79.24	5.224			
Repair PCCP & HMA Overlay[3]	Constant	–191.25	–7.12	R^2 = 0.75	105.33	52.63
	PTC[1]	49.71	4.813			

[1]PTC = pre-treatment condition of the pavement (IRI in in/mi).
[2]All sections are either NHS-Non IS or Non-NHS.
[3]All sections are Interstate (IS).

TABLE 6.6
Performance Jump Models for Flexible Pavements (SPS-3, SPS-5), LTPP Wet-Freeze Climates

SPS Code	Treatment Description	Pre-treatment Condition, PTC (IRI in in/mile)	Performance Jump (Ave IRI Drop), (in/mile)	β_0	β_1	R^2
SPS-310	Thin Overlay	91.99	19.14	−126.09	32.49	0.56
SPS-320	Slurry Seal	94.41	10.24	−106.32	25.699	0.8678
SPS-330	Crack Seal	86.52	2.85	−42.646	10.482	0.4644
SPS-350	Chip Seal	106.26	14.16	−3715.6	799	0.8211
SPS-502	2″/Min/Recycled	103.17	38.46	−450.58	107.65	0.8317
SPS-503	5″/Min/Recycled	125.96	71.98	−552.98	130.32	0.9402
SPS-504	2″/Min/Virgin	130.35	73.56	−464.85	111.75	0.9872
SPS-505	5″/Min/Virgin	115.81	58.24	−327.35	91.67	0.8901
SPS-506	2″/Max./Virgin	91.43	43.51	−406.93	100.06	0.99
SPS-507	5″/Max./Virgin	119.39	66.21	−534.39	126.5	0.99
SPS-508	5″/Max./Recycled	106.59	54.62	−372.77	92.254	0.9962
SPS-509	2″/Max./Recycled	120.08	63.95	−573.28	135.2	0.9874

where PTC = pre-treatment condition (in/mile of surface roughness).

The models developed using LTPP data confirmed that the "lower-level" treatments (thin overlay, slurry seal, crack seal, and chip seal) provided the least jumps in pavement performance. For this category of treatments, thin overlays were most effective, followed by chip seals and slurry seals. Crack sealing provided the smallest jump on pavement condition. This is consistent with expectation. Crack sealing is expected to yield little or no jump in performance but rather, a reduction in the rate of deterioration.

Compared with the "lower-level" treatments, the "higher-level" treatments provided the highest jumps in performance. However, it must be noted that this category of treatments were applied at lower levels of pavement condition. The mix type seems to play a major role in the treatment effectiveness. In certain cases, recycled overlays yielded a higher jump than virgin mixes. For a given mix type (virgin vs. recycled), minor structural overlays (5 inch) in most cases, provided much larger jumps compared with preventive (2-inch) overlays.

6.1.4 Factors Affecting the Performance Jump upon Treatments (Sensitivity Analysis)

For the models developed using Indiana data, the sensitivity of the performance jump with respect to the performance jump factors (treatment type, pre-treatment condition, and functional class) was analyzed.

Figure 6.2 presents the short-term effectiveness (IRI Drop) of various treatment types for flexible pavements. The trends of the PJ-PTC relationship were generally similar across the three functional classes. The three treatments afforded PJs ranging from 40 to 90 in/mile depending on the pre-treatment pavement condition. For Interstates, HMA overlay, PM and HMA Minor Structural Overlay provided very similar results while for microsurfacing, a more gentle PJ-PTC relationship was observed: smaller performance jumps as the pavement becomes poorer. For non-NHS Interstates, there seems to be very little difference in PJs across the functional classes. With regard to non-NHS pavements, thin HMA overlay and microsurfacing indicated similar results while HMA Minor Structural Overlay provided performance jumps that were higher (15 units higher) than that provided the other two treatments irrespective of pre-treatment pavement condition.

Figures 6.3 through 6.5 present the same results organized by treatment type and pre-treatment condition. With regard to microsurfacing, the treatment effectiveness (performance jump) shows greatest variation for non-Interstate pavements. For higher levels of pre-treatment condition (lower IRI), the performance jump provided by microsurfacing is higher than that provided by non-NHS pavements. However, for lower levels of pre-treatment condition (higher IRI), the opposite is true. With regard to HMA Minor Structural Overlay, the effectiveness of the treatment across the functional classes seems to converge at the pre-treatment condition decreases (higher IRI).

Figure 6.6 presents the short-term effectiveness (IRI Drop) of various treatment types for rigid pavements. The trends of the PJ-PTC relationship were somewhat different across the three functional classes. For higher levels of pre-treatment condition (lower IRI), PCCP overlay of PCC provides the highest performance jump, followed by repair PCC and HMA overlay, and lastly, PCC patching. For medium levels of pre-treatment condition (90–110 in/mile), PCCP overlay of PCC still provides the highest performance jump, followed by PCC patching and lastly, repair PCC and HMA overlay. For low levels of pre-treatment condition (>110 in/mile), PCC patching provides the highest performance jump followed by PCCP overlay of PCC still, and lastly, repair PCC and HMA overlay. Clearly, PCC patching is most sensitive to the pre-treatment condition of the pavement, and seems to be least suited for pavements in fair condition and most suited for those in very poor condition.

