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INDIANA DEPARTMENT OF TRANSPORTATION
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Strategic Scheduling of Infrastructure Repair and Maintenance

Volume 2

Developing Condition-Based Triggers for Bridge Maintenance and Rehabilitation Treatments

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16. Abstract

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

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

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

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EXECUTIVE SUMMARY

STRATEGIC SCHEDULING OF INFRASTRUCTURE REPAIR AND MAINTENANCE: VOLUME 2— DEVELOPING CONDITION-BASED TRIGGERS FOR BRIDGE MAINTENANCE AND REHABILITATION TREATMENTS

Introduction

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

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

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

Findings

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

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

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

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

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

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

Implementation

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

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

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1. INTRODUCTION

1.1 Background

Bridges are one of the most visible and important components of a transportation system. By providing crossings at critical locations, bridges maintain network continuity, traversing natural and manmade features that otherwise would add significant travel time and cost (Markow & Hyman, 2009). However, bridges in the U.S. highway system suffer from deficiency in terms of structural condition and functionality. According to the National Bridge Inventory (NBI) data of 2014 (FHWA, 2014), approximately 24% of the bridges in the U.S. are rated as either structurally deficient (SD) or functional obsolete (FO). Although the percentage of SD and FO bridges has been declining slowly over the last decade, owing to the persistent efforts of states and cities to prioritize bridge repairs and replacements, there is still much work to be done (ASCE, 2013). The Federal Highway Administration (FHWA) estimates that, to eliminate the nation's bridge deficient backlog by 2028, agencies would need to invest $20.5 billion annually, while only $12.8 billion is being spent currently (FHWA, 2010).

Given such circumstances, public agencies have been seeking to maintain, rehabilitate, and reconstruct their bridges both effectively and efficiently. Engineers have long relied on their experience and subjective judgment to decide when to preserve the bridge and what treatments to apply. According to Markow and Hyman (2009), not until the 1980s did the development of bridge management systems (BMS) begin in the United States.

As indicated in the FHWA bridge preservation guide (FHWA, 2011), the objective of a good bridge preservation program is to employ cost-effective strategies and actions to maximize the useful life of bridges. Specifically, agencies try to extend the service life of bridges as long as possible, while maintaining the various structural elements of the bridges above certain levels to assure the safety of the structures and the ride quality of road users. Agencies want to achieve these goals at minimum cost, both the costs for repair or construction work, and the costs to road users. User costs include the incremental vehicle operating costs (VOC) due to increased roughness of the bridge deck surface and travel time costs due to work zone delay. Thus, how to find the optimal timing or thresholds for implementing treatments to gain the "biggest bang for the buck" becomes the critical question facing the agencies.

According to an NCHRP survey (Krauss, Lawler, & Steiner, 2009) of forty-one U.S. states, four Canadian provinces, and Puerto Rico, only twenty-two agencies (48%) reported using specific guidelines or procedures when making decisions on deck treatment selection. Of those, only ten agencies (22%) had written procedures or decision trees. Two agencies were in the process of developing decision trees. The rest used only visual evaluation inspection, sometimes with supplemental testing, and conducted internal discussions to decide the appropriate rehabilitation method/process. The survey results also revealed that the guidelines or thresholds developed by different states could vary significantly.

Research studies have been making efforts aimed at establishing optimal asset management strategies, either for bridges or for pavements. However, a common problem with a lot of research studies is that their theoretical frameworks are too complicated to be adopted by agencies in practice, whereas their case studies are too simply designed to fully reflect real situations. In addition, most studies considered only time-based strategies rather than condition-based strategies.

1.2 Problem Statement

There exists a trade-off between the condition (or service) level of the bridges that agencies want to maintain, and the budget that agencies have to spend on the maintenance work. The life-cycle costs are directly related to the frequency and intensity of the treatments. A preservation strategy can be characterized by two extreme scenarios: a parsimonious scenario, and an unrestrained scenario (Khurshid, 2010; Pasupathy, Labi, & Sinha, 2007). The parsimonious scenario is characterized by long periods between treatments and thus a lower frequency of treatments, which is likely to result in a lower life-cycle cost, but a shorter service life and poorer condition of bridge components. In contrast, the unrestrained scenario is characterized by shorter periods between treatments, leading to a higher frequency of treatments. The unrestrained scenario would probably extend the service life of bridge and provide road users a better surface quality, but its drawback is higher agency costs.

Therefore, it can be hypothesized that, for each bridge treatment type, there exists a relationship between the level of bridge element condition at the time of treatment and the overall benefits (cost-effectiveness) associated with that level. Such a relationship, if adequately captured, could help pinpoint the optimal timing of the treatment, in other words, the condition level at which the treatment should be applied.

Two types of preservation strategies (or policies) have been adopted by agencies—time-based and condition-based. A time-based strategy is characterized by treatments that are implemented at fixed time intervals during an asset's service life. A condition-based strategy is characterized by the treatments that are triggered only if the element condition reaches a certain threshold.

The condition-based strategy makes more sense in practice, because under a time-based strategy, it is possible that, at the scheduled time threshold, a bridge element is still in good condition without the need to be repaired, or a bridge element has already reached an unsatisfactory condition, in which the ride quality (or even safety) to road users has been adversely affected.

Given the fact that few agencies have well-developed performance thresholds for bridge treatment selection and that these thresholds are mostly determined either by expert opinions of experienced bridge managers and engineers or by historical data, there is a need to establish more rigorous treatment thresholds based on analytical approaches including statistical modeling and optimization algorithms.

1.3 Study Objective and Scope

The major tasks of the current study are:

1. Developing appropriate condition-based thresholds for the commonly used bridge maintenance and rehabilitation (M&R) treatment types in Indiana.
   This task will develop a framework to assess the impact of different condition-based thresholds, and then identify the most appropriate condition-based thresholds, for each standard bridge M&R treatment. The framework will be applied to historical data to establish the appropriate thresholds for applying the standard bridge rehabilitation and preventive maintenance treatments that INDOT typically uses. This will be done for each bridge family.
2. Establishing appropriate life-cycle condition-based bridge M&R strategy.
   This task, which will be based on the results of Task 1, will develop long-term condition-based schedules for bridge M&R treatments. Specifically, for each bridge family, the appropriate treatment types and condition-based timings will be established over a given analysis period that reflects the life cycle of the bridges.

In addition to the two major tasks above, there are some other affiliated tasks of interest that could contribute to bridging the gap in the existing literature. They are listed as follows:

1. Measuring the consequences of non-optimal timing for individual treatments.
   On the basis of developed optimal timing, the consequences of deferred or premature treatment will be assessed.
2. Investigating possible differences between post-treatment and pre-treatment performance trends.
   Bridge deck overlay, for example, can improve the deck condition to a certain previous level. But will the performance trend (deterioration rate) after the overlay be similar to that before the overlay? The study intends to determine whether there is a statistically significant difference.
3. Developing performance jump models due to individual bridge treatments.
   This is an important intermediate procedure for the final cost-effectiveness analysis. However, no such models have been found in existing literature.

In terms of scope, the current study conducts analysis only on the bridges located on the state highway system that are operated and maintained by INDOT; bridges on local routes are excluded from the current study. Bridges are herein defined as road structures exceeding 20 feet in length that cross other features (rivers, rails, other roads). In addition, the current study will focus on the project level only (i.e., individual bridges). Budget constraints are not considered in the analysis, because the study aims at establishing the optimal thresholds in a general sense, instead of a constrained optimum.

1.4 Organization of This Volume

In this volume, Chapter 1 introduces the background, motivation, objectives and scope of the current study. Chapter 2 presents a review of the literature regarding the state of practices on developing bridge treatment thresholds by public agencies and academic studies. Chapter 3 describes the methodology framework for the current study, including data collection, deterioration models, performance jump models, cost models, and optimization formulations. Chapter 4 presents the life-cycle cost analysis results and proposes appropriate triggers and long-term M&R strategies. Chapter 5 summarizes the study results and concludes this volume.

2. LITERATURE REVIEW

To clarify the various aspects and issues associated with bridge maintenance and repair (M&R) scheduling, a review of past research was carried out. This chapter presents the significant outcomes from these studies in order to shed more light on the existing methodologies used for bridge maintenance and repair scheduling. This chapter also serves as a basis for identifying and evaluating the drawbacks of the existing methodologies and how the proposed methods can help to establish a more systematic and analytic decision process, leading to more appropriate M&R scheduling.

2.1 Typical Bridge Maintenance and Repair Types in Indiana

In the INDOT bridge and culvert preservation initiative (BCPI) policy statement (INDOT, 2014), bridge M&R treatments are categorized as preventive maintenance and corrective maintenance. *Preventive maintenance* in the BCPI is defined 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.” This is more like “routine maintenance” in the typical sense, because they are cyclical activities. *Corrective maintenance* in the BCPI is defined as “specific activities that are condition driven, intended to correct defects and prevent or reduce deterioration.” These activities may be more often referred to as “rehabilitation,” as in the Indiana Design Manual (INDOT, 2013). Besides, some of the “corrective maintenance” activities in the BCPI are treated as preventive maintenance in the Indiana Bridge Management System (IBMS) manual (Sinha, Labi, McCullouch, Bhargava, & Bai, 2009). However, although there is some inconsistency in categorization nomenclature in the different sources, such inconsistency does not affect the analysis, because the current study analyzes different M&R treatments specifically instead of “groups” of work types.

The typical bridge M&R treatments implemented in Indiana are summarized in Tables 2.1 and 2.2, based on the BCPI and the Indiana Design Manual, respectively.

TABLE 2.1
Preventive and Corrective Treatment Candidates (INDOT, 2014)

Preventive Treatments	Cleaning/Flushing Bridge Decks Substructure /Superstructure Washing Cleaning Deck Drains Cleaning/Lubricating Bearings Cleaning Joints Deck Sealing
Corrective Treatments	Deck Patching (shallow/deep) Approach Slab Repair/Replacement Joint Repair/Replacement Mudwall Patching Thin Deck Overlay (e.g. Polymeric Overlay) Spot Coating Substructure Patching/Sealing Superstructure Crack Mitigation Erosion Mitigation Debris Removal/Channel Cleaning Latex Modified Concrete (LMC) Overlay Slopewall Repair/Replacement Bearing Repair/Replacement Scour Mitigation Deck Crack Sealing

2.2 State of Practice of Condition-Based Scheduling for Bridge M&R Treatments

As indicated in Chapter 1, the current study focuses on condition-based scheduling rather than time-based scheduling. Time-based scheduling may be more useful in terms of budget planning and long-term M&R program, but when it comes to implementation of treatments, condition-based decision making makes more sense, because agencies would not repair a bridge that is still in good condition just because it reaches the pre-defined time for repair. In the long term, significant uncertainties from various causes will be involved, so that the pre-defined time-based strategies may not optimal. Condition-based strategies, in contrast, are less sensitive to uncertainties, because agencies can always wait until the appropriate condition thresholds before implementing the proper treatments.

Information on condition thresholds for bridge treatments was mostly found in technical reports prepared by or for public agencies, rather than in journal papers. Of those found in reports, most of them were based on expert opinions that came from surveys of bridge engineers and experts. Significant inconsistencies were found in different sources. Some important studies and information found for Indiana and other U.S. states are summarized in the following sections.

2.2.1 Practices of the State of Indiana

Indiana started to develop its own Indiana Bridge Management System (IBMS) in the 1980s. Gion et al. (1992) published the first edition of the user's manual for the implementation of the IBMS, which was based on a series of previous research reports by the Joint Transportation Research Project (JTRP) at Purdue University (Jiang & Sinha, 1989a; Saito & Sinha, 1989a, 1989b; Sinha et al., 1988). A decision tree module named DTREE was introduced and developed. The path through the tree was determined by variables such as Inventory Rating (IR), Deck Geometry (DG), and Vertical Clearance (VC), and trigger values controlled the flow of decisions through the tree. The latest version of the IBMS Manual, published in 2009 (Sinha et al., 2009), updated some modules in IBMS, and the DTREE was further expanded by incorporating preventive maintenance activities. Part of the updated DTREE is presented in Figure 2.1 as an illustration. The complete DTREE is presented in the Appendix E of this volume.

In the updated IBMS (Sinha et al., 2009), three new performance measures were added to DTREE for triggering preventive maintenance activities. The new performance measures are: deck patching (DP), which is expressed as a percentage representing the proportion of the sum of area that needs patching and already patched to the total deck area, wearing surface condition (WS), and joint condition (JC). WS and JC are based on a 0 (worst condition) to 9 (best condition) rating. These triggers were based on the expert opinions provided by INDOT bridge engineers. They may not necessarily represent the most appropriate thresholds, because they were mostly the results of experience-based judgment, which did not necessarily lead to the highest cost-effectiveness. Specifically, the developed performance thresholds are as follows (Sinha et al., 2009):

- If ($WS > 5$): Check joint condition (JC)
- If ($JC > 5$): Check for deck patching (DP)
- If ($JC \leq 5$): Replace joint

For NHS bridges:

- If $2 \leq DP \leq 10\%$: Patching
- If $10\% < DP < 30\%$: Deck Overlay
- If $DP \geq 30\%$: Deck Replacement

For non-NHS bridges:

- If $2 \leq DP \leq 15\%$: Patching
- If $15\% < DP < 30\%$: Deck Overlay
- If $DP \geq 30\%$: Deck Replacement

In the policy statement for bridge and culvert preservation initiative (BCPI) by INDOT (2014), the commonly-used bridge preventive maintenance and corrective maintenance treatments in Indiana were listed, and the condition-based candidate criteria for selection of treatments were established (presented in Tables 2.3 and 2.4). However, these candidate criteria should be regarded as the lower bounds or upper bounds of the performance measures, meaning that they are not necessarily the optimal treatment thresholds.

In the current Indiana Design Manual (INDOT, 2013), thresholds and effects of some of the bridge rehabilitation treatments are briefly described in the bridge rehabilitation chapter. It is noted that the thresholds for the LMC

TABLE 2.2
Bridge Deck, Superstructure, and Substructure Rehabilitation Techniques (INDOT, 2013)

Rehabilitation	Code	Technique
Deck Rehabilitation	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-7	Upgrade Bridge Railings
	BD-8	Upgrade Guardrail-to-Bridge-Railing Transitions
	BD-9	Joint Elimination
	BD-10	Concrete Sealants
	BD-11	Corrosion Inhibitors
	BD-12	Prefabricated Bridge Deck
Steel Superstructure Rehabilitation	SS-1	Grinding
	SS-2	Peening
	SS-3	Gas Tungsten Arc Remelt
	SS-4	Drilled Holes
	SS-5	Bolted Splices
	SS-6	Welding
	SS-7	Addition of Cover Plates — Strengthening
	SS-8	Introduction of Composite Action — Strengthening
	SS-9	Addition of New Stringers — Strengthening
	SS-10	Bearings
	SS-11	Post-Tensioning — Strengthening
	SS-12	Heat-Straightening
Concrete Superstructure Rehabilitation	CS-1	Remove or Replace Deteriorated Concrete
	CS-2	Pneumatically-Placed Mortar
	CS-3	Epoxy Injection
	CS-4	Low-Viscosity Sealant
	CS-5	Grouting
	CS-6	Concrete-Bridge-Seat Extension
	CS-7	Beam Strengthening: Post-Tensioning Tendons
Substructure or Foundation Rehabilitation	SF-1	Remove or Replace Deteriorated Concrete
	SF-2	Enlarge Footing
	SF-3	Riprap
	SF-4	Wingwall Repair
	SF-5	Deadman Anchorage
	SF-6	Drainage Improvements
	SF-7	Grout-Bag Underpinning
	SF-8	Pile-Section-Loss Repair
	SF-9	Jacketing Piers and Piles

overlay are different from what is stated in the IBMS manual. INDOT is currently updating the Indiana Design Manual to assure the consistency.

- *Patching:* The area to be patched is defined by sounding. Deck patching alone is usually only moderately successful, extending the service life of the deck from one to three years.
- *Latex-Modified Concrete (LMC) overlay:* Latex modified bridge-deck overlays have been successfully used by INDOT since the 1970s. LMC overlay is typically applied in conjunction with deck patching. For an LMC overlay project to qualify as a candidate for preventative maintenance, the deck, superstructure, and substructure must each 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 typically protects the bridge deck for 15 ± 5 years. The variation depends on the quality of the placement, annual truck traffic, and amount of winter salting. An overlay is placed at 1-3/4 in. thick after 1/4 in. of the deck is removed, producing a net 1½-in. increase in grade. The grade is adjusted by adding an HMA wedge on each approach. An overlay is not to be used over an existing overlay. The existing overlay must be milled off the deck prior to other preparation.
- *Polymeric overlay:* This flexible overlay consists of an epoxy polymer combined with a special aggregate. The wearing surface, deck, superstructure and substructure must each have a bridge inspection rating of 5 or higher in order to qualify as a candidate for a polymeric overlay. An average service life of 10 years can be assumed.

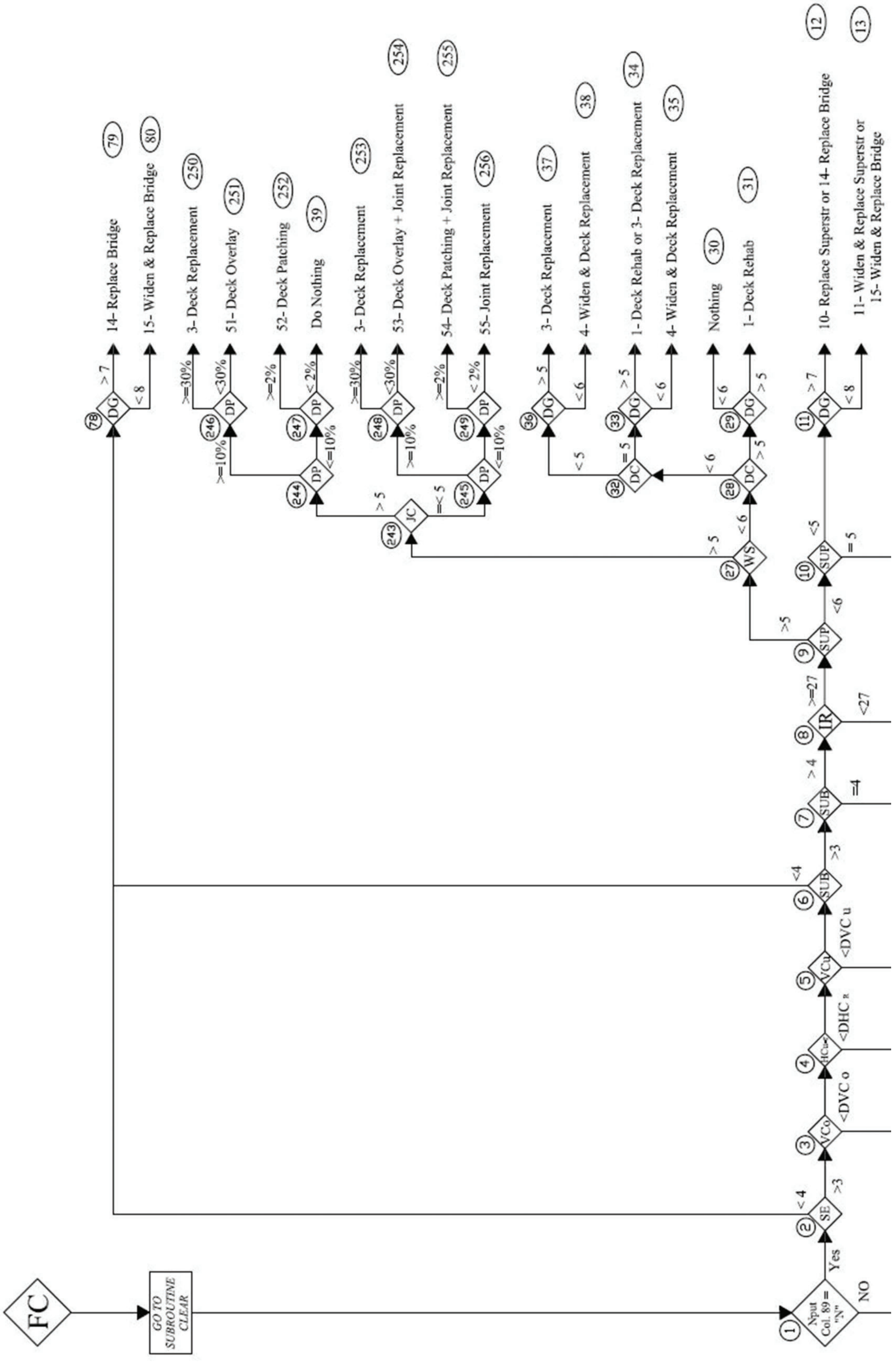

Figure 2.1 Partial DTREE for NHS bridges in IBMS (Sinha et al., 2009).