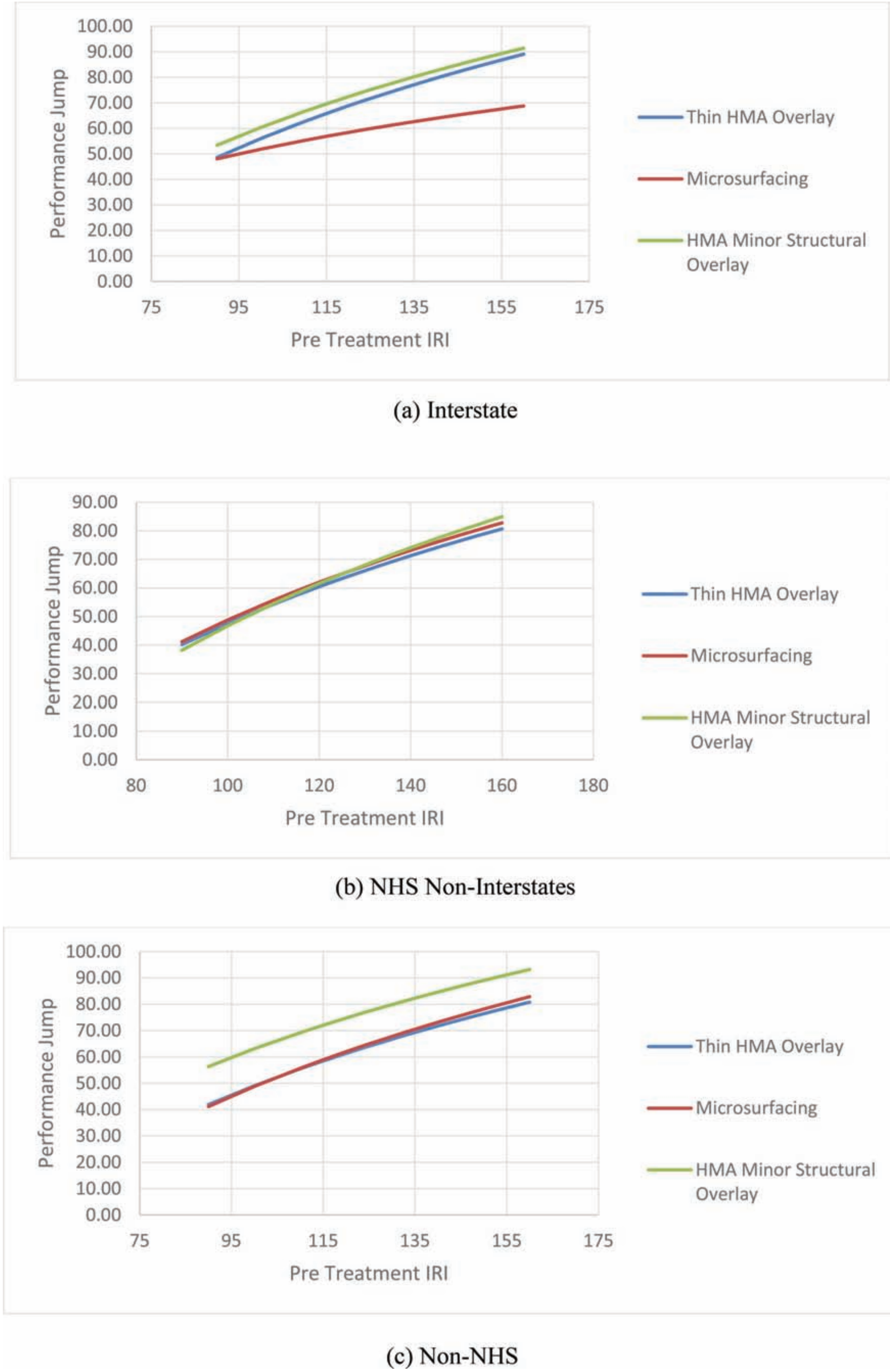
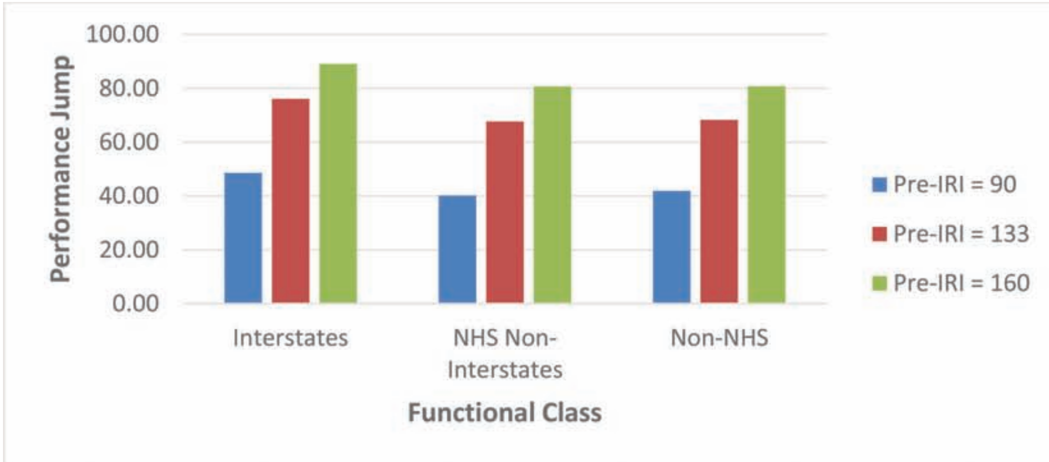
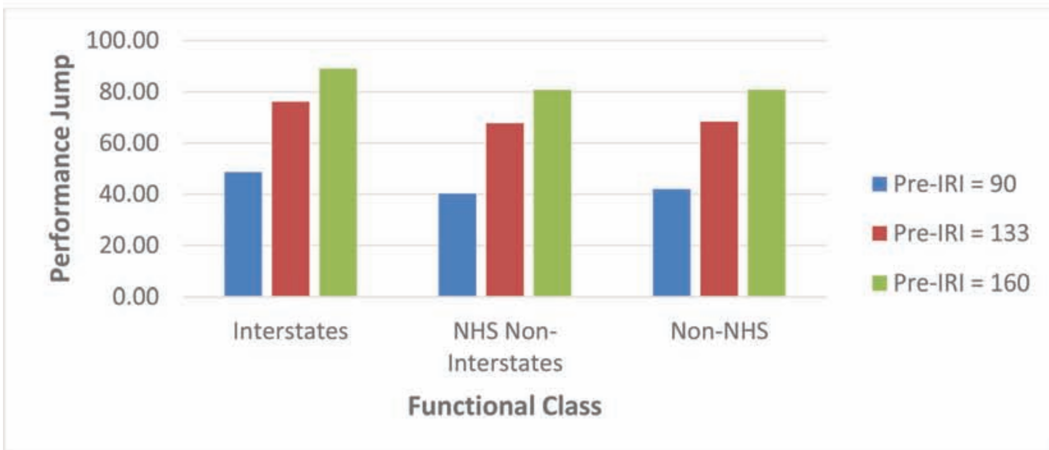


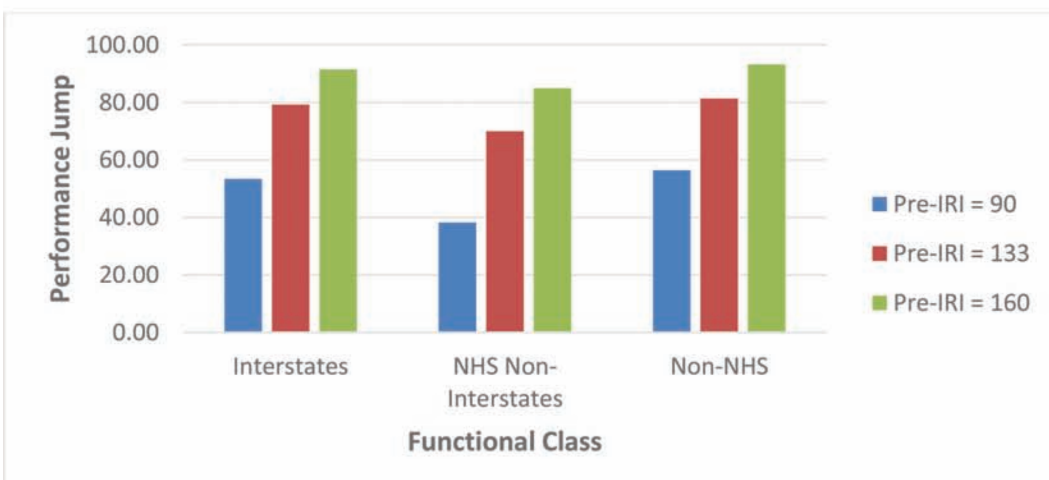
Figure 6.2 Impact (IRI drop) of different treatment types—flexible.



(a) Microsurfacing

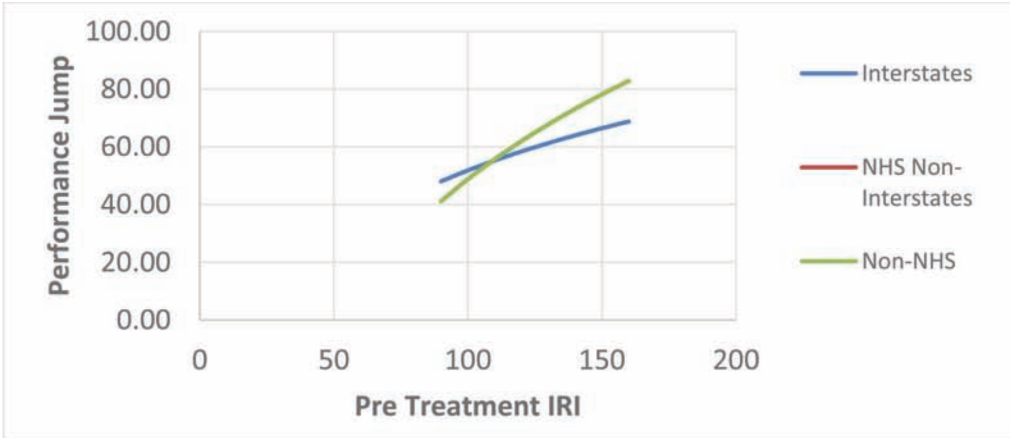


(b) Thin HMA Overlay

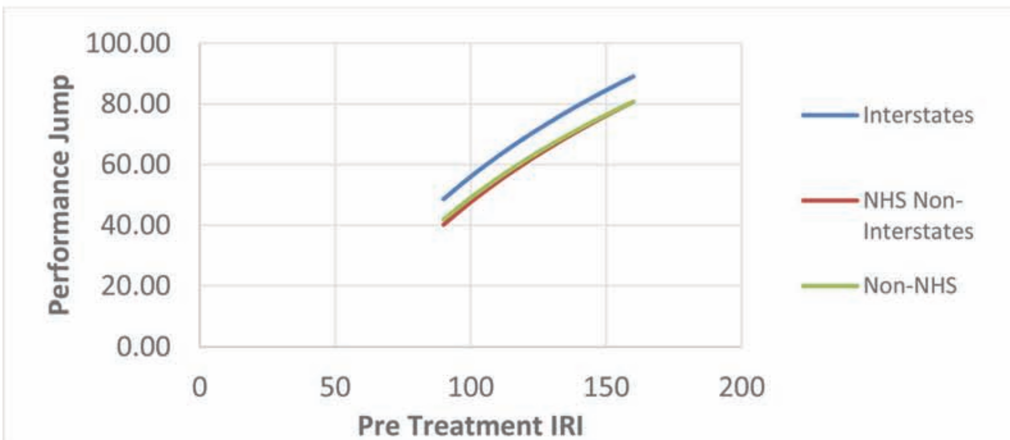


(c) HMA Minor Structural Overlay

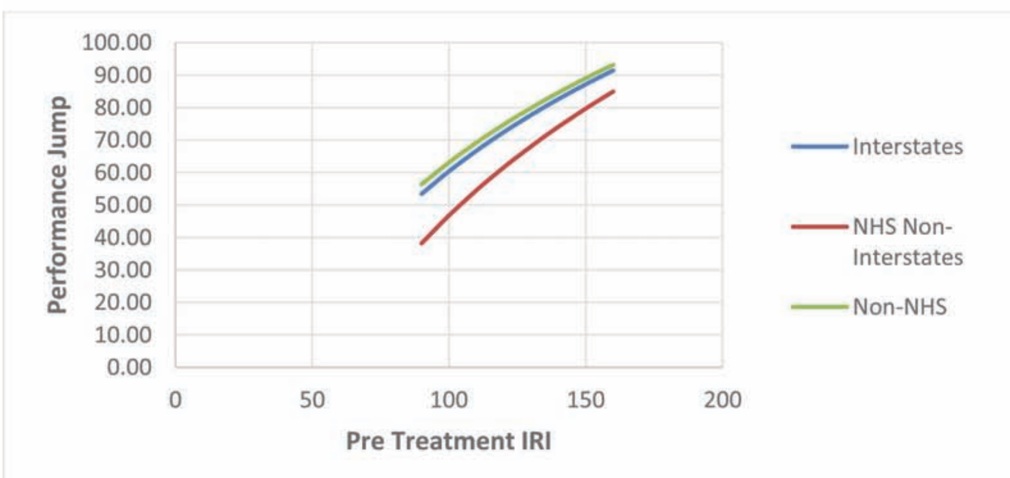
Figure 6.3 Impact (IRI drop) of functional class, for each treatment—flexible (very poor, poor, and fair pre-treatment condition).