TABLE 2.3
Preventive Treatments Candidate Performance Criteria (INDOT, 2014)

Preventive Treatments	Bridge Component	Condition Rating	Cycle (Years)[2]
Cleaning/Flushing Bridge Decks	Item 58[1]	>4	1
Substructure/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 & 58.16B & 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 2.4
Corrective Treatments Candidate Performance Criteria (INDOT, 2014)

Corrective Treatments	Bridge Component	Condition Rating	Other Criteria
Deck Patching (shallow/deep)	Item 58.01[1]	>4	D/SS[2] > 4; AND Maximum 10% deck patching
Approach Slab Repair/Replacement	Item 72X.02	<6	WS/D/SS > 4
Joint Repair/Replacement	Item 58.16	<6	WS/D/SS > 4
Mudwall Patching	Item 60.02	<6	WS/D/SS > 4
Thin Deck Overlay (e.g. Polymeric Overlay)	Item 58.01	>5	D/SS > 4; AND Maximum 10% deck patching
Spot Coating	Item 59B.01	<6	WS/D/SS > 4
Substructure Patching/Sealing	Item 60	N/A	WS/D/SS > 4
Superstructure Crack Mitigation	Item 59A.06 OR Item 59A.07	Check box indicating cracks	WS/D/SS > 4
Erosion Mitigation	Item 61	<6	WS/D/SS > 4
Debris Removal/Channel Cleaning	Item 61.03	<6	WS/D/SS > 4
Latex Modified Concrete (LMC) Overlay	Item 58.01	>3	D/SS > 5; AND Maximum 15% deck patching
Slopewall Repair/Replacement	Item 60	<6	WS/D/SS > 4
Bearing Repair/Replacement	Item 59A	<6	WS/D/SS > 4
Scour Mitigation	Item 113	= 2–3	Not programmed for bridge replacement
Deck Crack Sealing	Item 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).

A JTRP report by Frosch, Kreger, and Strandquist (2013) aimed at providing INDOT with an enhanced toolbox of bridge deck protective systems. The report recommended latex-modified concrete (LMC) overlays for bridge decks where more extensive damage is observed. Also, because LMC overlays provide a long service life, they are recommended for more critical bridges as both a preventive maintenance and a rehabilitation measure. Thin polymer overlays were recommended for situations where quick installations are required and where a thin protective system is needed; thin polymer overlays can be also considered as a preventative maintenance system on 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.

2.2.2 Practices of Some Other U.S. and Canadian DOTs

An NCHRP study by Krauss et al. (2009) conducted a survey sent to all U.S. and Canadian Departments of Transportation (DOTs), regarding their guidelines for selecting bridge deck treatments for different deck conditions and deck materials (a total of forty-nine responses were received from forty-one U.S. state DOTs, four Canadian provinces, and Puerto Rico).

Some general findings of the survey included:

1. Twenty-two agencies (48%) reported having specific guidelines or procedures. Of those, only ten agencies (22%) had written procedures or decision trees; two agencies were in the process of developing decision trees, and the rest used visual evaluation, sometimes with supplemental testing, and internal discussions to select appropriate rehabilitation methods or procedures.

2. Thirty-three (72%) agencies reported deck condition as a suitable basis for treatment selection. Two of those specifically correlated topside and underside conditions.
3. All agencies performed visual inspections, and some commonly used supplementary inspection techniques included hammer or chain sounding, chloride measurement, crack mapping/width measurement, and core sampling and strength testing.
4. Although guidelines were available, they were not mandatory and not necessarily used to make decisions for all cases.

Some examples of guidelines from selected DOTs in the United States and Canada are presented in Table 2.5.

Table 2.6 presents a summary of some information provided by the DOTs from the survey on the commonly used bridge maintenance and repair treatments, regarding their expected service life, unit cost, overlay thickness, estimated installation time, and trend of use by DOTs. It can be seen that the range of the provided information varied significantly across different DOTs.

Krauss et al. (2009) also proposed guidelines for bridge deck repair selection based on the compilation of the responses from the survey, review of literature, and the experience of the research team. Krauss et al. (2009) considered four major types of repair actions: (1) do nothing, (2) maintenance (patching, crack repairs, concrete sealer), (3) protective overlay, and (4) structural

TABLE 2.5
Guidelines for Triggers for Bridge Deck Treatments from Selected DOTs

DOT	Guidelines for Triggers for Deck Treatments
California	Full deck replacement triggered when subsurface distress exceeds 20% of the total deck area.
Connecticut & Massachusetts	Deck is replaced if 50% of the deck is in poor condition.
Illinois	Full deck replacement triggered when more than 35% of the deck requires patching.
Kansas	Decks with 3%–10% distress: use a polymer overlay; 10%–50%: distress use silica fume overlay; and >50% distress: do further inspection of the deck.
Virginia	Full deck replacement triggered when more than 25% of the deck requires patching, or is spalling or delaminating. Polymer overlays are used on decks in good condition, and gravity fill polymers are used to fill random shrinkage cracks.
Wyoming	Rigid overlay of silica fume-modified concrete for decks having extensive spalling and cracking, patching if the extent of spalling and delamination is less than a couple hundred square feet, and a crack healer/sealer if the deck displays cracking but not delamination. If a deck needs increased friction over a sealed surface, a polymer thin-bonded overlay may be used.
Ontario (Canada)	Patch, waterproof and pave the deck if less than 10% of the deck requires repair work; apply an overlay and then waterproof and pave with a wearing surface if more than 10% of the deck requires repair work.

TABLE 2.6
Summary of Survey on Bridge Rehabilitation/Repair Treatments Expected Service Life, Unit Cost, Etc. (Krauss et al., 2009)

Rehabilitation Method	Expected Service Life Range (years) [Mean]	Cost Range ($\$/ft^2$) [Mean]	Overlay Thickness (in.) [Mean]	Estimated Installation Time	Current Use
Rigid Overlays					
High performance concrete overlays	10–40 [16–29]	5–45 [17–25]	1–5 [1.6–3.5]	>3 days	Mixed
Low Slump Concrete Overlays	10–45 [16– 32]	4– 45 [13– 19]	1.5– 4 [2.0– 3.1]	>3 days	Static
Latex Modified Concrete Overlays	10–50 [14– 29]	1– 150 [18– 39]	1–5 [1.5– 2.7]	<24 hrs (UHELMC),[1] 1–3 days (LMC)[2]	Mixed
Asphalt-Based Overlays					
Asphalt Overlays with a Membrane	3–40 [12–19]	1.5–23.5 [3.1–7.6]	1.5–4 [2.4–3.1]	>3 days	Static
Miscellaneous Asphalt Overlays	5–20 [8–15]	1–3 [1 response]	0.38–2.5 [0.8–1.5]	1–3 days	Static
Other Rehabilitation/Repair					
Polymer Overlays	1–35 [9–18]	3–60 [10–17]	0.13–6 [0.5–1.4]	<24 hrs	Increasing
Crack Repair	2–75 [19–33]	No response	N/A	<24 hrs	Static
Sealers	1–20 [4–10]	0.33–15 [3–5]	N/A	<24 hrs	Increasing
Deck replacement	15–50 [27–32]	15–100 [43–53]	N/A	>3 days	Static

[1] Ultra high early cement with latex.
[2] High early (Type III) cement with latex.

rehabilitation (partial deck replacement, full depth deck replacement).

Various performance measures were used in the Krauss et al. (2009) report for the thresholds. They were intended to provide agencies with an overall or complete evaluation of the deck, rather than using only the condition ratings which is likely to involve subjectivity. The performance measures included:

1. *Percent Deck Distress and Condition Ratings*—determined by the percent of non-overlapping area of patches, spalls, delamination, and copper sulfate electrode (CSE) half-cell potentials more negative than -0.35V, by the NBI condition rating of the deck, and by a separate condition rating of the deck bottom surface (not in NBI).
2. *Estimated Time-to-Corrosion*—expressed as the estimated time until sufficient chloride penetration occurs to initiate corrosion over a given percentage of the reinforcing steel.
3. *Deck Surface Problems*—consideration of poor drainage, surface scaling, abrasion loss, or skid resistance problems.
4. *Concrete Quality*—related to concrete durability (Alkali Silica Reaction (ASR)/ Delayed Ettringite Formation (DEF)/freeze-thaw) and strength issues.

The guidelines and performance thresholds suggested by Krauss et al. (2009) for concrete bridge deck maintenance and rehabilitation are presented in Table 2.7.

2.3 Analytical Approaches for Bridge M&R Scheduling

Although M&R condition thresholds used in practice are largely based on expert opinions, a large number of research studies have attempted to develop optimal strategies for bridge maintenance and repair activities. However, most of these studies aimed at establishing the optimal strategy for the entire life cycle of the bridge or the bridge deck, rather than considering the optimal trigger thresholds for particular M&R treatments. Some of the significant studies regarding M&R strategy optimization are summarized in the following sections. In addition, other relevant aspects that are important components of the analysis are reviewed and summarized, including bridge deterioration modeling, effects of bridge M&R treatments (i.e., performance jump), and bridge cost models and user cost issues.

2.3.1 Optimization of Bridge M&R Strategy

Numerous studies have made efforts to establish an optimal strategy for bridge maintenance, repair, rehabilitation, and reconstruction activities. Various optimization techniques have been used, such as genetic algorithm (GA), ε-constraint method, and shuffled frog leaping (SFL). Many studies carried out multi-objective optimization, in which the objective functions include, but are not limited to, maximizing a condition index,

TABLE 2.7
Suggested Guidelines of Bridge Repair Based on Various Performance Measures (Slightly revised from Krauss et al., 2009)

	Performance Measures				
Primary Repair Category	Deck Distress		Time-to-Corrosion Initiation	Deck Surface Problems[6]	Concrete Quality Problems[7]
Do Nothing[5]	% Distress[1] % Distress + 1/2 cell[2] NBI deck[3] Deck underside rating[4]	<1% <5% 7 or greater 7 or greater	>10 years	None	None
Maintenance	% Distress % Distress + 1/2 cell NBI deck Deck underside rating	1%–10% 1%–15% 5 or greater 5 or greater	>5 years to >10 years	None	None
Overlay	% Distress % Distress + 1/2 cell NBI deck Deck underside rating	10%–35% 10%–50% 4 or greater 5 or greater	Ongoing to >5 years	Yes	Yes
Structural Rehab	% Distress % Distress + 1/2 cell NBI deck Deck underside rating	>35% >50% 3 or less 4 or less	Ongoing	Yes	Yes

[1] % Distress includes non-overlapping area of % patches, spalls, & delaminations.

[2] % Distress plus half-cell <-0.35 V (vs. copper sulfate). Less negative half-cell values may be used if determined to better represent actively corroding areas.

[3] NBI condition rating of deck.

[4] Condition rating of bottom of deck made using NBI condition rating scale.

[5] Select Do Nothing only if all conditions apply.

[6] Poor drainage, surface scaling, abrasion loss, or skid resistance problems.

[7] Concrete durability (Alkali Silica Reaction (ASR), Delayed Ettringite Formation (DEF), freeze-thaw) and strength issues.

maximizing a safety or reliability index, and minimizing life-cycle costs. The constraints include, but are not limited to, bounds of the condition index, safety and reliability index, and budgetary considerations. Some research focused on project-level or facility-level optimization, while others conducted analysis with respect to a network of bridges. There are also studies on general infrastructure management policy that can be applied to bridge management. Some such literature is reviewed and summarized in the following sections.

Hong and Hastak (2007) developed a Model for Evaluating Maintenance, Repair, & REhabilitation Strategies (MEMRRES) to build feasible MR&R action strategies for concrete bridge decks. Case studies were conducted to apply the tool to various state DOTs. An issue with this study was that some fundamental data used for the analysis, such as the deterioration rates, the effectiveness of MR&R actions, and the unit costs, were based on the questionnaire surveys collected from state DOTs. The subjectivity involved in those important data may reduce the accuracy in the analysis results.

Pasupathy et al. (2007) defined the deterioration of infrastructure as stochastic processes. The authors assumed that reconstruction brings the facility back to the state of a new-constructed facility. It was mathematically proved that the ratio of the total non-monetary benefit to the total monetary cost across several reconstruction periods is simply the ratio of the expected benefit to the expected cost up to the first reconstruction. The authors also selected four popular mathematical forms of facility performance, (i.e., exponential family, logistic family, polynomial family, and power family), and presented methods to determine the optimal reconstruction periods. This study investigated only time-based strategies and considered only the reconstruction activity.

Miyamoto, Kawamura, and Nakamura (2000) used genetic algorithm (GA) and ε-constraint methods to solve the multi-objective optimization problem that maximized the sum of author-defined "soundness scores" of "durability" and "load-carrying capability," and minimized the cost of maintenance measures during the analysis period. The algorithms in this study were integrated into a bridge management system developed by the authors.

Liu and Frangopol (2005a, 2005b) developed time-based life-cycle bridge maintenance planning through a multi-objective genetic algorithm in which the objective functions were condition index, safety index, and maintenance costs. Monte Carlo simulation was conducted to account for parameter uncertainties. Trade-off analysis was also carried out for bridge managers to choose a trade-off maintenance solution with respect to condition, safety levels, and costs.

Neves, Frangopol, and Cruz (2006a, 2006b) used two "fully probabilistically described" performance indicators—condition index (0 to 3, resulting from visual inspection) and safety index (measure of load-carrying capacity resulting from structural analysis). A multi-objective genetic algorithm was adopted to solve the optimization problem and the Latin hypercube sampling technique was used to compute the evolution in time of performance indicators and cost. The time of application of silane (a preventive maintenance action in the U.K.) and the safety index threshold at which rebuild is applied were determined in the forms of both Pareto solutions and dominated solutions.

Elbehairy, Elbeltagi, Hegazy, and Soudki (2006) introduced a model for integrated project-level and network-level decisions on bridge deck repairs, and two evolutionary-based optimization algorithms—genetic algorithm (GA) and shuffled frog leaping (SFL)—were applied to the model and compared. Both techniques were found to be equally suitable for dealing with the particular problem in the study.

Robelin and Madanat (2007) proposed a method that formulated a history-dependent deck deterioration model as an augmented state Markovian model. Then, the model was used in formulating and solving a reliability-based bridge maintenance optimization problem as a Markov decision process. A parametric example study was also conducted to compare the policies obtained through the augmented state Markovian model with those derived using a simpler Markovian model.

Patidar, Labi, Sinha, and Thompson (2007) developed a software package tool named Multi-Objective Optimization System (MOOS) which made some changes and improvements to Pontis (now AASHTOWare™ Bridge Management software). The tool can be applied to both the network level and the project level. For the network level, the optimization problem was formulated as a multi-choice, multi-dimensional knapsack problem (MCMDKP). It was found that the incremental utility-cost (IUC) ratio was the most robust among all the alternative heuristic approaches. For the project level, the objective was to maximize the utility of bridge actions in the long term by selecting from an array of scoping and timing alternatives. The bridge-level model separated fixed and variable costs of treatments and duly considered actions whose life-cycle benefit exceeds their initial variable costs, which was one of the features that made this tool different from Pontis.

Bai, Labi, Sinha, and Thompson (2013) proposed a method that first evaluated the network performance of each candidate project portfolio using network-level performance measures prior to employing a multi-attribute utility function, and then identified the optimal portfolio with the best network performance. The authors indicated that their method effectively incorporated decision-makers' preferences into decision making, avoided possible bias by relaxing the assumption of additivity (i.e., addition of individual project utility values to obtain a total utility score), and interpreted investment performance directly in terms of raw performance measures.

Apart from the above literature, there are a number of studies that did not focus on bridge management, but their methodology framework designed for general infrastructure or pavement management could be easily applied to bridges. Some selected studies are summarized and discussed below.

Khurshid (2010) developed a general framework for establishing the optimal asset performance threshold or trigger for treatment interventions. The author applied the framework to thin HMA overlay and functional HMA overlay. Irfan (2010) proposed a framework for developing optimal pavement life-cycle activity profiles. The nonlinear cost-effectiveness optimality was solved using mixed-integer nonlinear programming. Lamptey, Ahmad, Labi, and Sinha (2005) documented several sets of alternative pavement design and preservation strategies (both condition-based and time-based) through life-cycle cost analysis. Lamptey, Labi, and Li (2008) presented a case study for optimizing decisions on the best combination of preventive maintenance treatments and timings to be applied in the resurfacing life-cycle (interval between resurfacing events), for a given highway pavement section. Bai, Labi, and Sinha (2012) conducted a trade-off analysis for multi-objective optimization in transportation asset management. The authors generated Pareto frontiers using a proposed Extreme Points Non-Dominated Sorting Genetic Algorithm II (NSGA II) technique, which was an improvement over traditional NSGA II.

Madanat (1993) and Ben-Akiva, Humplick, Madanat, and Ramaswamy (1993) developed the Latent Markov Decision Process (LMDP), which took into account uncertainties in facility condition prediction and the random measurement errors in facility condition measurement. Such methodology quantified the “value of more precise information” in the infrastructure M&R decision process. Madanat and Ben-Akiva (1994) further extended the previous studies by incorporation of inspection policies. The authors assumed the inspection schedule was fixed in their first version of LMDP. In the second version of LMDP, they minimized the sum of inspection and M&R costs. The study showed again that the measurement uncertainty had an important impact on the M&R decision process. Durango and Madanat (2002) introduced two adaptive control (AC) approaches, the closed-loop control and the open-loop-optimal feedback control, to better control the uncertainties in terms of deterioration modeling, because these two ACs allowed the expectations about future deterioration to change as new actual condition information became available. Results showed that the AC schemes always performed better than the normally used scheme (called open-loop control scheme), which ignores the feedback from actual condition. The difference in the performance was more significant when the actual deterioration rate deviated more from the initially expected deterioration rate. Guillaumot, Durango-Cohen, and Madanat (2003) and Durango and Madanat (2008) further extended previous studies through integrating the LMDP and the AC schemes, that is, both accounting for uncertainty in measuring facility condition and allowing for feedback from actual condition to update the deterioration expectations.

2.3.2 Bridge Deterioration Modeling

Bridge deterioration models, or performance prediction models, are the basis of life-cycle assessment of bridges (Zayed, Chang, & Fricker, 2002), because the recommended strategies and predicted costs incurred throughout the entire service life significantly depend on the predicted bridge performance over the analysis period.