(a) Microsurfacing

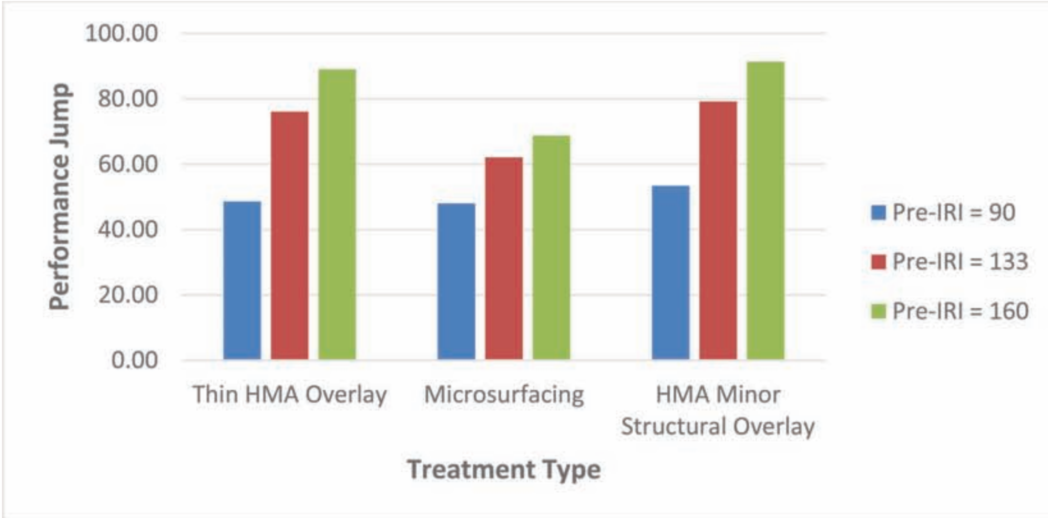


(b) Thin HMA Overlay

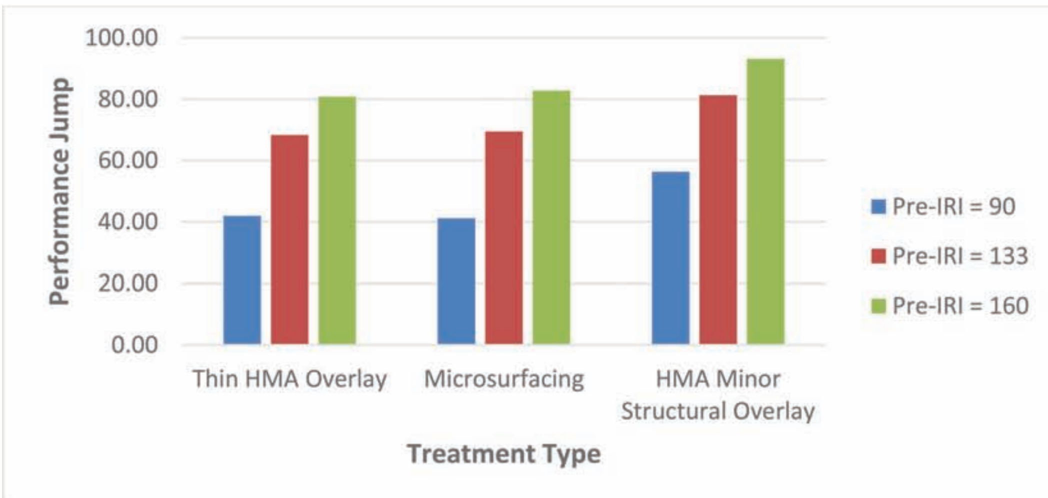


(c) HMA Minor Structural Overlay

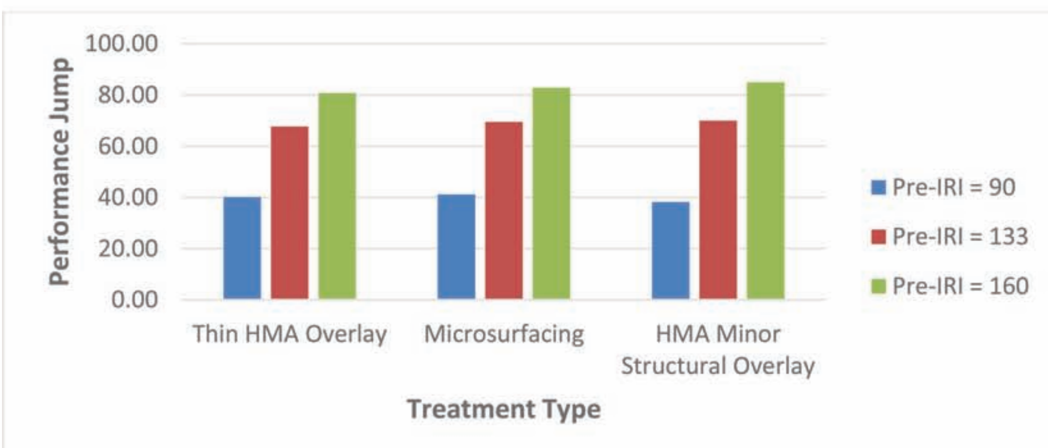
Figure 6.4 Impact (IRI drop) of functional class, for each treatment—flexible.



(a) Interstates

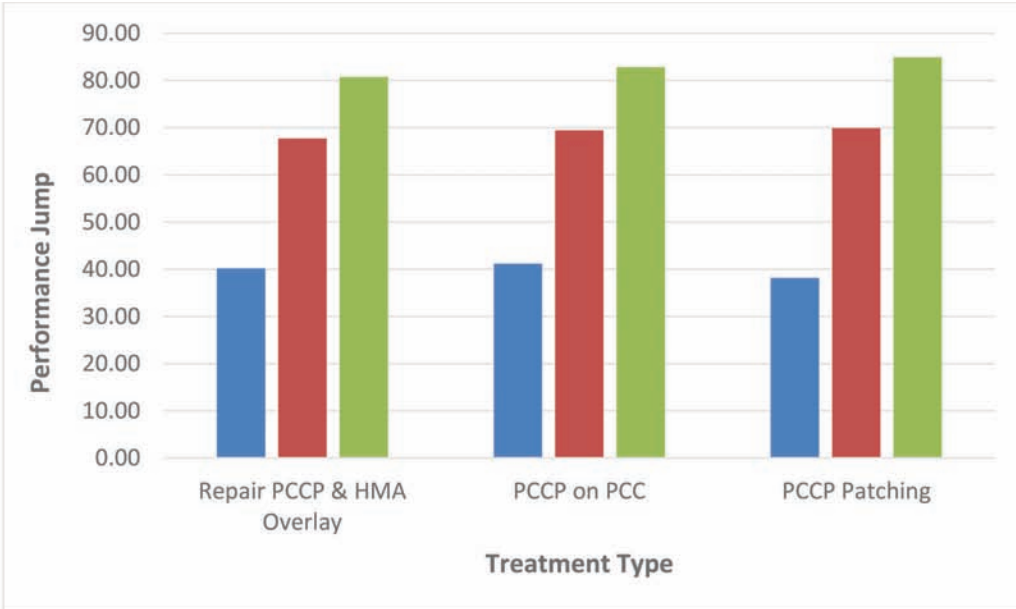


(b) Non-NHS

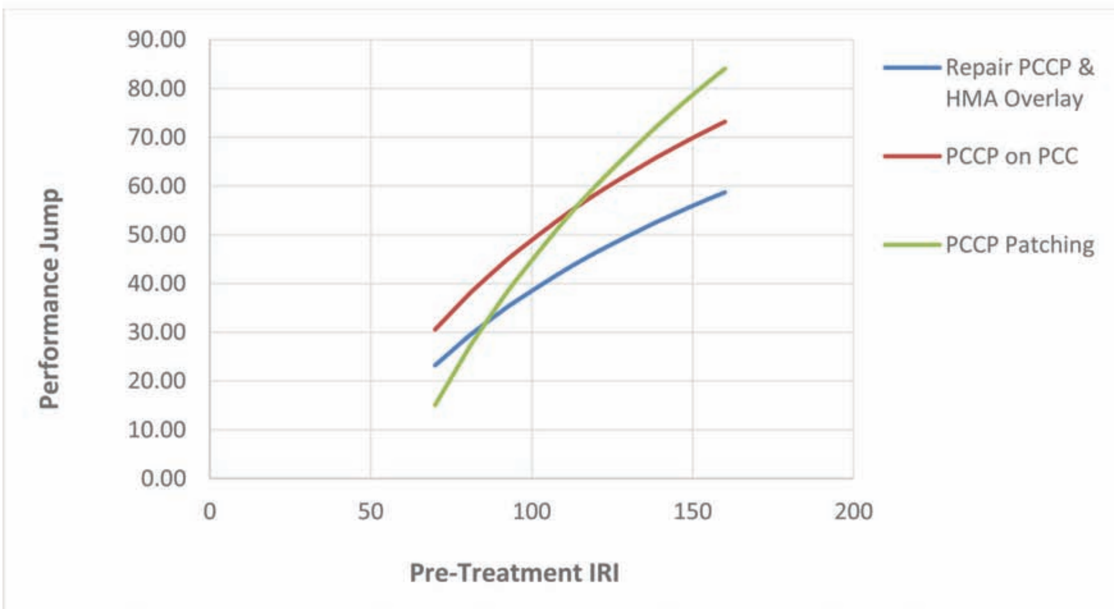


(c) NHS Non-Interstates

Figure 6.5 Impact (IRI drop) of treatment for each functional class—flexible (very poor, poor, and fair pre-treatment condition).



(a) Across treatment types (very poor, poor, and fair pre-treatment condition)



(b) Across different levels of pre-treatment condition

Figure 6.6 Impact (IRI drop) of treatment for each functional class—rigid.