Two types of models—deterministic models and stochastics models—have been studied extensively in the existing literature. Deterministic models were once used by some agencies primarily because of their simplicity and the clear relationship between the response variable (condition rating) and independent variables such as age, traffic and climate factors. Most deterministic models have used the regression technique, for which a wide range of mathematical forms have been fitted, including exponential functions and polynomial functions. However, deterministic models suffer from many limitations. For example, the regression approach does not adequately account for the uncertainty associated with bridge deterioration and the possible influence of unobserved variables (Jiang & Sinha, 1989b). Besides, as the bridge condition rating is typically expressed as an integer scale from 0 to 9 as defined in the National Bridge Inventory (NBI) (FHWA, 1995), the response variable is actually count data, which is inappropriate to be modeled using linear regression for which the predicted result is continuous.

In terms of stochastic models, Markovian transition probabilities have been used extensively in the field of infrastructure management to provide forecasts of facility condition (Cesare, Santamarina, Turkstra, & Vanmarcke, 1992; Jiang, Saito, & Sinha, 1987; Madanat & Wan Ibrahim, 1995). The state-of-the-art bridge management systems (BMSs), such as AASHTOWare™ Bridge Management software (BrM) (formerly Pontis) (Gutkowski & Arenella, 1998), BRIGIT (Hawk, 1995), and IBMS (Sinha et al., 2009), have all adopted the Markov-chain models to predict the performance of bridge components and networks.

Transitions are probabilistic in nature because infrastructure deterioration cannot be predicted with certainty due to unobserved explanatory variables, the presence of measurement errors, and the inherent stochasticity of the deterioration process (Madanat et al., 1995). Therefore, the Markov-chain model, which specifies the likelihood that the condition of a bridge component will change from one state to another in a unit time, is an appropriate tool to describe the probabilistic transition process of bridge deterioration.

However, the Markov-chain model is not always the most appropriate due to the two basic assumptions that it is based on: (1) future bridge condition depends only on the present condition and not on the past condition (i.e., state independence); (2) bridge inspections are performed at predetermined and fixed time intervals (i.e., constant inspection period) (Morcous, 2006). Many research studies have shown the impacts of violating these assumptions. Madanat, Karlaftis, and McCarthy,

(1997) attempted to control for heterogeneity in the panel data through a probit model with random effects and extended the model to investigate the presence of state dependence. Morcous (2006) evaluated the impact of more or less frequent inspections that result in unequally spaced condition data in terms of time, and found out that such variation in inspection period may lead to a 22% error in estimating the service life a bridge deck system. It is worth mentioning that although the state independence seems a strict condition, many studies (Madanat, Karlaftis, et al., 1997; Mishalani & Madanat, 2002; Morcous, 2006) showed, using actual data, that the null hypothesis of Markovian property (i.e., the predicted condition only depends on the current condition) was not rejected, indicating that the state independence assumption was acceptable within a certain confidence level.

In addition to the standard Markov-chain model, other models have also been used to estimate the transition probabilities. Bulusu and Sinha (1997) used two approaches, one based on the Bayesian approach and the other using a binary probit model. Expert opinions could be combined with observed data through the Bayesian approach. The binary probit model used a zero/one indicator variable for the condition switching state, and it also incorporated heterogeneity and state dependence due to the use of panel data. Madanat and Wan Ibrahim (1995) used the Poisson regression model, which is suitable for nonnegative integer response variable (count data), and also the negative binomial regression model, which is a generalization of Poisson model that relaxes the assumption of equality of mean and variance. Considering that another limitation of the Markov approach is that it does not recognize the latent nature of infrastructure deterioration (Madanat, Mishalani, & Wan Ibrahim, 1995), because deterioration is an unobservable entity whose manifestation results in observable surface and subsurface distress (Ben-Akiva & Ramaswamy, 1993). Madanat, Mishalani, et al. (1995) used the ordered probit model, which assumed the existence of an underlying continuous unobservable random variable and thus allowed for capturing the latent nature of infrastructure performance. Mishalani and Madanat (2002) used the time-based stochastic duration model to characterize the probability density function of the time it takes an infrastructure facility to leave a particular condition state once entered (referred to as state duration), given a set of explanatory variables. Mauch and Madanat (2001) observed that it is possible for the discrete-time state-based model (such as Markov chain) transition probabilities to be determined from the probability density function of state duration, and vice versa.

2.3.3 Effects of Bridge M&R Treatments on Deterioration Process

Although much research has been conducted on bridge deterioration modeling, the basic premise is that no major rehabilitation activities are implemented within the analysis period. The Markov-chain model, for example, requires that the condition either stays at the current state, or transfers to some lower state, implying the absence of rehabilitation activities that are likely to improve the condition state. As Madanat and Wan Ibrahim (1995) indicated, the estimation of transition probabilities for the case where rehabilitation is performed represents additional difficulties.

In fact, little research has been done to rigorously evaluate the effects of bridge M&R treatment on the deterioration process. Two possible effects brought about by the treatments are: (1) some major rehabilitation activities (such as deck overlay) may raise the deck condition by certain levels (e.g., from deck condition rating of 5 to 6 or 7); (2) some minor rehab or maintenance (such as deck patching) may not improve the condition significantly, but may reduce the deterioration rate within a certain period after the treatment.

In the current literature regarding optimal bridge M&R strategies, typically some simplified estimations of such effects (called "recovering effects" in some literature) are assumed. For example, Lee and Kim (2007) developed some "recovering effects" on a scale from 1 to 90 for different maintenance methods on various distress types, primarily based on opinions from experts in the field of bridge maintenance. Table 2.8 presents their results.

Hong and Hastak (2007) developed the average improvements of deck NBI condition rating after M&R

TABLE 2.8
Recovering Effect Value of M&R 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
Slab thickness increasing	40	40	40	40	40	40	40	40
Steel plate attaching	40	40	40	40	40	40	40	40
Carbon fiber sheets attaching	40	40	40	40	40	40	40	40
Replacement	90	90	90	90	90	90	90	90

actions based on their survey results received from 28 U.S. state DOTs, as presented in Table 2.9. However, some limitations of the results could be: (1) based on expert opinions only; (2) inconsistency across different DOTs; (3) not including pre-treatment condition.

Liu, Hammad, and Itoh (1997) assumed some simple "impacts" of maintenance methods on deterioration degree, presented in Table 2.10. The "deterioration degree" was defined by the authors at a scale of 0 (new deck) to 1 (structural failure level). The four maintenance methods were recommended by the authors to be applied with respect to different deterioration degree intervals.

TABLE 2.9
Average Improvement of Deck Condition Rating (NBI Scale) after M&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

TABLE 2.10
Impact on Deterioration Degree of Maintenance Methods (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

TABLE 2.11
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

Elbehairy et al. (2006) estimated the impacts of "light, medium, and extensive" repair options on the bridge deck condition rating, as shown in Table 2.11.

The updated IBMS manual (Sinha et al., 2009) provides a detailed table showing the effects of various repair activities and their combinations on the deck condition, superstructure condition, substructure condition, wearing surface condition, and service life. This is a good reference, but again, the limitations could be that it was based on expert opinions and it did not take into account the effect of pre-treatment condition. Also, some of the repair activities are not specific enough, such as deck rehabilitation and superstructure rehabilitation. Table 2.12 extracts the information from the IBMS manual for some common M&R treatments only.

2.3.4 Bridge Agency Cost Models and User Cost Issues

Estimation of agency costs and user costs is necessary for bridge life-cycle cost analysis. For agency costs, studies have been conducted to either build statistical cost models or develop average costs for different treatments, based on historical data. These cost models may need to be updated frequently, considering the improvement of technology and the change in materials costs and labor costs. As for user costs, debate has existed regarding whether to include user costs, what types of user costs to include, what the weight between user cost and agency cost should be, and so on. The following sections summarize selected studies related to these issues.

2.3.4.1 Bridge Agency Cost. From the perspective of work type, agency costs basically include routine maintenance costs, element rehabilitation costs, element replacement costs, and entire bridge replacement costs. From the perspective of cost items, agency costs could include, but are not limited to, materials, personnel, equipment, engineering, and acquisition costs.

Sinha, Labi, Rodriguez, Tine, and Dutta (2005) investigated INDOT bridge contract data and developed comprehensive cost models for various bridge work types, including deck rehabilitation, deck replacement,

TABLE 2.12
Improvement in Condition Rating and Extension of Service Life due to M&R Actions (Sinha et al., 2009)

Action	Improvement in Condition Rating and Service Life				
	Deck	Superstructure	Substructure	Wearing Surface	Service Life (years)
Deck rehab	1	0	0	3	15
Deck replacement	9	0	0	9	20
Superstructure rehab	0	2	0	0	25
Replace superstructure	9	9	1	9	40
Substructure rehab	0	0	2	0	15
Bridge replacement	9	9	9	9	65

superstructure rehabilitation, superstructure replacement, substructure rehabilitation, bridge widening, bridge replacement, and some combinations of these work types. Various cost model forms were adopted, such as linear, Cobb-Douglas, "constrained Cobb-Douglas," and "transformed Cobb-Douglas." The latest IBMS manual (Sinha et al., 2009) updated some of the old cost models and added some additional cost information collected from INDOT. For further details, readers may refer to these two studies.

Hawk (2003) described a methodology for bridge life-cycle cost analysis with risks incorporated and agency and user costs included. However, this study did not provide any actual cost models or cost information; it just showed the implementation of the framework through some hypothetical examples. There are also studies that focused on modeling particular bridge costs. For example, Hollar et al. (2013) investigated 461 bridge projects let by the North Carolina DOT between 2001 and 2009 and developed statistical models linking variation in the preliminary engineering costs with distinctive project parameters. The authors found that the preliminary engineering cost estimates for bridge projects were commonly and significantly underestimated. Oh, Park, and Kim (2013) collected cost data for 52 steel box girder bridges in Korea and built cost estimation models for steel box girder bridge substructures.

2.3.4.2 Bridge User Cost. The most typical bridge user costs include increases in travel time, vehicle operating costs, and possibly the number and severity of crashes incurred at work zones due to bridge maintenance, rehabilitation, and replacement activities. User costs should be treated as an important component of the decision-making process. FHWA (2002) indicated that, "though these user costs are not directly borne by the agency, they affect the agency's customers and the customers' perceptions of the agency's performance."

FHWA's Life-cycle Cost Analysis Primer (2002) pointed out that user costs may represent the greatest data challenge to LCCA implementation. One reason is that user costs are often so large that they may substantially exceed agency costs, particularly for transportation investments being considered for high-traffic areas.

FHWA (2002) further stated that agencies have been reluctant to rely on user cost estimates for several reasons. These include the difficulty in valuing user delay time, and the uncertainty that exists about the effects of agency activities on crash rates and vehicle operating costs. Therefore, the difficulty in assigning a hard number to user costs has made their comparison with actual agency budget figures problematic for many analysts. Besides, user costs do not debit agency budgets as do agency costs.

The calculation of the user costs has been examined by a number of studies. However, few studies focused on bridge user costs only. Son and Sinha (1997) considered several types of user costs that are unique to bridges, including user costs due to bridge weight limits, vertical clearance limits, and deck width. Bai, Labi, Sinha, and Thompson (2011) extended the previous research by solving the issue of multiple counting and, subsequently, overestimation of user detour cost when a bridge user detours for more than one reason. The authors also incorporated work zone user cost and delay cost due to bridge traffic capacity limitation into one bridge user cost calculation.

2.4 Summary of Literature Review

Based on the literature review of state of practices, not many agencies have established specific guidelines for triggering bridge treatments. For those who have, the guidelines are largely on the basis of expert opinions, which may suffer from subjectivity and inconsistency. Academic research studies mostly focused on time-based strategies rather than condition-based strategies. Also, most studies only discussed theoretical methodology framework and simplified the application to specific bridge treatments. In addition, little research has been done to evaluate and compare the pre- and post-effects of bridge M&R treatment on the deterioration trend. User cost issues have not been well addressed in most studies.

3. METHODOLOGY

This chapter discusses the methodology framework for developing the appropriate bridge maintenance and repair treatment thresholds. Data collection is described first. Then, methods for bridge component deterioration modeling, treatment effect (i.e., performance jump and extension of service life) modeling, and treatment cost modeling are presented.

3.1 Data Collection

3.1.1 Basic Bridge Characteristics

Data related to basic bridge characteristics, including the highway functional class, the Indiana highway district where the bridges are located, bridge structure length and deck width, type of wearing surface, and detour length, were collected from the National Bridge Inventory (NBI) database. The NBI database contains data for every bridge in Indiana from 1992 to 2015.

The different highway districts in Indiana have different average climate condition (e.g., temperature, precipitation, freeze-thaw cycles, and freezing index), and different average traffic condition (e.g., AADT and truck percentage). This can lead to different bridge deterioration rates and affect the frequency of bridge maintenance and repair.

Highway functional class could affect the design standards of the bridges. Different functional classes have different average traffic, leading to different bridge deterioration rates. In the current study, NBI Item 5B Codes are 1 – Interstate highway, 2 – U.S. highways, and 3 – state highways that are categorized as part of the National Highway System (NHS), while other functional classes are categorized as non-NHS.

Bridge structure length and deck width are coded in meters in the NBI database. These data are used for calculating the costs of deck treatments, work zone delay costs, and vehicle operating costs. Detour length is used for calculating user costs.

"Type of wearing surface" is used to identify the deterioration rates of different bridge wearing surfaces. By noting a change of type of wearing surface for every bridge during the analysis period (1992–2015), some bridge treatments, such as deck overlay, can be detected if it is not caused by deck replacement or bridge reconstruction. The most commonly used types of wearing surface in Indiana are (by NBI Item 108A codes): 1-Monolithic concrete, 3-Latex concrete or similar additive, and 6-Bituminous. Although 5-Epoxy overlay (a polymer overlay or thin deck overlay) currently does not have many entries in INDOT's NBI, it is being programmed and implemented more aggressively in recent years. Hence, polymer overlay also comes into the analysis in the current study, as recommended by INDOT.

3.1.2 Traffic Data

Traffic data, including average daily traffic (ADT) and percent trucks, were also collected from the NBI database. Truck traffic volume would affect the deterioration rates of bridge components, and ADT is used to calculate the user costs, including work zone delay costs and vehicle operating costs (VOC).

In addition, because the analysis period is the service life of bridge components (e.g., over 30 years for bridge decks), traffic growth needs to be taken into account. The annual traffic growth factors for 2004-2014 published by INDOT (INDOT, 2015) were used to calculate the average annual traffic growth factor. For urban and rural Interstates and principal arterials (freeways and expressways), the average annual traffic growth factor from 2004 to 2014 was calculated to be 0.72%. For urban and rural other principal arterials, minor arterials, collectors and locals, the factor was found to be negative, -0.23%. The negative traffic growth during this period could be largely due to the economy recession that occurred in 2008 and lasted for years. Considering that the negative growth would probably not continue in the long term, the positive growth factor (i.e., 0.72%) is used in the analysis for all functional classes. Besides, it is assumed that the annual traffic growth factor remains constant during the analysis period.

3.1.3 Condition Rating Data

Deck condition rating data were collected from the NBI database. The deck condition of every bridge in Indiana for each year from 1992 to 2014 was tracked. Wearing surface condition rating data were obtained from INDOT with the help of INDOT personnel. The wearing surface condition of all the INDOT-owned bridges from 2006 to 2015 was acquired. The change in bridge component condition rating was used to investigate the treatment effect (performance jump) and the post-treatment performance trend.

In addition to the raw condition rating data, some performance trend models (deterioration curves) were also acquired to be used as the pre-treatment performance trend. Wearing surface curves were collected from INDOT, and deck deterioration curves were obtained from another INDOT project SPR-3828 (Moomen, Qiao, Agbelie, Labi, & Sinha, 2015).

3.1.4 Project Type and Agency Cost Data

Bridge contract data, including the specific work type of M&R activities, contract costs, and letting finish date, was obtained from the SPMS database and the Site Manager database held by INDOT. The SPMS database contains bridge contracts from 1994 to 2011, although not every bridge contract during this period was recorded in this database and some contracts did not have NBI numbers. The Site Manager database contains more specific activity items and their corresponding costs for the period of 2009–2012. The costs for LMC overlays and deck replacement were obtained from the SPMS database. One cost model for polymeric overlays was provided by INDOT. Site Manager was used to attain cost information for some relatively minor activities, such as partial-depth deck patching and full-depth deck patching. In addition, some cost information provided in the IBMS manual (Sinha et al., 2009) was used as supplements and references, such as routine maintenance costs.

The inflation rate for construction costs was calculated based on the FHWA National Highway Construction Cost Index (NHCCI) from 2010 to 2014 (FHWA, 2015). The average annual inflation during 2010 and 2014 was calculated to be 1.15%. It is used for the entire analysis period of the current study.

3.1.5 Work Zone Duration and User Cost Data

Work zone duration data is used to estimate the user costs incurred during the bridge M&R treatments. Estimates of the work zone durations for some common treatments were obtained from INDOT personnel based on some historical contracts and expert opinions. The details are presented in Table 3.1, including the maintenance of traffic (MOT) type and their corresponding closure durations. The values in Table 3.1 are solely for time when traffic is affected and not the total contract time. Also, these estimates are for an average sized bridge.

The value of travel time of road users and the vehicle operating costs information were acquired from Sinha and Labi (2007). The IBMS manual (Sinha et al., 2009) was also used as a reference. Regarding the inflation rate of the user costs, the consumer price index (CPI)

TABLE 3.1
Work Zone Duration Estimates by Bridge Project Type (Source: Stephanie Wagner, INDOT, March 2016)

Work Type	MOT Type	Closures	Comments
Deck patching	Flagger	Restrictions during daytime hours for 2–3 days	Needs rapid set patch, which drives up the cost of the project
	Lane closure (4 or more lanes)	3 days per lane	
	Detour	3 days total	
Joint repair (BS or silicon seals)	Flagger	Restrictions during daytime hours for 2–3 days	If patching required, rapid set materials needed
	Lane closure (4 or more lanes)	3 days per lane	
	Detour	3 days total	
Joint repair (SS or modular joints)	Flagger	NOT typically an option	Partial deck reconstruction typically required
	Lane closure (4 or more lanes)	5–7 days per lane	
	Detour	5–7 days total	
Polymeric overlay	Flagger	Restrictions during daytime hours for 5 days	Needs rapid set patch, which drives up the cost of the project
	Lane closure (4 or more lanes)	5 days per lane	Often requires deck patching, otherwise polymeric overlays can be placed in two days
	Detour	5 days total	
LMC overlay	Detour	30–60 days (4–8 weeks)	
	Lane closure (4 or more lanes)	45–90 days (6–12 weeks)	Duration requires temporary traffic barrier, higher cost
	Lane closure (temp. signal)	45–90 days (6–12 weeks)	Typically requires shoulder strengthening, higher cost
Partial deck replacement	Detour	7–9 weeks	2 extra weeks for structure work on top of overlay, etc.
	Lane closure (4 or more lanes)	12–16 weeks	Duration requires temporary traffic barrier, higher cost
	Lane closure (temp. signal)	14–18 weeks	Typically requires shoulder strengthening, higher cost
Full deck replacement	Detour	7–9 weeks	
	Lane closure (4 or more lanes)	12–16 weeks	
	Lane closure (temp. signal)	14–18 weeks	Extra time required for shoulder strengthening to carry traffic

data from 1999 to 2014 was collected from the website of the Bureau of Labor Statistics (2016). The average annual growth rate of the CPI from 1999 to 2014 was calculated to be 2.35%. This value is used in the current study to estimate the annual increase in user costs during the analysis period.

3.2 Deterioration Models for Bridge Deck and Wearing Surface

Because the current study focuses on developing thresholds for bridge deck treatments, only the deterioration models for decks and wearing surfaces are discussed in this chapter. Wearing surface condition serves as the performance measure for triggering deck overlay activities, including latex-modified concrete (LMC) overlay and polymeric overlay. Deck condition can be affected by the wearing surface condition, because a wearing surface in good condition could provide better protection to the concrete deck and reinforced steel bars beneath it, so that the deterioration process of the deck is likely to be slowed.

3.2.1 Models for Bridge Deck

The methodology and results from INDOT project SPR 3828 (Moomen et al., 2015) were borrowed and used here. The statistical variables used for modeling deck deterioration are presented in Table 3.2.

The current study adopted deterministic models using linear regression, whose general form is:

$$y_i = \beta_0 + \beta_1 x_{1i} + \cdots + \beta_p x_{pi} + \varepsilon_i \tag{3.1}$$

where y_i is the ith observation of the response variable y, x_{pi} is the ith observation of the pth explanatory variable x_p, β_0 is the regression constant term, β_p is the regression coefficient of variable x_p, and ε_i is the disturbance term. The basic assumptions of the linear regression model include: $\varepsilon_i \approx N(0,\sigma^2)$, $Cov[\varepsilon_i,\varepsilon_j]=0$ for $i \neq j$, $Cov[X_i,\varepsilon_j]=0$ for all i and j.

To model deck deterioration, polynomial forms of the age variable are included in the regression model to reflect the nonlinear deterioration rates with age. Specifically, the model form is:

$$DCR=\beta_0+\beta_1 AGE+\beta_2 AGE^2+\beta_3 AGE^3+\beta\boldsymbol{X}+\varepsilon \quad (3.2)$$

where, $\boldsymbol{\beta X}$ represents the sum of the terms of other statistically significant variables.

ANOVA test results suggested that separate deck models should be developed for different Indiana highway districts and functional classes. Specifically, six deck models were developed—for bridge decks on the NHS and non-NHS highways in the northern (LaPorte and Fort Wayne), central (Crawfordsville and Greenfield), and southern (Seymour and Vincennes) districts of Indiana. The results are presented in Table 3.3. A plot of the model for NHS decks in northern districts is presented in Figure 3.1.

3.2.2 Models for Bridge Wearing Surface

The deterioration models for bridge wearing surface used in the current study were provided by INDOT. The models adopted the similar polynomial form. However, unlike the deck models, which incorporate other statistically significant variables in the model, the wearing surface models only include the age and its polynomial terms as variables. Other factors are taken

TABLE 3.2
Variables for Deck Deterioration Modeling (Source: Moomen et al., 2015)

Variable Type	Variable	Description
Response Variable	DCR	Deck NBI condition rating from 0 to 9
Explanatory Variable	AGE	Deck age (Years)
	INT	Dummy variable for bridges on Interstate (1 if yes, 0 otherwise)
	SKEW	Bridge skew (Degrees)
	LENGTH	Bridge length (Meters)
	SERVUNDER	Dummy variable for bridges under which the type of service is waterway (1 waterway, 0 otherwise)
	SPANNO	Number of spans in main unit of the bridge
	FRZINDX	Freeze Index (1000s of degree-days)
	NRFTC	Number of freeze-thaw cycles
	ADTT	Average daily truck traffic (in 1000s)
	DECKPROT	Dummy variable for deck protection (1 with protective system, 0 otherwise)

TABLE 3.3
Deck Deterioration Models by Highway District and Functional Class (Source: Moomen et al., 2015)

Highway District	Functional Class	Model
Northern	NHS	$DCR=8.55637-0.24129\cdot AGE+0.0096\cdot AGE^2-0.0001667\cdot AGE^3-0.04301\cdot SERVUNDER-0.01218\cdot SPANNO+0.051375\cdot DECKPROT-0.05182\cdot FRZINDX-0.01872\cdot ADTT$
	Non-NHS	$DCR=9.22454-0.244998\cdot AGE+0.01158\cdot AGE^2-0.00021831\cdot AGE^3-0.00136\cdot SKEW-0.01023\cdot SPANNO+0.39602\cdot DECKPROT-0.03037\cdot FRZINDX-0.01397\cdot NRFTC-0.08597\cdot ADTT$
Central	NHS	$DCR=8.1961-0.16459\cdot AGE+0.0068\cdot AGE^2-0.0001442\cdot AGE^3-0.06213\cdot INT-0.04249\cdot SERVUNDER-0.0005587\cdot LENGTH+0.50755\cdot DECKPROT-0.00769\cdot NRFTC$
	Non-NHS	$DCR=7.6959-0.09989\cdot AGE+0.00234\cdot AGE^2-0.00005094\cdot AGE^3-0.06901\cdot SERVUNDER-0.00119\cdot LENGTH+0.33696\cdot DECKPROT-0.03016\cdot ADTT$
Southern	NHS	$DCR=8.58845-0.09752\cdot AGE+0.00341\cdot AGE^2-0.0000855\cdot AGE^3-0.00186\cdot SKEW-0.00041603\cdot LENGTH+0.53671\cdot DECKPROT-0.06989\cdot FRZINDX-0.01421\cdot NRFTC-0.04431\cdot ADTT$
	Non-NHS	$DCR=8.05846-0.14617\cdot AGE+0.00663\cdot AGE^2-0.00015219\cdot AGE^3-0.00098333\cdot LENGTH+0.43363\cdot DECKPROT-0.06043\cdot FRZINDX-0.14681\cdot ADTT$

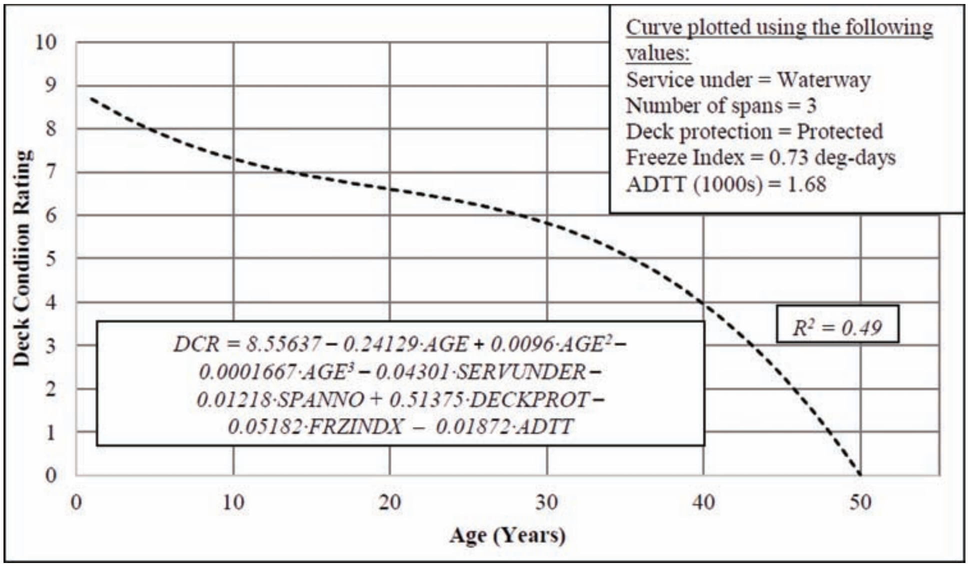

Figure 3.1 Illustration of deck model for northern districts, NHS (Moomen et al., 2015).

into account by using different categories, including highway district categories, wearing surface type categories, and initial deck condition categories. Separate wearing surface models are developed under each combination of categories. Specifically, for a particular category:

$$WSCR = \beta_0 + \beta_1 AGE + \beta_2 AGE^2 + \beta_3 AGE^3 + \varepsilon \qquad (3.3)$$

where $WSCR$ is the condition rating of the bridge wearing surface.

The results of the wearing surface models are presented in Table 3.4. The codes in each category are: for District, C-Crawfordsville, F-Fort Wayne, G-Greenfield, L-LaPorte, S-Seymour, V-Vincennes; for Type of Wearing Surface, 1-Monolithic concrete (concurrently placed with structural deck), 3-Latex Concrete or similar additive, 6-Bituminous, O-Others.

3.3 Performance Jump Models

Performance jump is defined in the current study as the improvement in the bridge component condition rating (e.g., deck rating and wearing surface rating) after an M&R treatment is carried out. Performance jump is often related to the component condition rating before the treatment: the lower the condition rating before the treatment, the greater the performance jump will typically be. The following sections discussed the performance jump effects caused by two commonly used deck overlays—LMC overlay and polymeric overlay. Statistical models were developed based on the historical data.

3.3.1 Latex-Modified Concrete (LMC) Overlay

According to the Indiana Design Manual (INDOT, 2013), a 1-3/4 inch thick LMC overlay is placed after 1/4 inch of the deck is removed, producing a net 1-1/2 inch grade increase. Therefore, an LMC overlay is supposed to bring improvement to the deck condition rating, because 1/4 inch of the original top layer is replaced, although the bottom part of the deck remains the same.

The historical data regarding the pre-treatment condition, post-treatment condition, and performance jump were summarized through investigation of three databases: (1) SPMS, which provides the time when LMC overlays were implemented, (2) NBI, which provides the deck condition rating every year and thus the change in deck condition rating, and (3) Wearing surface condition data from INDOT. It should be noted that the thresholds that triggered the LMC overlays found in the databases represented historical practices only. The triggers could mostly be the results of experience-based judgment, which did not necessarily lead to the optimal timing.

Figure 3.2 presents the distribution of the change in deck condition rating due to an LMC overlay. The number before the hyphen represents the pre-treatment deck condition and the number after the hyphen represents the post-treatment deck condition. The total number of observations is 380. The most frequent five scenarios are 7-7, 6-7, 6-6, 5-7, and 6-8. The reason why the deck condition does not improve after LMC overlay (such as 7-7 and 6-6) could be that, for a deck in a fairly good condition (7 or 6), although the top layer of the deck is removed and replaced, the overall rating of the deck does not change much (not enough improvement to be qualified as 8).

A statistical model was developed to capture the effect of pre-treatment deck condition on the performance jump. The model with the best fit occurred when the independent variable was transformed to its natural logarithm:

$$PJ_{Deck} = 8.9145 - 4.4686 \times \ln(PreDeck) \qquad (3.4)$$

where PJ_{Deck} is the performance jump of the deck condition due to the LMC overlay, and $\ln(PreDeck)$

TABLE 3.4
Wearing Surface Deterioration Models by Highway District, Initial Deck Condition, and Type of Wearing Surface (Source: INDOT)

			Model Coefficient			
District	**Initial Deck Condition**	**Type of WS**	β_0	β_1	β_2	β_3
C, S	0-5	1	9	-0.3051	0.0048	-3×10^{-5}
C, S	0-5	3, 6	9	-0.3828	0.0061	-4×10^{-5}
C, S	0-5	O	9	-0.3828	0.0061	-4×10^{-5}
C, S	6	1	9	-0.3051	0.0048	-3×10^{-5}
C, S	6	3, 6	9	-0.3828	0.0061	-4×10^{-5}
C, S	6	O	9	-0.3828	0.0061	-4×10^{-5}
C, S	7-9	1	9	-0.2388	0.0038	-2×10^{-5}
C, S	7-9	3, 6	9	-0.2996	0.0047	-3×10^{-5}
C, S	7-9	O	9	-0.2996	0.0047	-3×10^{-5}
F, G, V	0-5	1	9	-0.2417	0.0038	-2×10^{-5}
F, G, V	0-5	3, 6	9	-0.3032	0.0048	-3×10^{-5}
F, G, V	0-5	O	9	-0.3032	0.0048	-3×10^{-5}
F, G, V	6	1	9	-0.2417	0.0038	-2×10^{-5}
F, G, V	6	3, 6	9	-0.3032	0.0048	-3×10^{-5}
F, G, V	6	O	9	-0.3032	0.0048	-3×10^{-5}
F, G, V	7-9	1	9	-0.1891	0.0030	-2×10^{-5}
F, G, V	7-9	3, 6	9	-0.2373	0.0038	-2×10^{-5}
F, G, V	7-9	O	9	-0.2373	0.0038	-2×10^{-5}
L	0-5	1	9	-0.3088	0.0049	-3×10^{-5}
L	0-5	3, 6	9	-0.3874	0.0061	-4×10^{-5}
L	0-5	O	9	-0.3874	0.0061	-4×10^{-5}
L	6	1	9	-0.3088	0.0049	-3×10^{-5}
L	6	3, 6	9	-0.3874	0.0061	-4×10^{-5}
L	6	O	9	-0.3874	0.0061	-4×10^{-5}
L	7-9	1	9	-0.2417	0.0038	-2×10^{-5}
L	7-9	3, 6	9	-0.3032	0.0048	-3×10^{-5}
L	7-9	O	9	-0.3032	0.0048	-3×10^{-5}

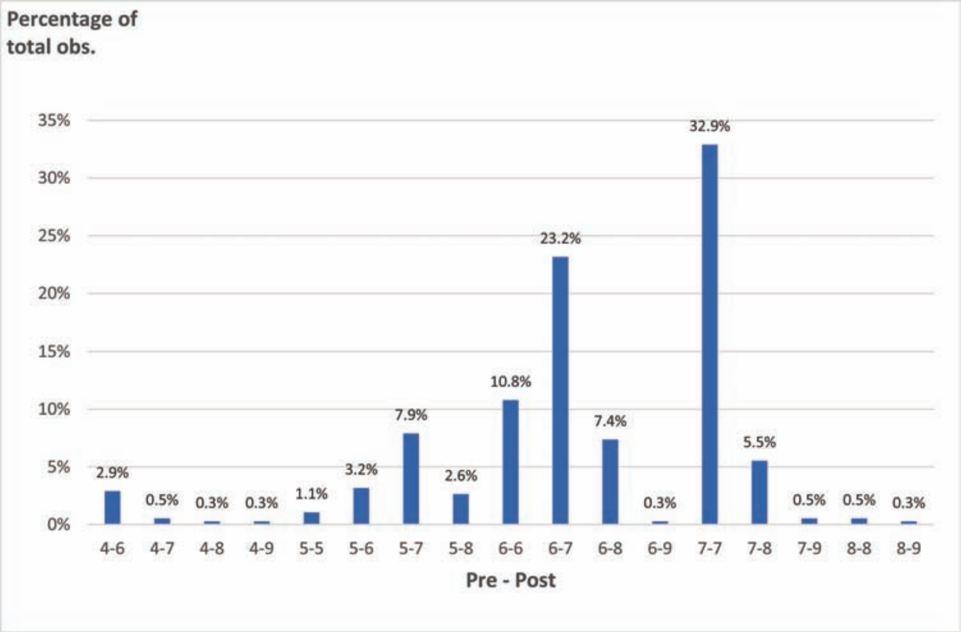

Figure 3.2 Distribution of pre- and post-LMC overlay deck condition change.

is natural logarithm of the deck condition prior to the implementation of the LMC overlay, where $PreDeck \in \{4,5,6,7,8\}$. Table 3.5 presents the details of the model estimation.

It is found that ln(*PreDeck*) is statistically significant (p-value almost zero) and the sign of the parameter is negative, indicating that the pre-treatment deck condition imposes an inverse effect on the performance jump, that is, the higher (lower) the pre-treatment deck condition, the smaller (greater) the performance jump will be.

The effect of LMC overlay on the wearing surface condition also needs to be investigated, because the trigger of LMC overlay is primarily based on the wearing surface condition rather than the deck condition. Figure 3.3 presents the distribution of the historical trigger values in terms of wearing surface condition for LMC overlay. The total number of observations is 66.

It can be observed that the majority of LMC overlays was carried out when the wearing surface condition was 5, and nearly 25% carried out at 6. These historical data represent the actual practices, not necessarily the optimal choices. As for the post-treatment wearing surface condition, because LMC overlay is a complete replacement of the existing wearing surface, the post-treatment wearing surface should be regarded as new and its condition should theoretically be 9, although in reality, it was often recorded as 8. In the current study, it is assumed that the wearing surface condition returns to 9 after an LMC overlay (Zhang, 2016).

3.3.2 Polymeric Overlay

Polymeric overlay (or polymer overlay) has not been used much by INDOT until recent years. Therefore, not enough observations are found in the databases to build statistical models. According to INDOT experts, a polymeric overlay itself typically does not lead to improvement in deck condition, but other repair work such as deck patching prior to the polymeric overlay could result in moderate improvement to the deck. Polymeric overlay can also be applied to a new deck as a preventive maintenance rather than a rehabilitation treatment.

Based on the limited number of observations, the trigger values of wearing surface condition for polymeric overlay can be 8, 7, 6, or 5. The treatment effects in terms of change in deck condition (pre-post) can be (with relative frequency) 8-8 (13%), 7-8 (9%), 7-7 (30%), 6-7 (21%), 6-6 (18%), and 5-6 (9%). As for the post-treatment wearing surface condition, similar to LMC overlay, it is assumed that the wearing surface condition returns to 9 after a polymeric overlay (Zhang, 2016).

TABLE 3.5
Model Estimation Results of LMC Overlay Performance Jump

Variable	Coefficient	Std. Err.	t-Statistic	p-Value
Intercept	8.9145	0.4047	22.0251	9.27E-70
Ln (PreDeck)	-4.4686	0.2226	-20.060	1.79E-61
Adjusted R^2	0.514			
No. of Obs.	380			

3.4 Post-Treatment Effects

Post-treatment effects refer to how the bridge deck and wearing surface would perform after an LMC overlay or a polymeric overlay. It is likely that the deterioration rates would slow down by some extent for a certain period after the overlay, because as the Indiana Design Manual (INDOT, 2013) indicates, an 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. Therefore, the deterioration curve after the treatment may not follow the same pattern as that before the treatment, and the service life of the bridge deck would probably be extended.

3.4.1 Latex-Modified Concrete (LMC) Overlay

For LMC overlay, the post-treatment deck performance uses the same deterioration curves shown in

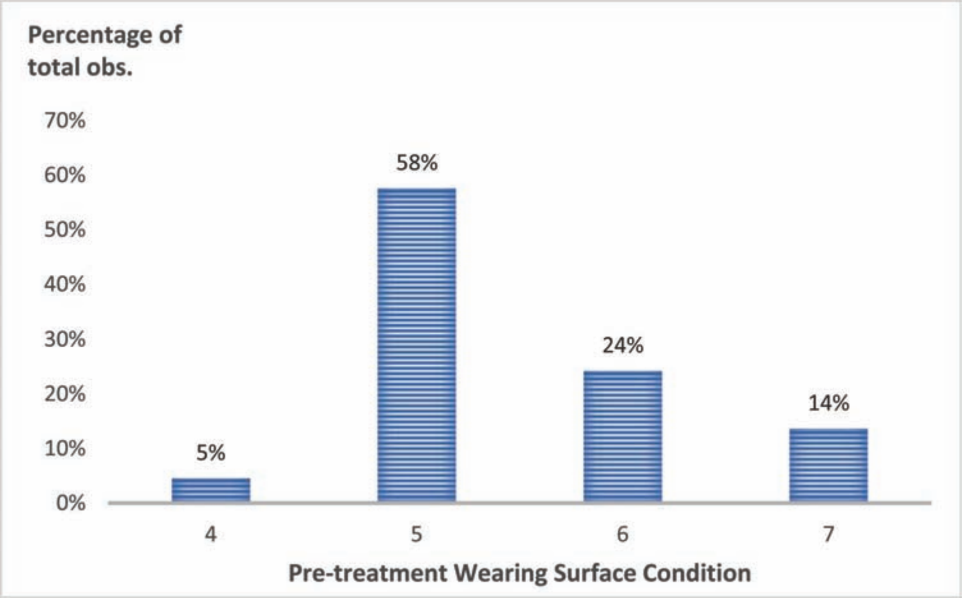

Figure 3.3 Distribution of pre-LMC overlay wearing surface condition (Triggers).