6.2 Treatment Service Life

6.2.1 Deterioration Curve after the Treatment

The functional form that was found most intuitive is:

$$\text{Performance} = \text{EXP}(\alpha + \beta\text{AATA} \cdot \text{t} + \gamma\text{ANDX} \cdot \text{t})$$

Tables 6.7 through 6.9 present the model results. The model results were consistent with intuition.

6.2.2 Estimating the Treatment Life from the Deterioration Curve

When the asset condition reaches a critical threshold value (PI_{trig}), the value of t gives the treatment service life of the treatment:

$$t_{SL} = \frac{\ln\left(PI_{pre-treatment}\right) - \alpha}{\beta.\text{AATA} + \gamma.\text{ANDX}}$$

TABLE 6.7
Description of the Model Variables

Variable	Description
Performance Indicator, PI (Response variable)	Performance Indicator measured in terms of International Roughness Indicator (IRI in in/mi) or Pavement Condition Rating (PCR)
Age, t = service life in years	Time or treatment service life since the last intervention treatment
AATA·t = Accumulated Annual Truck Traffic Loadings (million-years)	The product of average annual truck traffic volume (in millions) and time (years) since the last intervention treatment, t, and it represents the accumulated average annual truck traffic experienced by the treated pavement section at a given year
ANDX·t = Accumulated Annual Freezing Index (thousands-years)	The product of average annual freeze index (in thousands) and time since the rehabilitation treatment, t, which represents the accumulated annual freeze index experienced by the treated pavement section at a given year
Constant term, α	Representing some non-dimensional characteristic of performance prediction
β and γ	Estimated coefficients for model explanatory variables: age or a surrogate of age, i.e., accumulated annual truck traffic loadings and accumulated annual freeze index

TABLE 6.8
Flexible Pavement Performance-vs.-Age Models for Each Treatment (Interstates)

Treatment Type	Model Variable	Symbol	Coefficient Value	p-value[1]	Model Stat.
Microsurfacing	Constant Term	α	4.121	0.000	R^2 = 0.53
	Accumulated Traffic Loading (AATA·t)	β	0.015	0.001	
	Accumulated Climate Effects (ANDX·t)	γ	0.153	0.000	
Thin HMA Overlay	Constant Term	α	4.169	0.001	R^2 = 0.48
	Accumulated Traffic Loading (AATA·t)	β	0.027	0.001	
	Accumulated Climate Effects (ANDX·t)	γ	0.028	0.000	
HMA Minor Structural Overlay	Constant Term	α	3.995	0.000	R^2 = 0. 61
	Accumulated Traffic Loading (AATA·t)	β	0.022	0.001	
	Accumulated Climate Effects (ANDX·t)	γ	0.092	0.000	

[1]p value implies that selected variables are statistically significant at 95% confidence level.

TABLE 6.9
Flexible Pavement Performance-vs.-Age Models for Each Treatment (NHS Non-Interstates)

Treatment Type	Model Variable	Symbol	Coefficient Value	p-value	Model Stat.
Microsurfacing	Constant Term	α	4.121	0.000	R^2 = 0.53
	Accumulated Traffic Loading (AATA·t)	β	0.015	0.001	
	Accumulated Climate Effects (ANDX·t)	γ	0.153	0.000	
Thin HMA Overlay	Constant Term	α	4.237	0.000	R^2 = 0.59
	Accumulated Traffic Loading (AATA·t)	β	0.023	0.001	
	Accumulated Climate Effects (ANDX·t)	γ	0.079	0.000	
HMA Minor Structural Overlay	Constant Term	α	4.229	0.000	R^2 = 0. 71
	Accumulated Traffic Loading (AATA·t)	β	0.014	0.000	
	Accumulated Climate Effects (ANDX·t)	γ	0.059	0.000	

This equation is used only when the post-treatment performance function is of exponential form. The average service life for each treatment can be estimated (Tables 6.10 and 6.11) based on mean values of accumulated annual truck traffic volume (AATA = 2.5 millions) and accumulated freezing index (AADX = 0.490 thousands). In addition, given the expected variation in the factor values, a range of treatment service lives can be established. Figures 6.7 and 6.8 present the life of flexible and rigid pavements treatments respectively, using data from Indiana. Thin HMA overlays seems to have the highest long-term effectiveness at Interstates and non-Interstates and least for non-Interstate NHS pavements. HMA Minor Structural Overlay seems to

TABLE 6.10
Flexible Pavement Performance-vs.-Age Models for Each Treatment (Non-NHS)

Treatment Type	Model Variable	Symbol	Coefficient Value	p-value	Model Stat.
Microsurfacing	Constant Term	α	4.121	0.000	$R^2 = 0.53$
	Accumulated Traffic Loading (AATA·t)	β	0.015	0.001	
	Accumulated Climate Effects (ANDX·t)	γ	0.153	0.000	
Thin HMA Overlay	Constant Term	α	4.160	0.000	$R^2 = 0.52$
	Accumulated Traffic Loading (AATA·t)	β	0.014	0.001	
	Accumulated Climate Effects (ANDX·t)	γ	0.101	0.000	
HMA Minor Structural Overlay	Constant Term	α	4.011	0.000	$R^2 = 0.67$
	Accumulated Traffic Loading (AATA·t)	β	0.089	0.000	
	Accumulated Climate Effects (ANDX·t)	γ	0.108	0.000	

TABLE 6.11
Rigid Pavement Performance-vs.-Age Models for Each Treatment (Interstates Only)

Treatment Type	Model Variable	Symbol	Coefficient Value	p-value	Model Stat.
[1]PCCP Patching	Constant Term	α	4.328	0.000	$R^2 = 0.71$
	Accumulated Traffic Loading (AATA·t)	β	0.018	0.000	
	Accumulated Climate Effects (ANDX·t)	γ	0.013	0.000	
[1]Repair PCCP & HMA Overlay	Constant Term	α	3.624	0.000	$R^2 = 0.\ 61$
	Accumulated Traffic Loading (AATA·t)	β	0.024	0.000	
	Accumulated Climate Effects (ANDX·t)	γ	0.048	0.001	
[1]PCCP Overlay of PCC Pavement	Constant Term	α	3.554	0.000	$R^2 = 0.57$
	Accumulated Traffic Loading (AATA·t)	β	0.015	0.000	
	Accumulated Climate Effects (ANDX·t)	γ	0.039	0.000	

TABLE 6.12
Estimated Service Lives of Flexible Pavements (SPS-3 and SPS-5), LTPP Wet-Freeze Climates

SPS Code	Treatment Description	Service Life at IRI=130	Service Life at IRI=160
SPS-310	Thin Overlay	7	9
SPS-320	Slurry Seal	7	9
SPS-330	Crack Seal	6	10
SPS-350	Chip Seal	7	9
SPS-502	2″/Min/Recycled	8	10
SPS-503	5″/Min/Recycled	7	9
SPS-504	2″/Min/Virgin	6	8
SPS-505	5″/Min/Virgin	9	>10
SPS-506	2″/Max./Virgin	9	>10
SPS-507	5″/Max./Virgin	>10	>10
SPS-508	5″/Max./Recycled	>10	>10
SPS-509	2″/Max./Recycled	>10	>10

be most long-lived at non-Interstate NHS pavements, followed closely by Interstate pavements. In addition, using the performance models developed for each of the LTPP treatments and performance thresholds of 130 and 160 in/mile, the service life of each treatment was estimated. Table 6.12 presents the estimated service lives of flexible pavements in LTPP wet freeze climates. The service life of the treatments are generally consistent with those in the published literature (Geoffroy, 1996; Hall et al., 2001; Irfan, Khrushid, & Labi, 2009; Irfan, Khurshid, Labi, & Flora, 2009; Peshkin, 2004).