Section 3.2.1, but the post-treatment deterioration restarts from a "jumped" condition based on the performance jump model developed in Section 3.3.1. Although this method does not reflect the decrease in the deterioration rates, it captures the extension of deck service life in an alternative way. The Indiana Design Manual (INDOT, 2013) indicates that LMC overlays typically protect the deck for 15 ± 5 years.

The post-treatment wearing surface performance is considered using the wearing surface models under different "initial deck condition" discussed in Section 3.2.2. For example, if the deck condition is 5 when the LMC overlay is carried out, then the new wearing surface performance after the overlay would follow the model for "initial deck condition = 0 to 5," which deteriorates faster than that for "initial deck condition = 7 to 9" (Zhang, 2016).

3.4.2 Polymeric Overlay

For polymeric overlay, the effect on the extension of deck service life was attempted to be estimated based on the limited project observations. Specifically, for a particular bridge on which a polymeric overlay was implemented, its post-treatment deck condition for each year was tracked. Then from the NBI database, other bridges that have similar characteristics (highway district, functional class, ADT, truck percentage, etc.) to that bridge and have not experienced overlays were sorted out. The average time that these bridges stay at certain conditions were determined (e.g., condition 8 for t_1 years, 7 for t_2 years, 6 for t_3 years), and these averaged results were compared with the life of the bridge with a polymeric overlay. However, due to the small sample issue, significant variation was found. The best estimate that can be made from the data is that polymeric overlay could extend the deck service life for approximately 5 to 8 years, which may also be affected by the deck condition when the polymeric overlay is applied. The Indiana Design Manual (INDOT, 2013) states that the average service life of polymeric overlays is approximately 10 years. As for post-treatment wearing surface performance, the same method as for LMC overlay mentioned in Section 3.4.1 was used (Zhang, 2016).

3.5 Cost Models

3.5.1 Agency Costs

Agency cost models were developed based on both the SPMS database that contains contract costs from 1994 to 2010 and the Site Manager database that contains more detailed contract pay item costs from 2009 to 2012. Costs in different years were converted into 2010 constant dollars using the National Highway Construction Cost Index (NHCCI) (FHWA, 2015).

3.5.1.1 LMC Overlay Unit Cost Model. The cost data for the LMC overlay was not only for the LMC wearing surface itself, but also for the LMC overlay contracts that typically included hydrodemolition and deck patching, which are the preparation work for the LMC overlay, and asphalt wedging of the approach roadway because LMC overlays raise the driving surface of the bridge. Therefore, the unit cost of LMC overlays is likely to be affected by the pre-treatment deck condition because more preparation work may be needed when the LMC overlay is placed on a deck in poorer condition. Besides, very often the unit cost of a construction work is affected by the economies of scale. In this case, specifically, the greater the deck area (overlay area) is, the lower the unit cost is likely to be.

To account for these factors, the variables of pre-treatment deck condition and deck area were included, and the following model form that captures the economies of scale in terms of deck area was adopted:

$$\ln(UCL) = \beta_0 + \beta_1 \cdot PreDeck + \beta_2 \cdot \ln(DeckArea) + \varepsilon \quad (3.5)$$

where UCL is the unit cost of the LMC overlay contract (\$/ft^2), $PreDeck$ is the deck condition before the LMC overlay is placed, $DeckArea$ is the total area of the deck (ft^2) that is assumed to represent the LMC overlay area, $ln(\cdot)$ represents the natural logarithm, $\beta_i, i = 1,2,3$ are the estimated parameters, β_0 is the estimated constant term, and ε is the disturbance term.

The estimation results are presented in Table 3.6. The t-statistics and p-values indicate that both the pre-treatment deck condition and the deck area have significant influences on the LMC overlay unit cost. The signs of the variables are also intuitive. Specifically, better pre-treatment deck condition would decrease the unit cost, and larger deck area would also reduce the unit cost, reflecting the economies of scale. The sample mean of the LMC overlay unit cost is calculated to be \$62.81/ft^2, and the sample standard deviation is \$44.47/ft^2 which is quite large, given the sample mean.

Figure 3.4 illustrates the LMC overlay unit cost model results, including the raw data points and the fitted curves. The models for different pre-treatment deck condition are plotted separately (Zhang, 2016).

3.5.1.2 Polymeric Overlay Unit Cost Model. Because the number of polymeric overlay contracts is limited, it is difficult to build a reliable cost model from the limited data. Therefore, in the current study, a cost formula

TABLE 3.6
Model Estimation Results of LMC Overlay Unit Cost (\$/ft^2)

Variable	Coefficient	Std. Err.	*t*-Statistic	*p*-Value
Intercept	9.4748	0.5138	18.440	9.78E-54
PreDeck	-0.0897	0.0417	-2.150	0.0322
Ln (DeckArea)	-0.5634	0.0484	-11.655	8.45E-27
Adjusted R^2		0.276		
No. of Obs.		358		

provided by INDOT is adopted. The formula is as follows:

$$CPO = [(DeckArea \times 16.8) + 35000] \times 1.05 \tag{3.6}$$

where CPO is the total cost of the polymeric overlay contract ($), $DeckArea$ is the total area of the deck (ft^2) that is assumed to represent the polymeric overlay area, 35000 is the estimated cost of maintenance of traffic (MoT) ($), and 1.05 is a multiplier.

The unit cost can be easily obtained through dividing both sides of the formula by DeckArea: Unit Cost = (16.8+35000/DeckArea)*1.05. This unit cost formula indicates the economies of scale in terms of the deck area. Figure 3.5 illustrates the effect. The unit cost of polymeric overlay decreases as the deck area increases (Zhang, 2016).

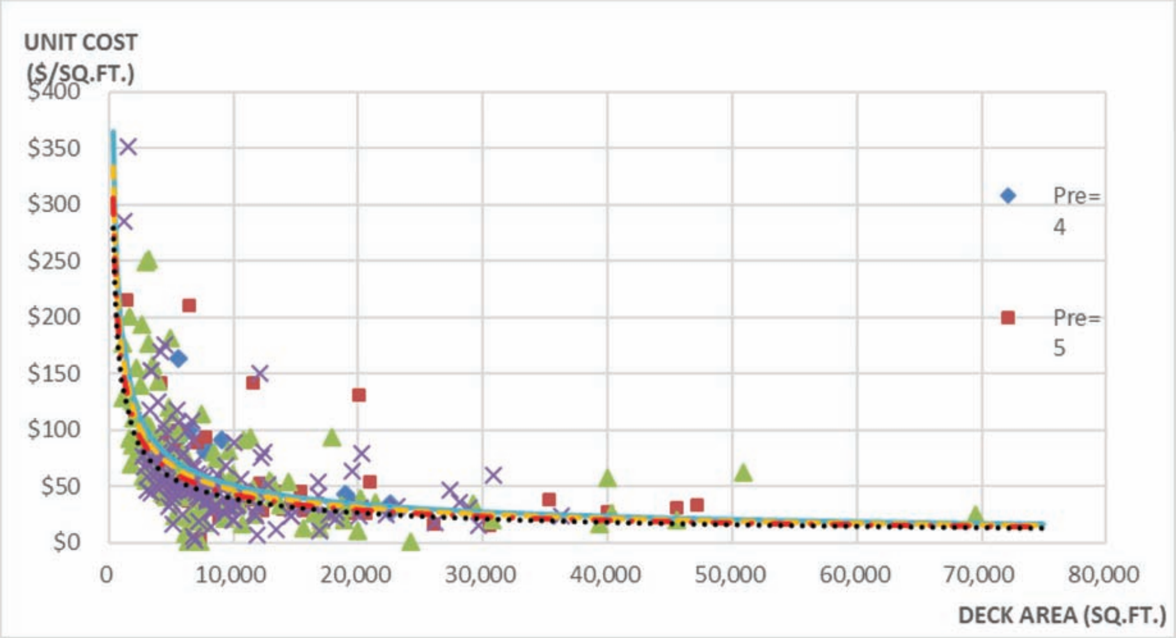

Figure 3.4 LMC overlay unit cost models.

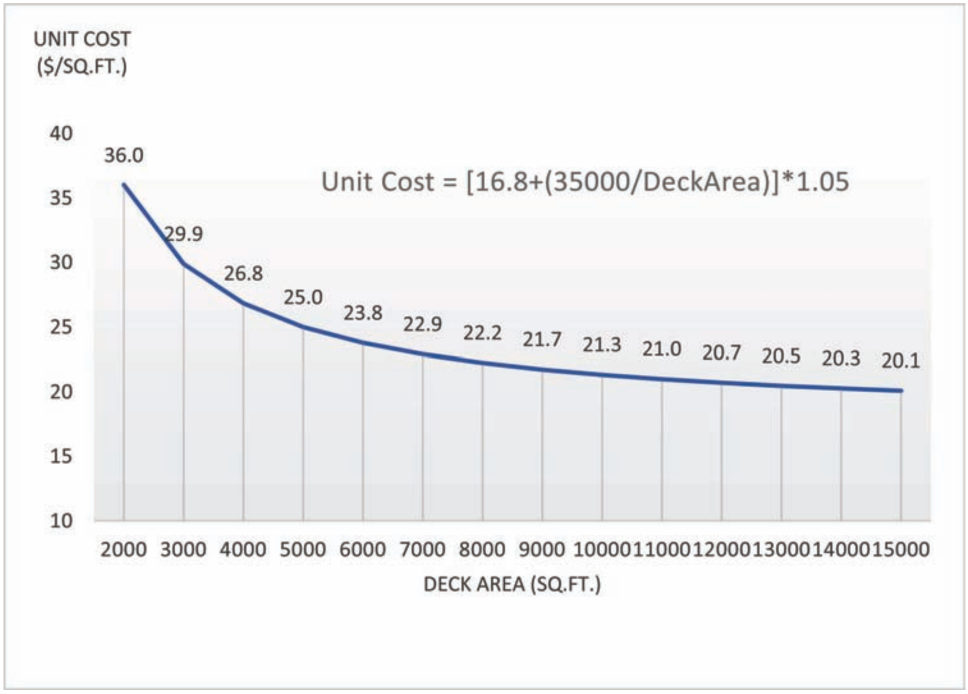

Figure 3.5 Polymeric overlay unit cost model.

3.5.1.3 Deck Replacement, Deck Patching, and Other Maintenance Costs. For deck replacement, the unit cost was not found to be statistically significantly related to either deck area or pre-treatment deck condition. Therefore, only the average unit cost was used. The average unit cost for bridge deck replacement was found to be \$76.22/ft^2 in 2010 constant dollars, and the standard deviation was \$50.10/ft^2.

For partial-depth deck patching, the patching area was found to be a statistically significant variable, implying the economies of scale, although the overall model fit (adjusted R-squared) was not high. Model estimation results are presented in Table 3.7. The average unit cost of partial-depth patching based on the contract data in Site Manager is \$34.46/ft^2 in 2010 constant dollars, with standard deviation \$47.25/ft^2.

For full-depth deck patching, the patching area was not found to be a statistically significant variable. Thus, only the average unit cost was used: \$48.56/ft^2 in 2010 constant dollars, with standard deviation \$68.13/ft^2.

For other maintenance and repair costs, the data in the IBMS manual (Sinha et al., 2009) was used as a reference. Table 3.8 presented the costs in 2007 constant dollars for the Interstates and other highways. Bridge hand cleaning and flushing is carried out every year in Indiana. However, the activity types "bridge repair" and "other bridge maintenance activities" are ambiguous. It is assumed in the analysis that they are also maintenance work carried out on an annual basis (Zhang, 2016).

3.5.1.4 Inflation Rate of Agency Costs. To figure out the average annual inflation rate for agency costs, the National Highway Construction Cost Index (NHCCI) by FHWA (2015) was used. Because the NHCCI set the index for 2003 as 1.0 and the indices for other years are all compared with 2003, the equation to calculate the average annual inflation rate is:

TABLE 3.7
Model Estimation Results of Partial-Depth Deck Patching Unit Cost (\$/ft^2)

Variable	Coefficient	Std. Err.	t-Statistic	p-Value
Intercept	99.5434	23.3809	4.257	0.00012
Ln (DeckArea)	-11.1393	3.8293	-2.909	0.00589
Adjusted R^2		0.154		
No. of Obs.		42		

TABLE 3.8
Unit Costs for Other Bridge Maintenance and Repairs (\$/Activity Unit)

Activity Type	Activity Unit	Interstates	Other Highways
Hand Cleaning	Per Deck	64.87	51.26
Flushing	Per Deck	38.67	34.14
Bridge Repair	Per Repair	463.28	455.87
Other Maintenance	Per Maintenance	378.90	337.32

$$Index_i \times (1+r)^{j-i} = Index_j \tag{3.7}$$

where r is the average annual inflation rate to be determined, $Index_i$ and $Index_j$ are the NHCCI in Year i and j, respectively.

The calculated average annual inflation rate for agency M&R costs using 2010-2014 NHCCI is 1.15%.

In addition, the life-cycle cost analysis of the current study used a discount of rate of 4%, which is the rate typically used by INDOT (Jiang, Zhao, & Li, 2013).

3.5.2 User Costs

The user costs considered in the current study are the travel time delay due to work zones of bridge deck rehabilitation (overlays) and deck replacement, and the incremental vehicle operating costs (VOC) during normal operations caused by the increasing wearing surface roughness.

3.5.2.1 Travel Time Costs due to Work Zone Delay. The estimated average work zone durations of various M&R activities were provided by INDOT engineers and presented in Table 3.1 under Section 3.1.5. It was mentioned in Table 3.1 that lane-closure policy is typically used when there are four or more lanes, and detour policy is used when there are fewer than four lanes. In the current study, it is assumed that the lane-closure policy is used for deck rehabilitation work on NHS highway bridges, because NHS highway bridges typically have more lanes and these bridges are more important links that are typically not entirely closed to traffic, while the detour policy is used for deck rehabilitation work on non-NHS bridges. For bridge deck replacement work, it is assumed that detour policy is used for all bridges.

For bridges using the lane-closure policy, the method for estimating the travel time costs of delay is:

$$TTC = \sum_{i=1}^{k} TTC_i = \sum_{i=1}^{k} [VTT_i \times (\frac{L}{S_{iC}} - \frac{L}{S_{iN}}) \times ADT_i \times D_R] \tag{3.8}$$

where TTC_i represents of the travel time costs (\$) of vehicle class i, k is the total number of vehicle classes, VTT_i is the average value of travel time (\$/hr) of vehicle class i, L is the structure length (mi) of the bridge, S_{iC} is the average travel speed (mph) of vehicle class i on the bridge during lane closure period, S_{iN} is the average travel speed (mph) of vehicle class i on the bridge during normal operation period, ADT_i is the average daily traffic of vehicle class i crossing the bridge, D_R is the average work zone duration (days) of the rehabilitation activity R.

For bridges using the detour policy, the method for estimating the travel time costs of delay is:

$$TTC = \sum_{i=1}^{k} TTC_i = \sum_{i=1}^{k} [VTT_i \times (\frac{DL}{S_{iD}} - \frac{L}{S_{iN}}) \times ADT_i \times D_R] \quad (3.9)$$

where TTC_i represents of the travel time costs ($) of vehicle class i, k is the total number of vehicle classes, VTT_i is the average value of travel time ($/hr) of vehicle class i, DL is the detour length (mi) assigned for each bridge in the NBI database, S_{iD} is the average travel speed (mph) of vehicle class i on the detour route during bridge closure period, L is the structure length (mi) of the bridge, S_{iN} is the average travel speed (mph) of vehicle class i on the bridge during normal operation period, ADT_i is the average daily traffic of vehicle class i crossing the bridge,D_R is the average work zone duration (days) of the rehabilitation activity$R$.

For the current study, due to data availability, the vehicles are grouped only as autos and trucks. Regarding value of travel time, there is significant variability among studies. The current study adopted data from Sinha and Labi (2007). The values of travel time for autos and trucks are approximately $26/hr and $35/hr, respectively, in 2005 dollars. Detour length (DL), structure length (L), and ADT_i (i = auto, truck) are taken from the NBI database. S_{iC} and S_{iD} are both assumed to be 35 mph. S_{iN} is assumed to be 55 mph for NHS and 45 mph for non-NHS. D_R takes the average value from Table 3.1. For example, work zone duration of LMC overlay using detour is 4–8 weeks, thus 6 weeks (42 days) is used for the current study (Zhang, 2016).

3.5.2.2 Vehicle Operating Costs due to Surface Roughness

3.5.2.2 Vehicle Operating Costs due to Surface Roughness. The vehicle operating costs caused by increasing surface roughness during normal traffic operations are sometimes not considered in previous studies. However, such costs could account for a significant proportion of the user costs. As indicated by Sinha and Labi (2007), motion of vehicle tires on a rough pavement surface is associated with greater resistance to movement, which can lead to higher levels of fuel consumption compared to traveling at a similar speed on a smooth surface; and a bumpy ride, which leads to increased vibration and wear and tear on vehicle parts. Also, an indirect effect of poor surface conditions is that road users may be forced to drive at lower speeds, leading to higher fuel consumption. Therefore, M&R projects such as overlays that improve deck surface condition can lead to reductions in VOCs.

In the current study, the VOCs included in the user costs are the incremental VOCs—the additional VOCs due to increased roughness (i.e., the total VOCs minus the base VOCs for a new wearing surface). The equation for the VOC adjustment factor is from Barnes and Langworthy (2003):

$$m = 0.001 \cdot [(IRI - 80)/10]^2 + 0.018 \cdot [(IRI - 80)/10] + 0.9991 \quad (3.10)$$

where IRI is the international roughness index of the road surface (bridge deck surface, in the current study) and m is the calculated VOC adjustment multiplier. The relationship between the incremental VOCs and the IRI is presented in Figure 3.6. The equation sets IRI = 80 as the base IRI with its m = 1.00. When the IRI starts to increase, m also increases. Then, the incremental VOCs due to surface roughness is calculated as $Base\_VOC \times (m - 1.0)$.

No IRI models were found in the existing literature for bridge wearing surface or deck surface. Therefore, the IRI performance models developed for pavements are used instead. It is expected that this assumption will not have much impact on the results, because a bridge deck with bituminous wearing surface is similar to a composite pavement (flexible on rigid), and a deck with

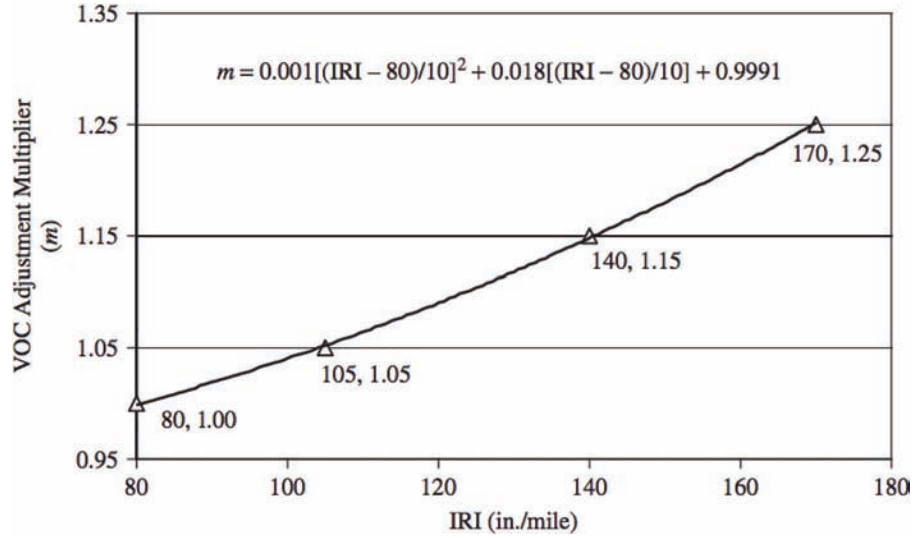

Figure 3.6 VOC adjustment factors for surface roughness (Barnes & Langworthy, 2003).

LMC overlay is similar to PCCP overlay on a PCC pavement.

Two forms of IRI performance models were tried. The first is the exponential form developed by Irfan, Khurshid, Labi, and Flora (2009) and Khurshid, Ifran, Labi, and Sinha (2008):

$$IRI = e^{(\beta_0 + \beta_1 \cdot AATT \cdot t + \beta_2 \cdot ANDX \cdot t)} \tag{3.11}$$

where IRI is the value of international roughness index (in/mi) for a treated pavement section in a given year after treatment, $AATT$ is the average annual truck traffic (in millions), $ANDX$ is the average annual freeze index (in thousands), t is the time since the pavement treatment (years), and βs are the estimated coefficients.

The second IRI performance model is the linear form developed by Bardaka (2012):

$$IRI = -232.26 + 4.863 \times Treatment\_Age + 1.368 \times Precipitation + 117.84 \times Log(Pretreatment\_IRI) \tag{3.12}$$

where *Treatment_Age* is the time since the pavement treatment (years), *Precipitation* is in in/year, *Log* is the logarithm to the base 10, and *PreTreatment_IRI* is the IRI (in/mi) prior to the pavement treatment.

The exponential form resulted in a deterioration rate that seemed unreasonably fast when applied to the bridge wearing surface. The linear form led to more reasonable results, so it was adopted for the current study. For the base VOC, the current study used the value from the IBMS manual (Sinha et al., 2009)—1.5 dollars per mile for all vehicle types, in 2007 dollars.

3.5.2.3 Inflation Rate of User Costs. The consumer price index (CPI) published by the Bureau of Labor Statistics (2016) was used to calculate an average annual inflation rate for user costs. The method is similar to that for calculating the inflation rate for agency costs:

$$CPI_i \times (1+r)^{j-i} = CPI_j \tag{3.13}$$

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

The calculated average annual inflation rate of user costs using 1999–2014 CPI data is 2.35%, and it is assumed to remain the same for the analysis period in the current study.

The annual growth of traffic is also considered. Increasing number of road users lead to increasing user costs. The average annual traffic growth factor for Indiana is calculated as 0.72%, as was mentioned in Section 3.1.2.

With respect to the issue of weights between agency costs and user costs, the current study conducted sensitivity analyses using agency:user weights from 1:1 to 10:1. The results are presented in the next chapter.

3.6 Optimization of Life-Cycle Costs

The optimization framework in the current study is based on life-cycle cost analysis (LCCA). The objective is to minimize the sum of the weighted agency costs and user costs incurred during the entire service life of the bridge deck, by selecting the appropriate condition thresholds that trigger deck rehabilitation treatments (LMC overlays and polymeric overlays) and deck replacement. The selection of the triggers will affect the life-cycle deterioration trend of the bridge deck and wearing surface, and the frequency of implementing the treatments. It will thus affect the service life of the deck, and the incurred agency costs and user costs during the life cycle. There are typically upper and lower bounds on the triggers for implementing the treatment. The upper and lower bounds in the current study are based on historical data and expert opinions.

The formulation of the optimization problem is as follows:

Objective function:

$$\min_{T_p,T_l,T_r} \sum_{t=1}^{L} \left[(AC_t + wUC_t) \cdot \frac{1}{(1+r)^t} \right] \cdot \frac{r(1+r)^L}{(1+r)^L - 1} \tag{3.14}$$

where AC_t and UC_t are the agency costs and user costs incurred in year t; w is the weight for user costs; T_p, T_l, and T_r are the trigger conditions for polymeric overlay, LMC overlay, and deck replacement, respectively; L is the service life of the bridge deck given T_p, T_l, and T_r; and r is the discount rate.

In Equation 3.14,

$$AC_t = I_{mt}C_m + I_{pt}C_p + I_{lt}C_l + I_{rt}C_r \tag{3.15}$$

$$UC_t = VOC_t + I_{wt}TTC_w \tag{3.16}$$

$$L = f_L(T_p, T_l, T_r) \tag{3.17}$$

where C_m, C_p, C_l, and C_r are the costs for minor repairs and maintenance (m), polymeric overlays (p), LMC overlays (l), and deck replacement (r); $I_{xt} \in \{0,1\}$, $\forall t, x = m,p,l,r$ (i.e., I_{xt} is the indicator of whether treatment x is implemented in year t); VOC_t is the total vehicle operating costs in year t; TTC_w is the travel time costs due to work zone delays; I_{wt} is the indicator of whether there are work zone delays in year t; and L is a function of T_p, T_l, and T_r.

In Equation 3.15,

$$C_p(T_p, q_p) = u_p(T_p, q_p) \cdot q_p \tag{3.18}$$

$$C_l(T_l, q_l) = u_l(T_l, q_l) \cdot q_l \tag{3.19}$$

$$C_m(q_m) = u_m(q_m) \cdot q_m \tag{3.20}$$

$$C_r(q_r) = u_r(q_r) \cdot q_r \tag{3.21}$$

where C_p (as a function of T_p and q_p) is equal to the product of the unit cost of polymeric overlay u_p (as a function of T_p and q_p) and the quantity of polymeric overlay q_p (e.g., in areas); C_l (as a function of T_l and q_l) is equal to the product of the unit cost of LMC overlay u_l (as a function of T_l and q_l) and the quantity of LMC overlay q_l (e.g., in areas); C_m (as a function of q_m) is equal to the product of the unit cost of minor repairs and maintenance u_m (as a function of q_m) and the quantity of minor repairs and maintenance q_m (in various units); and C_r (as a function of q_r) is equal to the product of the unit cost of deck replacement u_r (as a function of q_r) and the quantity of deck replacement q_r (e.g., in areas).

In Equation 3.16,

$$VOC_t = f_V(T_t, WS_t) \tag{3.22}$$

$$WS_t = f_W(A_w, PJ_w, O_w) \tag{3.23}$$

$$TTC_w = f_T(ADT, D, MoT) \tag{3.24}$$

where incremental VOCs due to surface roughness in year t (VOC_t) is a function of total traffic volume in year t (T_t) and the wearing surface condition at year t (WS_t); WS_t is a function of the age of wearing surface (A_w), the performance jumps in wearing surface condition due to treatments (PJ_w), and other factors (O_w) that affect wearing surface condition such as traffic and climate condition; travel time costs due to work zone delays (TTC_w) are a function of average daily traffic (ADT) affected by the work zones, detour length (D), and type of maintenance of traffic (MoT) that affects the work zone durations and lane closure policies.

In Equation 3.17,

$$L = f_L(T_p, T_l, T_r) = f_D^{-1}(T_r) \tag{3.25}$$

$$DK_t = f_D(A_d, PJ_d, O_d) \tag{3.26}$$

where deck service life (L) that is determined by T_p, T_l, and T_r is also equal to the time when deck condition (DK) reaches T_r (an inverse function of f_D); f_D is the function for deck condition at year t that is affected by the age of the deck (A_d), the performance jumps in deck condition due to treatments (PJ_d), and other factors (O_d) that affect deck condition, such as traffic and climate condition.

Constraints:

$$T_{pl} \le T_p \le T_{pu} \tag{3.27}$$

$$T_{ll} \le T_l \le T_{lu} \tag{3.28}$$

$$I_{pt} = 1 \text{ if } WS_t = T_p \tag{3.29}$$

$$I_{lt} = 1 \text{ if } WS_t = T_l \tag{3.30}$$

$$I_{rt} = 1 \text{ if } DK_t = T_r \tag{3.31}$$

$$I_{mt} + I_{pt} + I_{lt} + I_{rt} = 1, \forall t, \; for \; I_{mt}, I_{pt}, I_{lt}, I_{rt} \in \{0,1\} \tag{3.32}$$

$$I_{wt} = 1 \text{ if } I_{pt} + I_{lt} + I_{rt} = 1, \forall t \tag{3.33}$$

where in constraints Eq. 3.27 and Eq. 3.28, T_{pl} and T_{pu} are the lower bound and upper bound for the trigger of polymeric overlay, based on historical data and expert opinions; T_{ll} and T_{lu} are the lower bound and upper bound for the trigger of LMC overlay, based on historical data and expert opinions; constraints Eq. 3.29, Eq. 3.30, and Eq. 3.31 mean that costs for p, l, and r are incurred only when these treatments are triggered; constraint Eq. 3.32 means that for any given year t, only one type of treatment among m, p, l, and r is implemented; constraint Eq. 3.33 means that costs for work zone delays are incurred only when p, l, or r is implemented.

Considering that the mathematical formations presented above used some general function forms $f(\cdot)$, they may lose some detail regarding the interactions among different variables and parameters. Also, the overall problem solving process is not intuitive. Therefore, explanatory graphs, as presented in Figures 3.7, 3.8, and 3.9 on the following page, are created to better illustrate and explain all the parameters and variables, and the overall ideas of this optimization problem. Figure 3.7 shows how the deck condition and wearing surface condition change with the implementation of treatments, and Figures 3.8 and 3.9 show the agency costs and the user costs incurred throughout the bridge deck service life (Zhang, 2016).

It should be noted that Figures 3.7 through 3.9 present only one example scenario of the life-cycle M&R strategies, that is, one polymeric overlay followed by another LMC overlay before deck replacement. The figures serve to provide a conceptual illustration; the magnitudes may be exaggerated or reduced. In Figure 3.9, the incremental VOCs refer to the additional vehicle operating costs during normal operations caused by increasing deck surface roughness, that is, the total VOCs minus the base VOCs associated with a new wearing surface.

4. RESULTS AND ANALYSIS

This chapter presents the results derived from the methodology established in the previous chapter. Analysis and implications of the results are also discussed.

The results are presented in terms of three district categories (northern: Fort Wayne and LaPorte; central: Crawfordsville and Greenfield; southern: Seymour and Vincennes), two highway functional class categories (NHS and non-NHS), and two overlay implementation strategies (LMC overlays only, and polymeric overlay

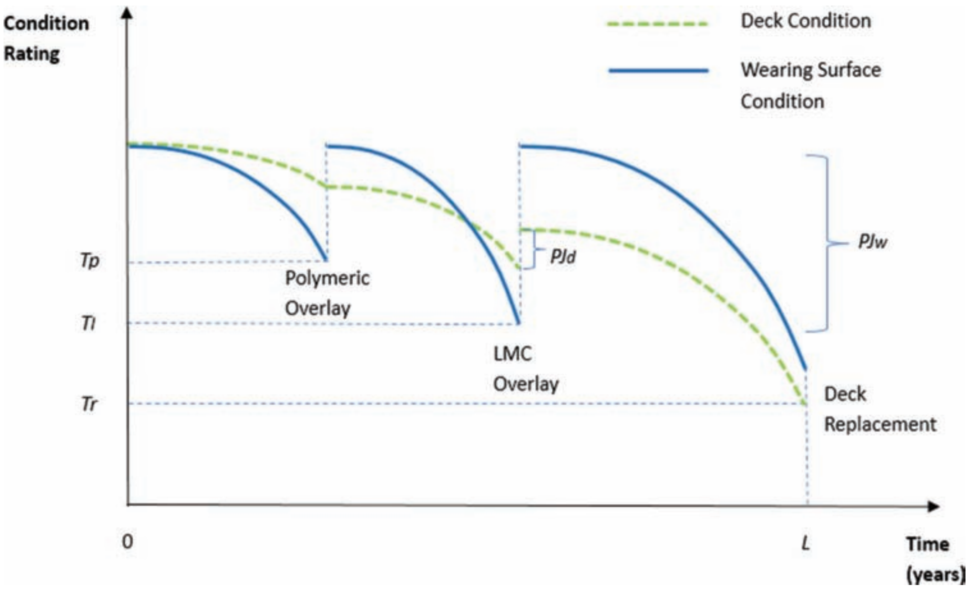

Figure 3.7 Illustration of change in deck and wearing surface deterioration due to M&R treatments.

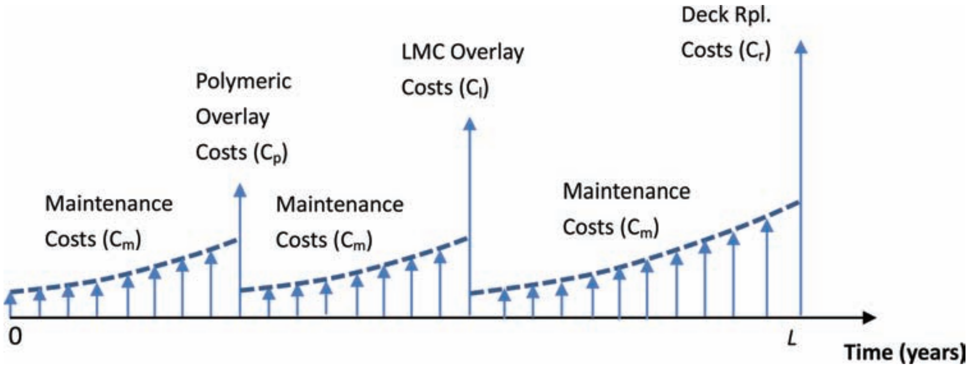

Figure 3.8 Illustration of agency costs incurred through deck service life.

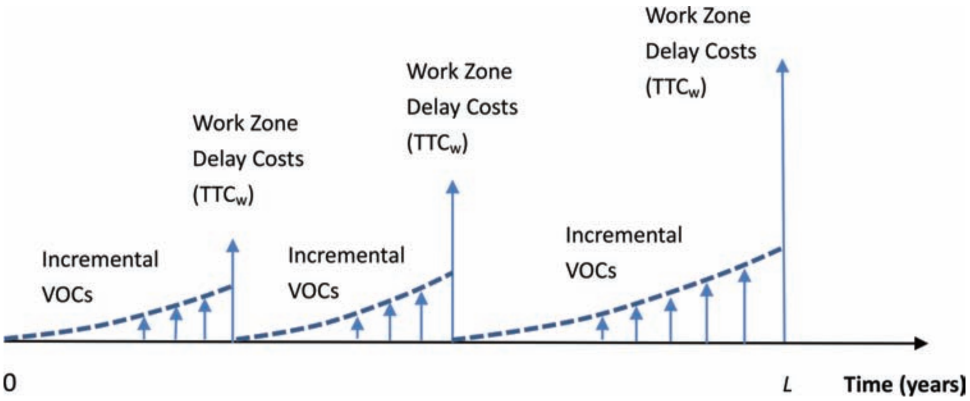

Figure 3.9 Illustration of user costs incurred through deck service life.

followed by LMC overlays). Therefore, the results contain a total of $3 \times 2 \times 2 = 12$ combinations of categories.

The highway districts were analyzed separately because different highway districts in Indiana typically have different climate conditions, such as average temperature and annual precipitations, that affect the deterioration of bridge components. The wearing surface models developed by INDOT and the deck models developed by Moomen et al. (2015) all had different parameters for different districts. The highway functional classes were also analyzed separately because NHS highways tend to have higher design standards, and the distributions of vehicle classes also vary across different functional classes. Regarding the overlay strategies, polymeric overlays have been used more frequently in the last 10 years in Indiana. The polymeric overlays are typically implemented on a deck in a relatively good condition or even on a new deck as a preventive maintenance treatment. LMC overlays are typically used on an older deck as a corrective treatment. Therefore, the current study considered two alternative overlay strategies: (1) only LMC overlays are implemented one or more times during the life cycle of the deck; (2) polymeric overlay is placed at an early stage of the life cycle, and then LMC overlays are used as deck rehabilitation treatments once or more during the rest of the life cycle.

4.1 Basic Bridge Statistics and Climate Data for Indiana Highway Districts

The basic statistics for bridges in the six Indiana highway districts are summarized in Table 4.1, including average daily traffic (ADT) on the bridges, percent trucks on the bridges, detour length, structure length, and deck widths. The data in Table 4.1 were used in the deterioration models and in calculating user costs.

The basic climate statistics for the six Indiana highway districts are presented in Table 4.2. The data were collected from National Oceanic and Atmospheric Administration (NOAA). They were used in some of the deck deterioration models and the IRI model as variables.

4.2 Life-Cycle Cost Analysis Results

Based on the models developed in Sections 3.2 through 3.5, the optimization framework discussed in Section 3.6 was applied to obtain the appropriate trigger condition results.

In terms of the upper and lower bounds defined in constraints 3.27 and 3.28, based on the historical data and expert opinions from INDOT engineers, LMC overlays were chosen to be applied when the wearing surface condition lies between 5 and 7 (i.e., $T_{ll} = 5$ and $T_{lu} = 7$), and polymeric overlays were chosen to be applied when the wearing surface condition lies between 6 and 8 (i.e., $T_{pl} = 6$ and $T_{pu} = 8$). In addition, the Indiana Design Manual (INDOT, 2013) requires that the deck must have a condition rating of 5 or higher when the LMC overlay is implemented, and both the wearing surface and the deck must have a condition rating of 5 or higher when the polymeric overlay is implemented. For LMC overlays, WS = 8 is not considered because LMC overlay is a rehabilitation treatment and is not used on a new deck. WS = 4 is not considered because, when the wearing surface condition drops to 4, the deck condition would typically drop under 5, which violates the requirement of the Indiana Design Manual. Besides, the roughness of the wearing surface would be too severe for the road users when its condition reaches 4.

The variable that determines the deck service life (L) is the trigger condition for deck replacement (T_r). In the analysis, T_r was set to 4, which is the lower bound condition for deck replacement, because most decks were found to be replaced at condition 4. Some cases with deck replacement at condition 5 or higher could be based on geometric considerations rather than structural considerations. Therefore, for the current study, only the triggers for polymeric overlays (T_p) and LMC overlays (T_l) were used as the variables to be optimized.

Because the condition ratings of bridge components use integers from 0 to 9, the enumeration technique can be used to investigate the life-cycle cost results for every candidate trigger threshold. Such a method would also help complete the tasks of examining the consequences of inappropriate (premature or deferred) timing of treatments.

In this chapter, the life-cycle cost analysis results for only one typical district and functional class category are presented, due to space limitations. The results for other districts and functional classes can be found in the Appendix A of this volume.

Table 4.3 and Figure 4.1 present the results for the bridges on NHS highways in central districts. The life-cycle costs were calculated in terms of EUAC (Equivalent Uniform Annual Cost) for comparisons under different analysis periods (service life). The EUACs were normalized by deck area to obtain generalized results. Also, the EUACs were calculated with respect to agency costs only, user costs only, and total costs.

This scenario assumed that only LMC overlays are implemented throughout the life cycle. “Do nothing” serves as a base case for the purpose of comparison, and it assumes that no major deck rehabilitation treatments (LMC overlays) are applied, except for minor repairs and maintenance. Triggers at “5,” “6,” or “7” mean that the LMC overlays are implemented when the surface condition of the deck reaches 5, 6, or 7. LMC overlays are allowed to be used for multiple times during the service life of the deck. In the current study, it turns out that LMC overlay is used once for Trigger 5, twice for Trigger 6, and three times for Trigger 7, given that the deck is replaced at condition 4. The trend makes sense because, if the overlay is triggered at a better condition, it will be triggered more frequently. According to INDOT practices, for steel bridges, typically 1 to 2 applications of LMC overlays are implemented before the deck is replaced; for concrete bridges, 2 to 3 LMC overlays are implemented. The detailed life-cycle strategies are illustrated by Figures 4.4 through 4.6 in the next section of this chapter (Zhang, 2016).

Based on the results in Table 4.3, under the “do nothing” case, the deck was supposed to have a service life of 35 years (i.e., when deck condition reaches 4). If the LMC overlay is triggered at condition 5 and triggered once, deck service life was extended by 8 years and reached 43 years. Similarly, if the LMC overlay is triggered at condition 6 (or 7) for twice (or three times), deck service life would reach 47 years (or 53 years).