6.3 Performance Jump Cost-Effectiveness of the Pavement Surface Treatments

Figures 6.9 and 6.10 present the cost-effectiveness of the flexible and rigid surface treatments, respectively. This is done using two different measures of cost-effectiveness. Type I is the change in the pavement rating per treatment intensity ($/m^2). For Type I, a treatment that yields a bigger change in pavement rating for a given intensity, is considered more cost effective. Type II is the treatment intensity ($/m^2) that is needed to yield a given change in the pavement rating per treatment intensity. For Type II, a treatment for which a smaller intensity is needed to yield a unit change in pavement condition is considered more cost effective. Type II is the reciprocal of Type I. Both charts in the figure suggest that from the perspective of pavement performance jump, microsurfacing is the most cost-effective treatment for flexible pavements, and PCC patching is the most cost-effective for rigid pavements.

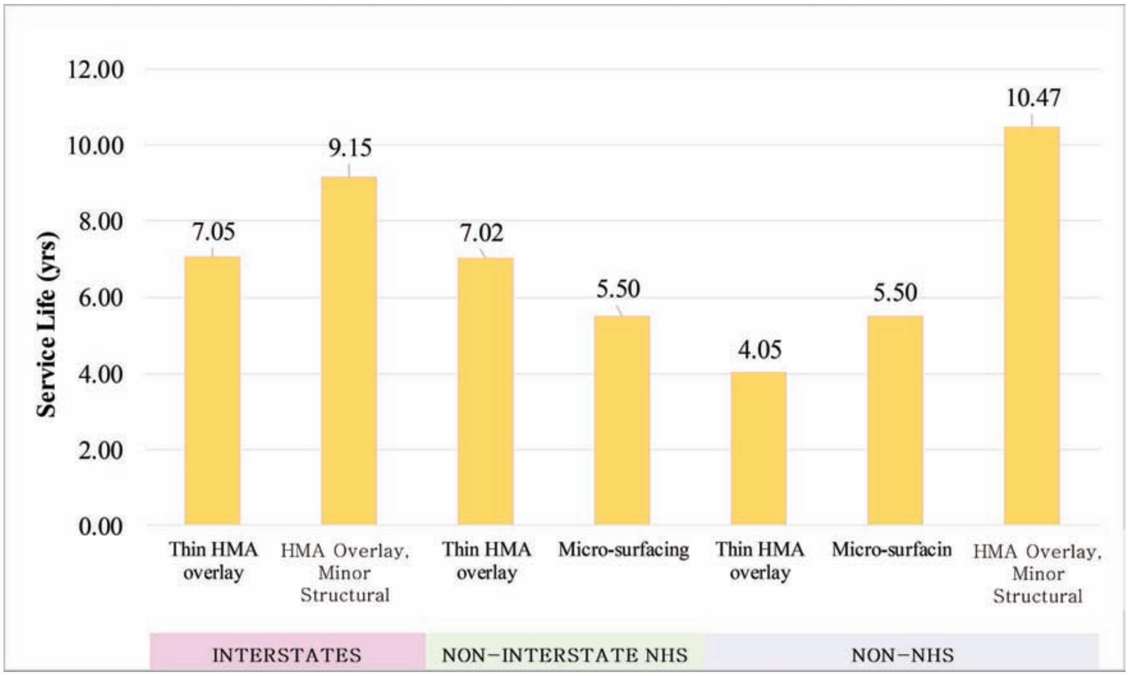


Figure 6.7 Estimated treatment life, flexible pavements—Indiana data.

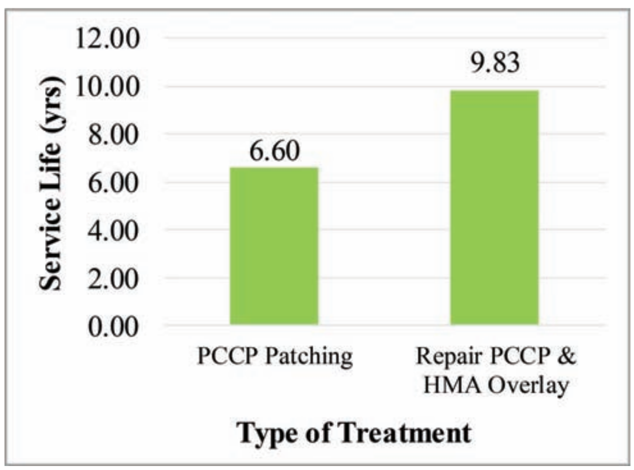


Figure 6.8 Estimated treatment life, rigid Interstate pavements—Indiana data.

Similar to the case for bridge treatments, two points must be borne in mind:

- The surface defects that warrant these treatments may be different, therefore it may not be a prudent exercise to make a direct comparison of their relative cost-effectiveness.
- The cost effectiveness computations are based on a short-term measure of effectiveness (performance jump). It may be better to compare them based on their cost-effectiveness in the longer term, for example, the treatment life (years) per treatment intensity ($\$/m^2$).

6.4 Service Life Cost-Effectiveness of the Pavement Surface Treatments

Figures 6.11 and 6.12 present the service life cost-effectiveness of the flexible and rigid surface treatments, respectively. Similar to the performance jump cost effectiveness, this is done using two different measures of cost-effectiveness. Type I is the treatment life per treatment intensity ($\$/m^2$). For Type I, a treatment that yields a longer service life for a given intensity, is considered more cost effective. Type II is the treatment

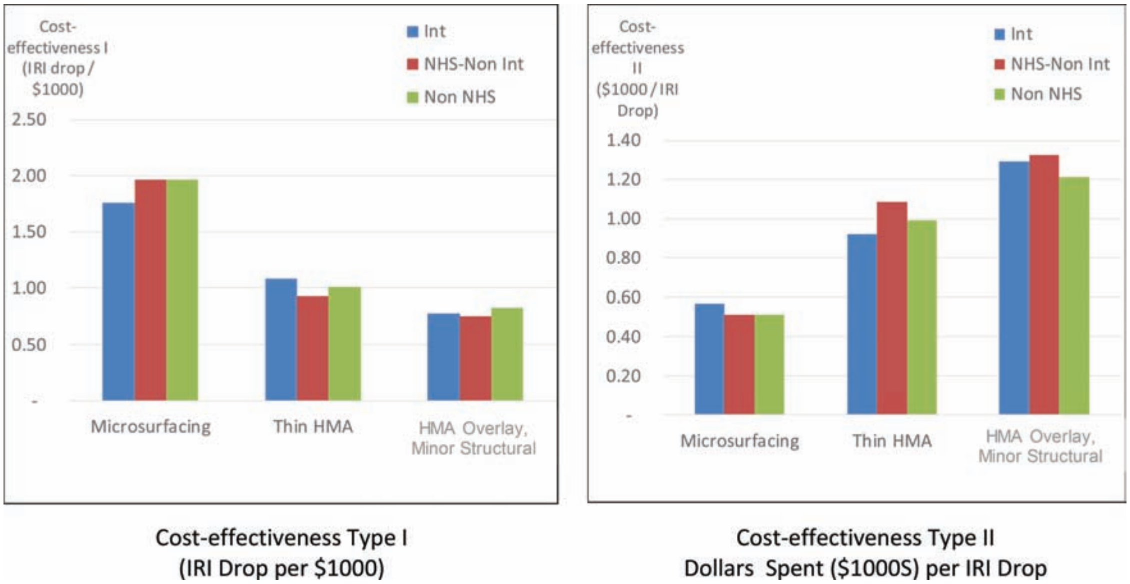


Figure 6.9 Cost-effectiveness of flexible pavement treatments.

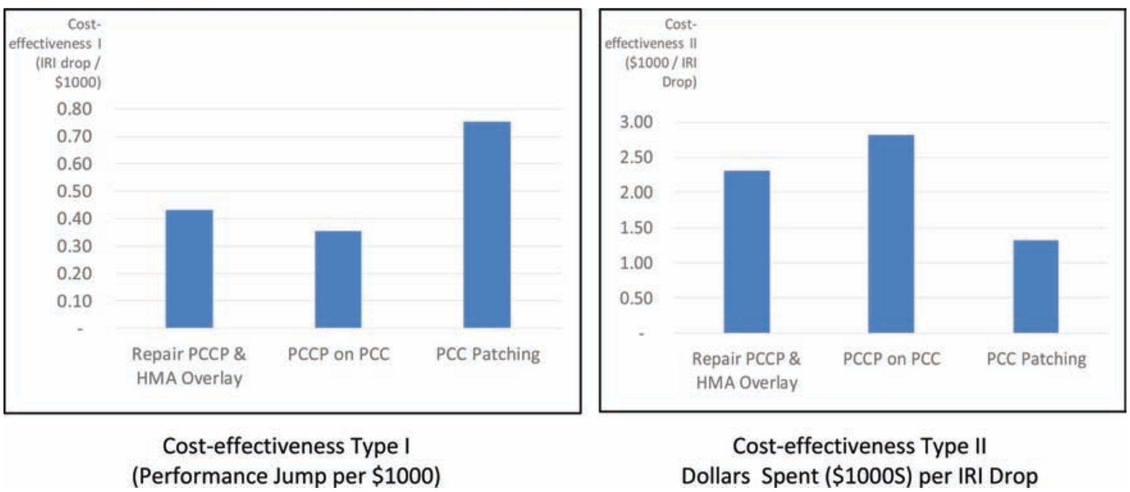


Figure 6.10 Cost-effectiveness of rigid pavement treatments.

intensity ($/m^2) that is needed to yield a unit time (year) per treatment intensity. For Type II, a treatment for which a smaller intensity is needed to yield a unit service life is considered more cost effective. Type II is the reciprocal of Type I. Both charts in the figure suggest that from the perspective of pavement service life, microsurfacing is the most cost-effective treatment for flexible pavements, and PCC patching is the most cost-effective for rigid pavements. Again, it should be borne in mind that the surface defects that warrant these treatments may be different, therefore it may not be a prudent exercise to make a direct comparison of their relative cost-effectiveness.

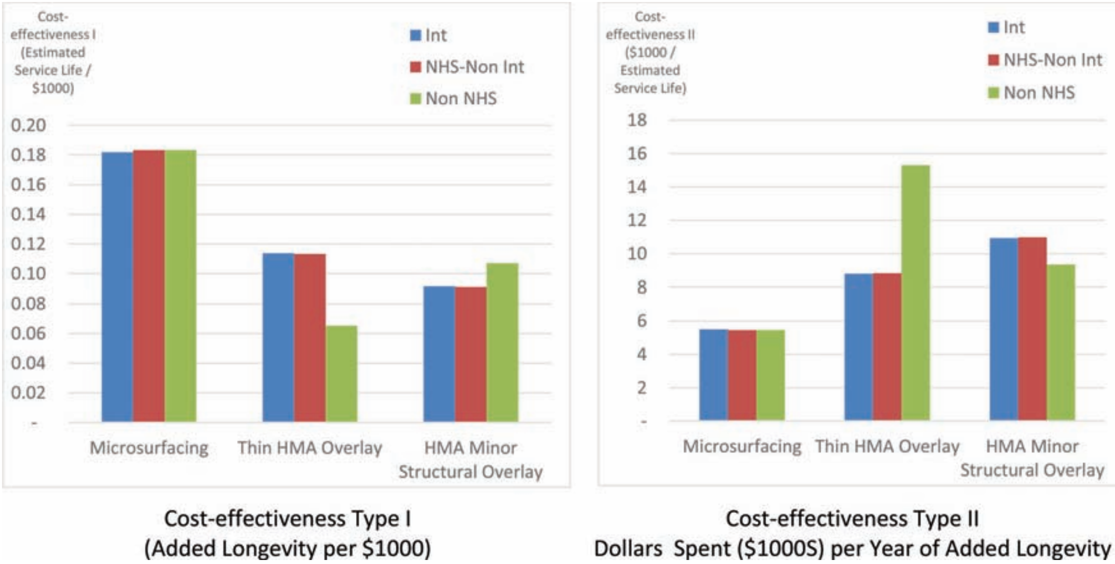


Figure 6.11 Service life cost-effectiveness of flexible pavement treatments.

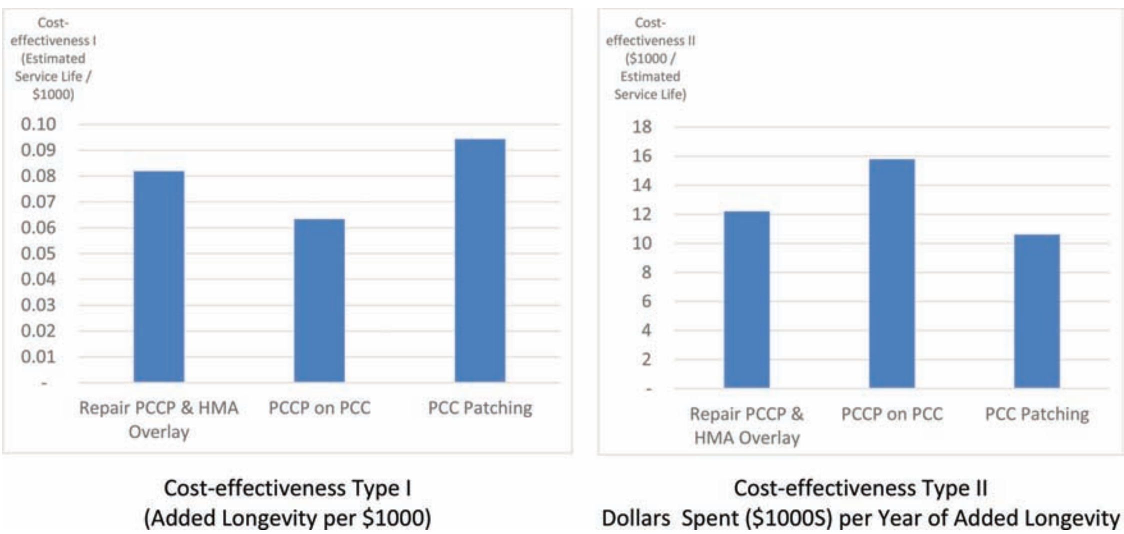


Figure 6.12 Service life cost-effectiveness of rigid pavement treatments.