TABLE 4.1
Statistics for Bridges in Indiana Highway Districts (Source: NBI 2014)

Functional Class		INT	NHS	NNHS	INT	NHS	NNHS
Northern Districts		**Fort Wayne**			**LaPorte**		
ADT	Mean	11,641	8,605	6,295	36,054	11,797	8,817
	Max	53,146	52,193	52,422	181,670	88,373	171,080
	Min	102	102	711	110	102	102
Truck%	Mean	13	13	9	14	10	9
	Max	43	58	50	37	46	40
	Min	4	4	1	5	2	0
Detour Length (km)	Mean	3	4	7	2	6	7
	Max	40	19	64	10	37	40
	Min	2	2	2	2	0	2
Structure Length (m)	Mean	57	42	37	64	57	46
	Max	376	245	250	337	366	417
	Min	17	10	7	18	8	7
Deck Width (m)	Mean	14	13	12	21	15	14
	Max	30	34	34	108	34	52
	Min	9	10	8	8	10	8
Central Districts		**Crawfordsville**			**Greenfield**		
ADT	Mean	16,174	7,217	3,696	53,132	10,560	6,798
	Max	61,680	37,139	35,010	280,000	54,620	45,216
	Min	3,870	733	130	1,115	0	804
Truck%	Mean	28	10	11	9	8	9
	Max	50	62	46	99	28	19
	Min	5	2	1	2	4	1
Detour Length (km)	Mean	3	8	9	2	5	6
	Max	37	108	50	10	24	37
	Min	0	2	0	0	2	2
Structure Length (m)	Mean	67	53	42	66	41	35
	Max	598	643	641	1,069	248	166
	Min	16	7	6	9	7	7
Deck Width (m)	Mean	14	13	11	20	14	11
	Max	71	31	28	56	45	31
	Min	11	9	5	8	8	8
Southern Districts		**Seymour**			**Vincennes**		
ADT	Mean	27,084	9,910	6,234	9,249	8,328	5,724
	Max	171,336	42,066	50,634	32,000	43,859	62,241
	Min	3,060	2,035	102	163	133	102
Truck%	Mean	11	10	9	16	9	10
	Max	34	24	23	38	32	33
	Min	5	5	2	1	5	2
Detour Length (km)	Mean	4	6	9	3	5	10
	Max	29	19	158	26	35	129
	Min	0	2	0	2	2	2
Structure Length (m)	Mean	70	53	46	74	69	45
	Max	626	269	944	1,367	733	826
	Min	18	9	7	9	8	7
Deck Width (m)	Mean	15	13	11	14	14	12
	Max	42	33	39	83	49	30
	Min	5	8	6	9	8	8

TABLE 4.2
Climate Statistics for Indiana Highway Districts (Source: NOAA)

Districts		Temperature (F)	Annual Precipitation (in)	Freeze Index
Northern	Fort Wayne	49.60	37.64	511
	LaPorte	49.67	38.83	542
Central	Crawfordsville	51.40	40.41	389
	Greenfield	50.67	39.95	390
Southern	Seymour	53.51	44.78	138
	Vincennes	55.00	46.00	85

TABLE 4.3
Life-Cycle Agency and User EUAC Results for Central Districts, NHS, LMC Overlays Only (AC:UC=1:1)

Trigger	Do Nothing	WS = 5	WS = 6	WS = 7
Deck Service Life (years)	35	43	47	53
(Agency EUAC)/(Deck Area) ($/ft^2)	**1.78**	2.69	3.85	5.14
(User EUAC)/(Deck Area) ($/ft^2)	17.33	15.14	13.24	**12.36**
(Total EUAC)/(Deck Area) ($/ft^2)	19.11	17.83	**17.09**	17.50

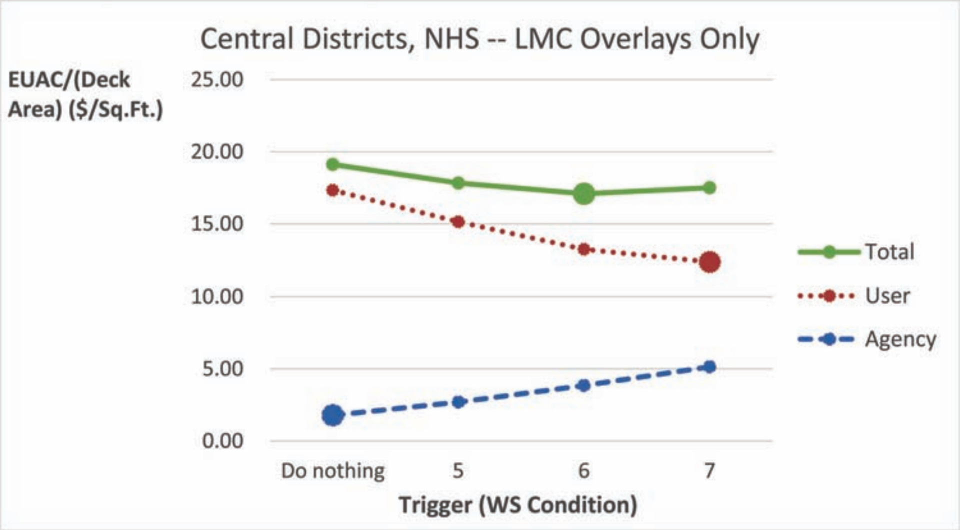

Figure 4.1 Life-cycle agency and user EUAC results for central districts, NHS, LMC overlays only (AC:UC=1:1).

With respect to the EUAC results, if only agency cost is considered, "do nothing" led to the lowest EUAC. This indicates that the extended service life due to overlay activities did not compensate the additional costs of the overlays. However, if "do nothing" is not considered as a realistic case, then Trigger 5 led to the lowest EUAC among candidate Triggers 5, 6, and 7. This is because, although Triggers 6 and 7 led to longer service life, their costs were also higher due to more frequent implementations of overlays.

The total user costs are combinations of user costs due to work zone delays and surface roughness. If the overlays are triggered more frequently (e.g., trigger at condition 7), there will be more work zone delays leading to more travel time costs. However, the average surface condition would be better than that with less frequent overlays, and this leads to lower VOCs during normal operations. The results in Table 4.3 and Figure 4.1 show that Trigger 7 leads to the lowest user cost EUAC.

The total EUAC when combining agency and user costs with equal weight (1:1) is lowest when Trigger 6 is used. Such a result indicates a trade-off between the agency costs and the user benefits.

Table 4.4 and Figures 4.2 and 4.3 present the results for the scenario in which both polymeric and LMC overlays are implemented. It was assumed that the polymeric overlay is used before LMC overlays and used at a better wearing surface condition than for LMC overlays, based on historical data. It was also assumed that the polymeric overlay can be implemented only once during the life cycle, while LMC overlays can be implemented multiple times. "Do nothing" again serves as a base case for the purpose of comparison. It assumes that no major deck rehabilitation treatments (polymeric or LMC overlays) are applied, except for minor repairs and maintenance.

TABLE 4.4
Life-Cycle Agency and User EUAC Results for Central Districts, NHS, Polymeric and LMC Overlays (AC:UC=1:1)

Trigger	Do Nothing	P8L7	P8L6	P8L5	P7L6	P7L5	P6L5
Deck Service Life (years)	35	45	45	41	47	41	47
(Agency EUAC)/(Deck Area) ($/ft^2)	**1.78**	6.38	4.90	3.81	4.56	3.71	3.08
(User EUAC)/(Deck Area) ($/ft^2)	17.33	**12.35**	13.09	14.66	12.78	14.25	13.65
(Total EUAC)/(Deck Area) ($/ft^2)	19.11	18.73	17.99	18.47	17.34	17.96	**16.73**

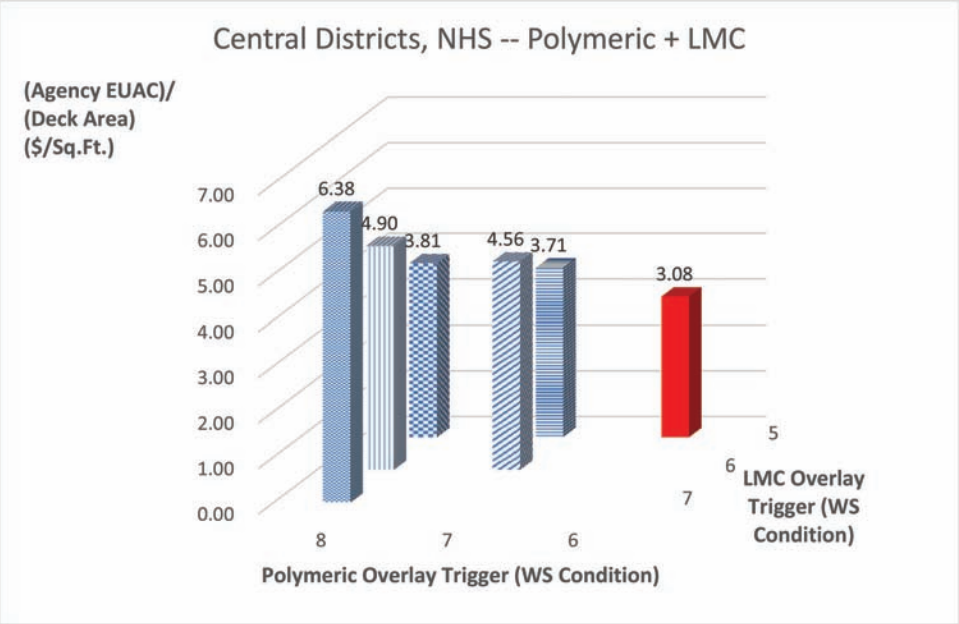

Figure 4.2 Life-cycle agency EUAC results for central districts, NHS, polymeric and LMC overlays.

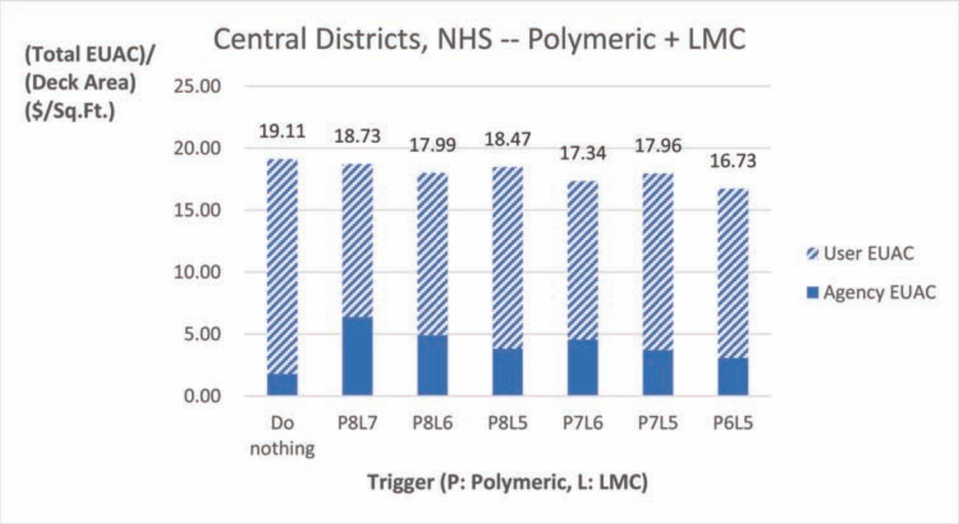

Figure 4.3 Life-cycle total EUAC results for central districts, NHS, polymeric and LMC overlays (AC:UC=1:1).

Trigger "PaLb" refers to that the polymeric overlay is implemented at wearing surface condition rating of "a" (a = 8, 7, 6), and the LMC overlay is implemented at wearing surface condition rating of "b" (b = 7, 6, 5). The detailed life-cycle strategies are illustrated by figures in the next section of this chapter (Zhang, 2016).

Based on the results in Table 4.4, the "do nothing" case would have a service life of 35 years. Triggers

"P7L6" and "P6L5" both led to the longest total service life—47 years.

With respect to the agency EUAC results, if only agency cost is considered, "do nothing" again led to the lowest EUAC. If "do nothing" is not considered as a real case, then Trigger "P6L5" has the lowest EUAC, because it leads to the longest service life and it has fewer frequent overlay activities.

The user costs did not show a clear trend, because user costs are combinations of travel time costs due to work zone delays and VOCs due to surface roughness. The "do-nothing" case turned out to have the highest user EUAC. This indicated that the added VOCs due to poor surface condition under "do-nothing" outweighed the work zone delay costs in cases where overlays were implemented. The results also showed that Trigger "P8L7" led to the lowest user cost EUAC with respect to other triggers that have lower condition, indicating again that the user benefits gained from (or user costs reduced by) smoother deck surface outweighed the user costs incurred by the more frequent work zones.

Trigger "P6L5" turned out to have the lowest total EUAC when agency and user costs were combined using weights 1:1. This trigger result is the same as that when only agency cost is considered. Agency costs had more influence than user costs in this scenario, in which both polymeric and LMC overlays are implemented.

Furthermore, it may seem that the differences in the EUACs across triggers are not significant. However, when the normalized EUAC is multiplied by the deck area and then by the number of years in its life cycle, the difference could be large. For example, for a bridge with structure length = 150ft, deck width = 50ft, and service life = 35 years, 1 unit difference in EUAC/(Deck Area) can cause $1 \times 150 \times 50 \times 35 = \$262{,}500$ of difference through the life cycle, without considering the discount rate.

The life-cycle analysis results for other categories (i.e., central districts non-NHS, northern districts NHS and non-NHS, and southern districts NHS and non-NHS) are presented in Appendix A of this volume. It turned out that the results across various highway district categories were consistent. However, the results between NHS and non-NHS were different, probably because of the assumption that detour policy was used for non-NHS bridges, which caused much higher user costs when there were more frequent overlay treatments (Zhang, 2016).

4.3 Recommended Appropriate Bridge Deck Life-Cycle M&R Strategies

Results presented in the previous section indicated that:

1. For NHS bridges, (a) if only LMC overlays are used, Trigger WS = 6 led to the least combined EUAC of agency and user costs (weight = 1:1), whereas Trigger WS = 5 led to the least agency EUAC if user costs were not taken into account; (b) if both polymeric and LMC overlays are used, Trigger P6L5 (Polymeric at WS=6 and LMC at WS=5) led to the least EUAC, regardless of whether user costs were included.
2. For non-NHS bridges, (a) if only LMC overlays are used, Trigger WS = 5 led to the least EUACs, regardless of whether user costs were included; (b) if both polymeric and LMC overlays are used, Trigger P6L5 (Polymeric at WS=6 and LMC at WS=5) led to the least EUAC, regardless of whether user costs were included.

In this section, the life-cycle deck M&R strategies with the optimal EUAC results are illustrated using profiles, and some examples of other candidate strategies are also presented. Again, to save space, only results for Central Districts, NHS are presented here. Results for other district and functional class categories can be found in Appendix B and Appendix C of this volume.

Figure 4.4 illustrates the appropriate condition-based deck M&R strategy for central districts, NHS bridges, when only LMC overlays are used, given that both agency and user costs were considered. The blue solid curves refer to the change in wearing surface condition rating. Before the implementation of the first overlay, it was assumed that the deck surface was monolithic concrete (concurrently placed with the structural deck) (NBI Item 108A Code =1). When the wearing surface (deck surface) condition dropped to 6, the first LMC overlay was implemented, bringing the wearing surface condition back to 9. Meanwhile, the overlay also caused some improvement to the deck condition rating, based on the performance jump model developed in Section 3.3. Then, the new LMC wearing surface deteriorated in accordance with the model for LMC, given an initial deck condition around 6. When the LMC wearing surface condition reached 6 again, the second LMC overlay was triggered. Again, the wearing surface condition was improved to 9 and the deck condition was improved to some extent. The termination of the deck life cycle was when the deck condition dropped to 4, which triggered the deck replacement. The LMC overlay was not triggered a third time in this analysis, because the deck was near the end of its service life and it was considered to be not cost-effective to trigger a third overlay. In addition, in real practice, overlays cannot be applied indefinitely. Typically, 1 to 2 applications of LMC overlays are implemented before the deck is replaced, according to INDOT practice. In addition, in Figure 4.4, the black dotted curves indicate the trends of deck condition. The purple dashed curve refers to the original deck deterioration curve, assuming that no major rehabilitations were applied. The service life under the "do nothing" case was 35 years, and the service life was extended by 12 years to a total of 47 years through two implementations of LMC overlays.

The concepts illustrated in Figure 4.5 are similar to those in Figure 4.4. The difference is that, Figure 4.5 shows only one LMC overlay, which was triggered at WS = 5, instead of the two overlays in Figure 4.4. This strategy was calculated to be appropriate when only agency costs are considered. The result was intuitive

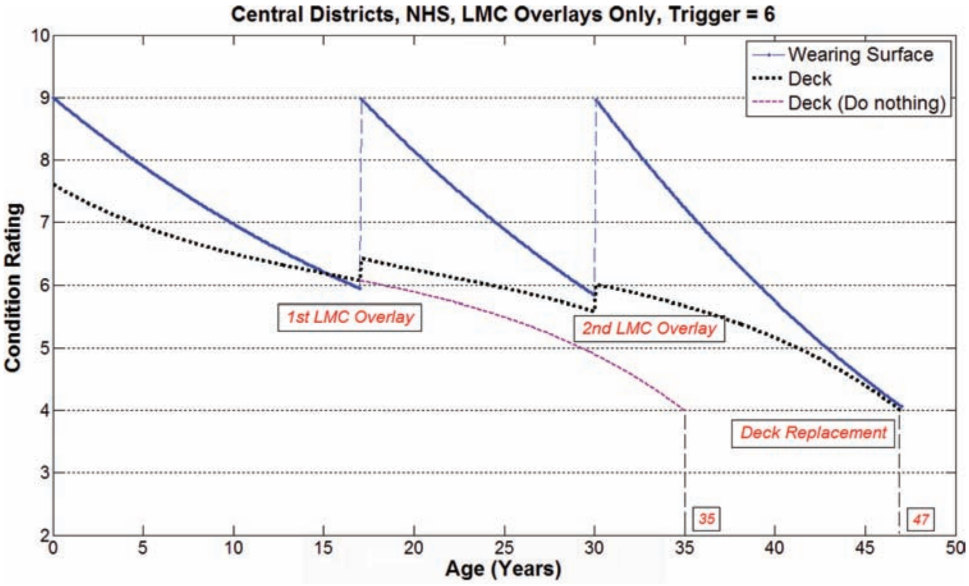

Figure 4.4 Appropriate condition-based bridge deck M&R strategy for central districts, NHS, LMC overlays only (agency and user costs 1:1 combined).