7. CONCLUDING REMARKS

7.1 Summary and Conclusions

Assessments of the efficacy of agency interventions is important for continuous performance monitoring and feedback, and for evaluation and comparison of alternative interventions. For example, by how much is bridge deck condition rating enhanced due to deck overlay? What is the jump in pavement condition when it receives a thin HMA overlay? As a first step in answering questions such as these, the infrastructure agency establishes performance indicators that serve as a basis for making informed judgment about the efficacy of their interventions. Any measure of effectiveness (for example, the instantaneous improvement in the infrastructure condition just after the intervention jump in performance, sudden reduction in the deterioration rate, are expressed in terms of the performance indicators.

This report presents a set of numbers or formulae that represent the levels of impact of each treatment typically applied to INDOT's assets. These impacts are expressed in terms of the requisite performance indicators. These are in the form of:

1. Average (mean) impact level of each treatment type under consideration.
2. The other statistical parameters of the impact level of each treatment type, for each asset type (pavements and bridges): minimum impact, maximum impact, range, and standard deviation.
3. A statistical model (for each asset type) that predicts the impact level of each treatment type as a function of initial asset condition, treatment intensity, and other variables.
4. Sensitivity charts.
5. Cost-effectiveness values.

INDOT's asset managers seek to quantify the impact of each treatment on asset rating for a variety of reasons: (i) to generate requisite input data for use in INDOT's Pavement Management System and Bridge Management System software packages because these packages require the user to input the new value of asset condition just after each of the standard treatments is applied, (ii) to make judgments (for decision support purposes) of the effectiveness of specific past or future (proposed) treatments in terms of increased rating, and ultimately in terms of asset life extension, and (iii) to compare the effectiveness of alternative treatments that differ by treatment type, material, procedure, or work source (work done in-house versus work done by contract).

The developed numbers or formula for the treatment effectiveness and cost-effectiveness are useful for INDOT in selecting and defending the choice of pavement and bridge treatments. Further, these results can serve as default reset values for purposes of "what-if" analysis in INDOT's PMS and BMS software packages; for example, what will be the predicted post-treatment rating in response to a hypothetical future application of a specific MR&R treatment. That way, the post-treatment level of performance can be predicted. Therefore, implementation is expected to occur in the use of INDOT's asset decision making and programming software packages including DTIMS. Also, because the pavement analysis in MEPDG includes deterioration curves (and simulation thereof) under different damaging effects and maintenance effects, the study results can be used in pavement analysis.

Quantitative statements of the maintenance effects, or the MOEs (expressed in terms of a performance indicator) helps in in assessing prospective competing treatments for an individual asset. PIs help reflect the concerns of the infrastructure stakeholders which include the infrastructure owner or operator, regular users of the infrastructure, and communities located proximal to the infrastructure. Typically, the most desirable treatment is that which provides the optimal value of the MOE. The use of PI-based MOEs is particularly prudent in the present environment that is characterized by the need for transparency, high user expectations, rapidly-aging infrastructure, and yet, funding limitations or uncertainty. Using PI-based MOEs, the agency can make investment decisions in a more pragmatic, defensible, and transparent manner.

7.2 Contribution to the State-of-the-Art and State of Practice

The study framework for optimizing treatments over the life-cycle of pavements is based on established economic principles. Such a comprehensive optimization tool would considerably improve overall investment decisions over the life-cycle of different pavement families (surfaces and functional classes). The post-treatment performance trends documented in this study can be used to predict or estimate the impacts of changing climate or traffic loading levels on the service lives of the MR&R treatments. This report thus provided input data using which agencies may update their current project-level MR&R schedules that had been largely based on expert opinion and historical practice. Optimal MR&R schedules are useful for life-cycle cost analysis of alternative pavement M&R strategies, highway needs assessment studies and pavement management in general. The study confirmed the findings of previous studies that the pre-treatment pavement performance, treatment type, pavement family and/ or functional classes were major significant predictors of the performance jump upon treatment: treatment application on a poorly performing pavement yields a greater performance jump. In this study, this phenomenon was observed for all the treatments investigated.

One of the principal tenets of highway asset management is the acquisition of full and reliable knowledge, at any time, of the state of the highway assets and their rate of performance loss (Dawson, Walsh, Purnell, & Rogers, 2014; Haas et al., 1994; Shehu, Elma, Endut, & Holt, 2014; Taggart, Tachtsi, Lugg, & Davies, 2015). The framework presented in this report can help agencies to increase their awareness of the effectiveness and cost-effectiveness of their maintenance treatments. Also, with treatment cost-effective models, agencies are better equipped to make more defensible prescriptions of treatments for pavement and bridge maintenance (Taggart et al., 2015; Wang, 2013; Wu, Groeger, Simpson, & Hicks, 2010).

The practice of asset management often involves the use of processes and concepts that are intended for purposes of decision support. The models and cost-effectiveness charts developed in this report are not intended to serve as a cure all for investment questions regarding bridge and pavement surface treatment selection. Rather, the analysis results are meant to help the asset manager to make a balanced and rational decision-making using the models herein, duly tempered with expert knowledge about the site in question. At pointed out in a recent JTRP report, making the best decision will often require sound engineering judgment, candid consideration of project constraints, due consideration of a project's local environment, administrative practices and culture at the area of its jurisdiction, and flexibility.

7.3 Future Work

The treatment-specific post-treatment effects, performance jumps, cost and project (workzone) duration models developed in the study could be improved using more detailed data items such as pavement layer thicknesses, subgrade quality, and design and construction features to take cognizance of variation of attributes within pavement families. The effect of changing the performance indicator (for example, using PCR or RUT instead of IRI), on the optimal solution, could be investigated. Further, future work could incorporate probabilistic elements directly into the optimization procedure to yield robust solutions.

Highway asset owners continue to maintain management databases for their pavements and bridges (Moloney, McKenna, Fitzgibbon, & McKeogh, 2017). As such, data on the pre- and post-treatment performance of bridges and pavements are becoming increasingly available at several other agencies. These agencies use different treatments and performance indicators, and have different ways of categorizing their pavements and road classes (Adey, Garcia-Soto, & Senn, 2017; Dong & Huang, 2012; Lytton, 1987). This report's framework can be used to assess the cost-effectiveness of any treatment type, performance indicator, pavement surface material type, or road class.

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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.

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The recommended citation for this publication is:

Saeed, T. U., Qiao, Y., Chen, S., Alqadhi, S., Zhang, Z., Labi, S., & Sinha, K. C. (2017). *Effects of bridge surface and pavement maintenance activities on asset rating* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2017/19). West Lafayette, IN: Purdue University. https://doi.org/10.5703/1288284316573