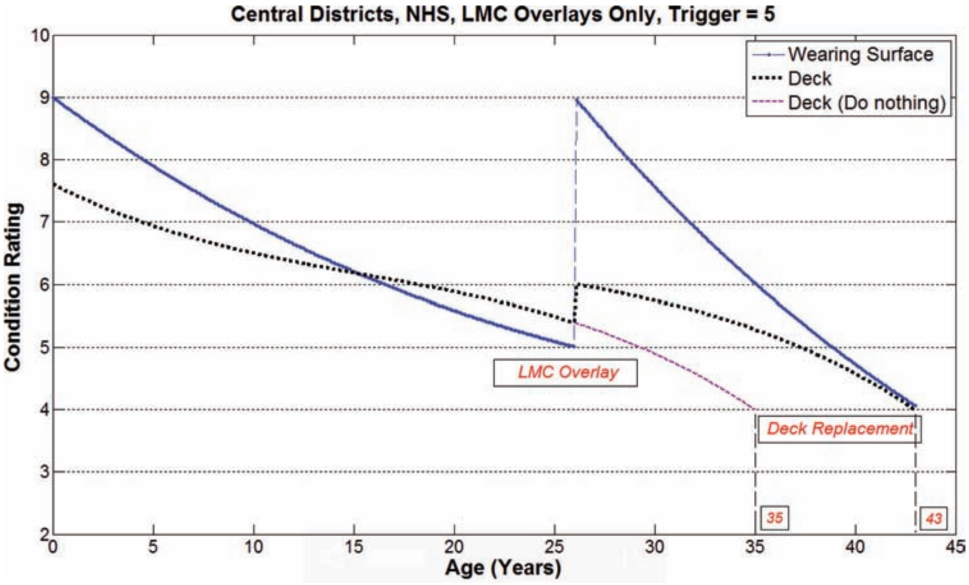

Figure 4.5 Appropriate condition-based bridge deck M&R strategy for central districts, NHS, LMC overlays only (agency costs only).

because, the less frequently the overlays were triggered, the less costly it would be for the agency.

Figure 4.6 presents the life-cycle profile of the appropriate strategy if polymeric overlays and LMC overlays were both implemented. The green thick solid curve indicates that the deck was protected under the polymeric wearing surface during that period. Other legends are the same as in Figure 4.4. The service life of the polymeric overlay is typically from 10 to 15 years. In Figure 4.6, the polymeric overlay was triggered at WS = 6, and the LMC overlay was triggered at WS = 5. The life cycle terminated when deck condition dropped to 4, which triggers deck replacement.

Figure 4.7 and Figure 4.8 present two examples of other candidate strategies that were found to be not most cost-effective. For the strategy in Figure 4.7, LMC overlays were triggered at WS = 7 and triggered three times during the life cycle. More than three overlays were not considered, because that would not conform to current engineering practice. Furthermore, although the service life can be extended to 53 years, this strategy would cost more to the agencies. Its life-cycle EUAC turned out to be higher than the others. Figure 4.8 shows the strategy of P8L6 for the scenario that both polymeric and LMC overlays are implemented. Polymeric overlay was triggered at WS=8 and LMC was

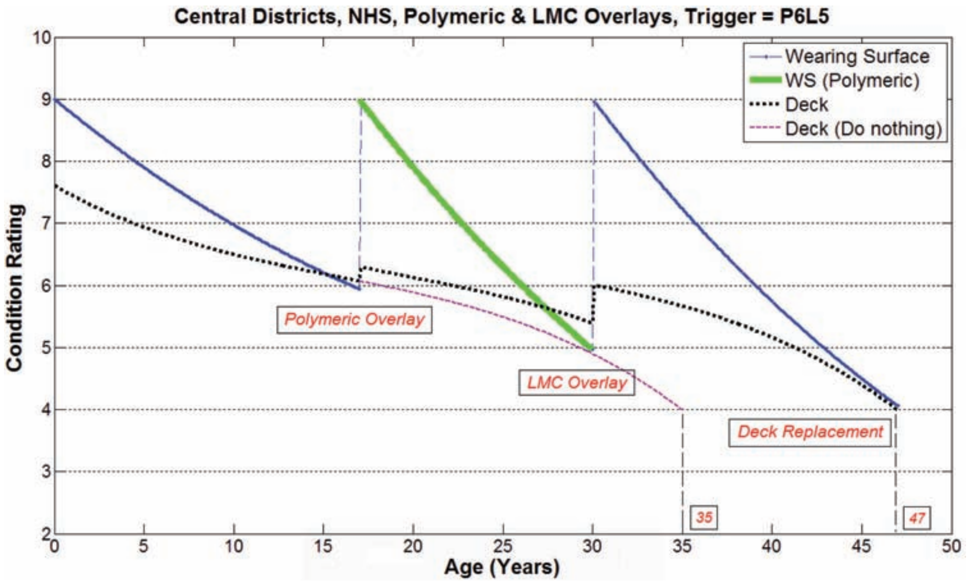

Figure 4.6 Appropriate condition-based bridge deck M&R strategy for central districts, NHS, polymeric and LMC overlays.

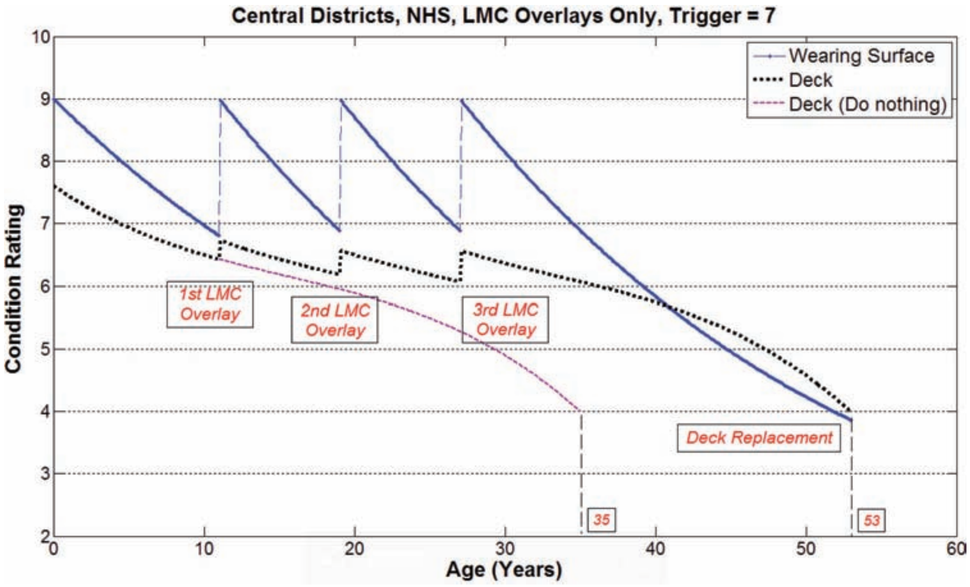

Figure 4.7 Example profile of other candidate deck M&R strategies for central districts, NHS, LMC overlays only (Trigger WS=7).

triggered at WS=6 twice. This strategy was also found to be not the most cost-effective strategy (Zhang, 2016).

4.4 Sensitivity Analysis

The analysis results presented in the previous sections of this chapter used fixed parameters and deterministic models for deterioration, performance jump, and costs. However, the change in parameter values could change the EUAC results, and thus could possibly affect the appropriate trigger thresholds. There are various factors that can affect the results, such as deck area (which affects agency costs), traffic volume (which affects user costs), discount rate (which affects EUAC), and some other assumptions made in the analysis.

In this section, sensitivity analysis with respect to two significant factors was conducted to investigate the robustness of the results of the triggers (i.e., how the change in the two factors could possibly influence the results).

The first tested factor was the weight between the agency costs and the user costs. As was mentioned in Chapter 2, the issue of user costs has been the challenge to LCCA implementation. There has been inconsistency regarding whether to incorporate user costs, and if incorporated, what types of user costs to include, and what the weight should be between the user costs and the agency costs. For example, does $1 of agency cost equal $1 of user cost in the decision making process? The current study does not establish a fixed weight, but provides the results under different assumed weights. As a result, INDOT can have the flexibility to choose the weights based on their needs.

The second tested factor was the traffic volume. In the previous analysis, the average traffic volumes for categories of highway districts and functional classes were used. However, even in the same category, the traffic volume on different individual bridges can vary a lot. The traffic mainly affects the amount of user costs. It can also affect the deterioration rates of the deck and wearing surface.

Table 4.5 and Figure 4.9 present the sensitivity analysis results in terms of weights between agency costs and user costs, for bridges in northern districts NHS highways, using LMC overlays only (Zhang, 2016).

It can be found that, when the weights between agency and user costs equaled to AC:UC=1:1 or 2:1, Trigger WS = 6 resulted in the lowest total EUAC. When the weight for agency costs was dominant (AC:UC=10:1), the "do nothing" case gave the least EUAC. The overall trend was that, when agency costs played a more significant role, the trigger would shift to less frequent overlay activities. This makes sense, because an agency would prefer fewer frequent treatments to reduce expenditures. The diamond points in Figure 4.9 indicated the triggers with lowest EUAC for each scenario.

Table 4.6 presents the sensitivity analysis results in terms of weights between agency costs and user costs, for bridges in northern districts NHS highways, using both polymeric and LMC overlays. Trigger P6L5 has the least EUAC for weights of 1:1, 2:1, and 4:1. "Do nothing" has the least EUAC when agency costs start to become dominant (6:1 and above). There was not as clear a trend as with the LMC only policy, because the trigger cases from left to right did not imply the frequency of treatments. For example, P8L5 does not necessarily indicate more frequent treatments than P7L6, or vice versa. But one trend that was certain was that, when agency costs got more weight, the result would shift its preference to the trigger that had lower agency EUAC. In this case, specifically, Trigger P6L5

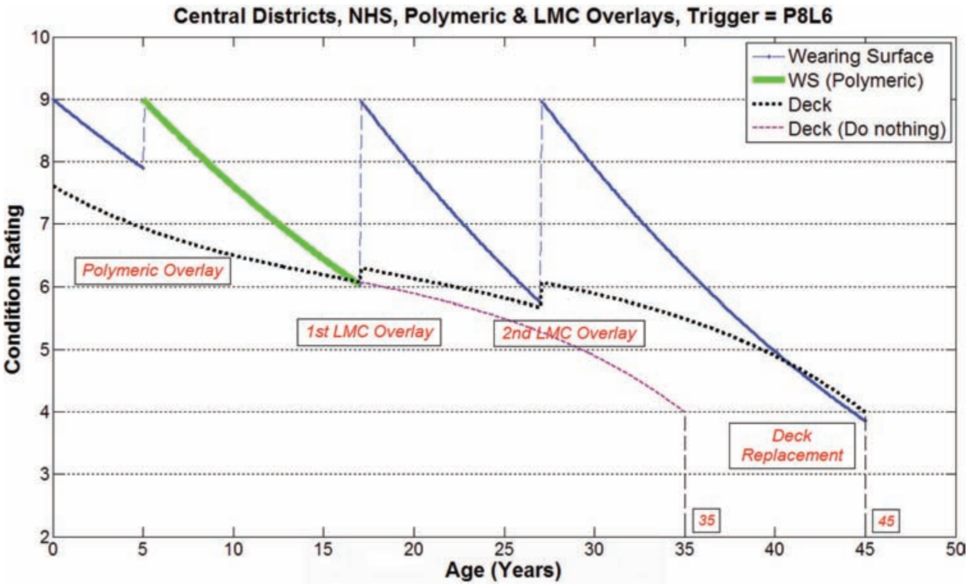

Figure 4.8 Example profile of other candidate deck M&R strategies for central districts, NHS, polymeric and LMC overlays (Trigger = P8L6).

TABLE 4.5
Sensitivity Analysis for Weights between Agency and User Costs for Northern Districts, NHS, LMC Overlays Only

		Trigger			
	Weight (AC:UC)	**Do Nothing**	**WS = 5**	**WS = 6**	**WS = 7**
(Total EUAC) / (Deck Area) ($/ft^2)	1:1	25.33	22.57	**21.23**	22.55
	2:1	13.46	12.50	**12.42**	13.78
	4:1	7.53	**7.46**	8.02	9.40
	6:1	**5.56**	5.79	6.55	7.94
	8:1	**4.57**	4.95	5.82	7.21
	10:1	**3.97**	4.44	5.38	6.77

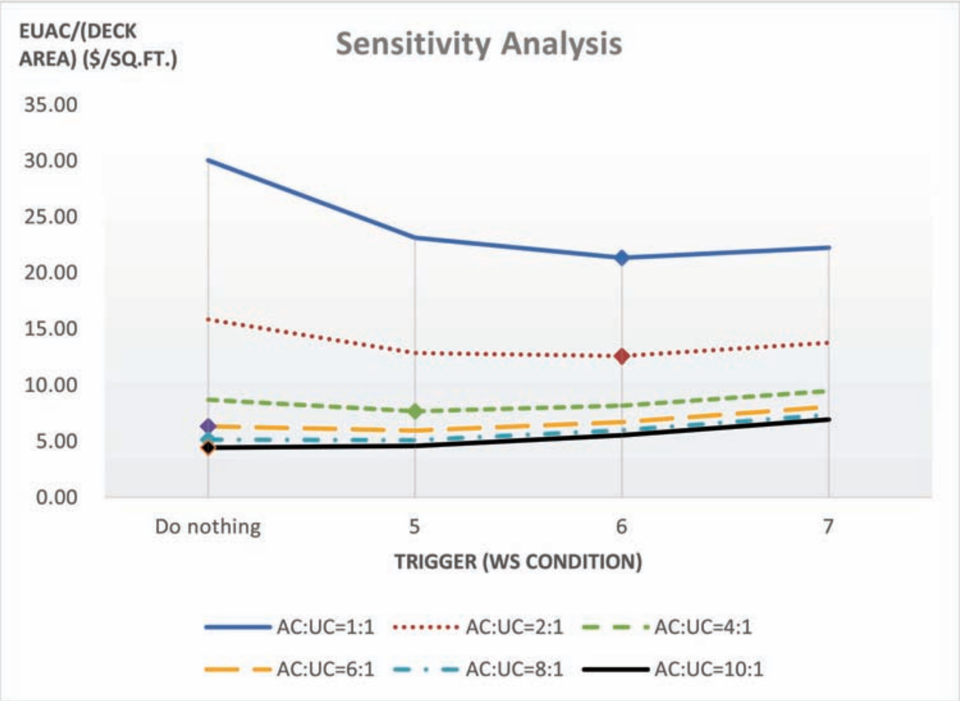

Figure 4.9 Sensitivity analysis for weights between agency and user costs for northern districts, NHS, LMC overlays only.

TABLE 4.6
Sensitivity Analysis for Weights between Agency and User Costs for Northern Districts, NHS, Polymeric and LMC Overlays

		Trigger						
	Weight (AC:UC)	**Do Nothing**	**P8L7**	**P8L6**	**P8L5**	**P7L6**	**P7L5**	**P6L5**
(Total EUAC) / (Deck Area) ($\$/\text{ft}^2$)	1:1	25.33	20.54	20.30	21.61	20.55	21.74	**19.72**
	2:1	13.46	12.95	12.18	12.50	12.32	12.62	**11.75**
	4:1	7.53	9.15	8.11	7.94	8.20	8.06	**7.27**
	6:1	**5.56**	7.88	6.76	6.42	6.83	6.54	5.78
	8:1	**4.57**	7.25	6.08	5.66	6.14	5.78	5.03
	10:1	**3.97**	6.87	5.67	5.20	5.73	5.32	4.58

TABLE 4.7
Sensitivity Analysis for Traffic Volume for Northern Districts, NHS, LMC Overlays Only (AC:UC=1:1)

		Trigger			
	Traffic (ADT)	**Do Nothing**	**WS = 5**	**WS = 6**	**WS = 7**
(Total EUAC) / (Deck Area) ($\$/\text{ft}^2$)	2,000	**4.68**	5.04	5.90	7.28
	5,000	9.31	**8.97**	9.33	10.70
	10,000	17.01	15.51	**15.05**	16.40
	20,000	32.43	28.59	**26.50**	27.79

had the lowest agency EUAC, except for "do nothing," and it also had the lowest total EUAC under AC:UC=1:1. Thus, when the weight for AC increased, the result would not shift to other triggers, but would furher strengthen the advantage of P6L5, until AC became really dominant (AC:UC=10:1) and "do nothing" took over the position.

Table 4.7 and Figure 4.10 present the sensitivity analysis results, in terms of traffic volume (ADT), for bridges in northern districts NHS highways, using LMC overlays only. In fact, the increase in ADT had a similar effect to that of increasing the weight of user costs, because the user costs largely depended on the number of road users. Therefore, when ADT increased, the trigger with the least EUAC would shift to the ones with more frequent overlays.

The diamond points in Figure 4.10 indicate the triggers with lowest EUAC for each scenario. Table 4.8

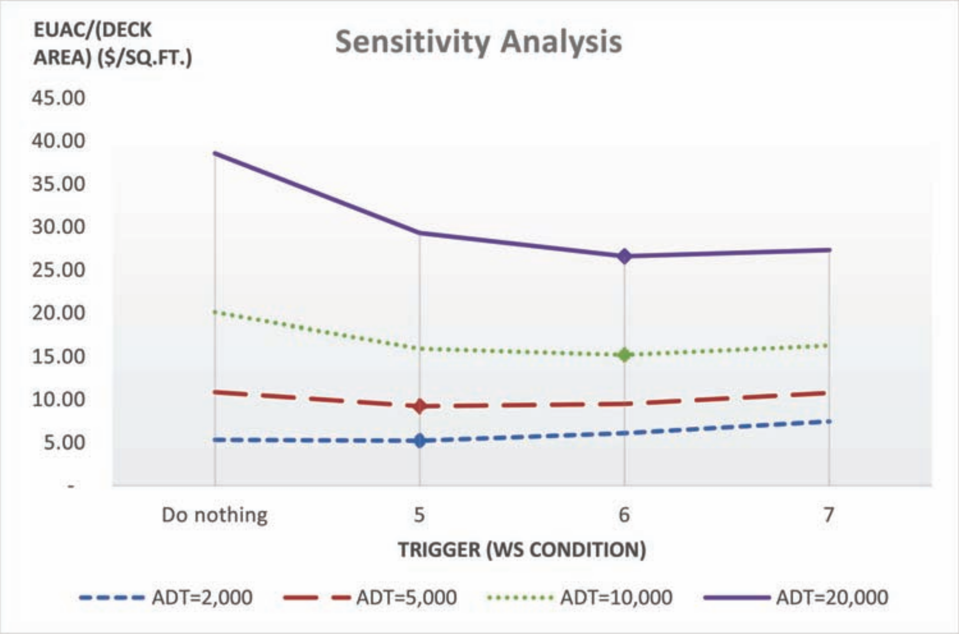

Figure 4.10 Sensitivity analysis for traffic volume for northern districts, NHS, LMC overlays only (AC:UC=1:1).

TABLE 4.8
Sensitivity Analysis for Traffic Volume for Northern Districts, NHS, Polymeric and LMC Overlays (AC:UC=1:1)

		Trigger						
	Traffic (ADT)	**Do Nothing**	**P8L7**	**P8L6**	**P8L5**	**P7L6**	**P7L5**	**P6L5**
(Total EUAC) / (Deck Area) ($/ft^2)	2,000	**4.68**	7.32	6.15	5.75	6.23	5.87	5.12
	5,000	9.31	10.28	9.32	9.30	9.43	9.42	**8.61**
	10,000	17.01	15.21	14.60	15.23	14.78	15.35	**14.43**
	20,000	32.43	**25.08**	25.17	27.07	25.48	27.20	26.08

presents the sensitivity analysis results in terms of traffic volume (ADT), for bridges in northern districts NHS highways, using both polymeric and LMC overlays. It was found that when ADT reaches 20,000, which means that user costs become more dominant, P8L7 led to the lowest total EUAC because the frequent overlays would provide users with smoother wearing surface and thus lower VOC costs (Zhang, 2016).

The sensitivity analysis results for other highway districts and functional class categories can be found in Appendix D of this volume.

4.5 Discussion and Limitations

The current study sought to find the appropriate trigger thresholds for some major bridge deck M&R treatments through life-cycle cost analysis, based on the currently available data and resources. The study also established appropriate life-cycle deck M&R strategies for different highway district and functional class categories. The results looked reasonable in general. However, two main possible limitations still exist.

First, it can be found that, for some cases, the differences in the EUAC results across different candidate triggers were not significant. The results in the current study were based on fixed parameters and deterministic models. It is easy to understand that, when risks and uncertainties are introduced to the analysis, the differences in EUACs would become more ambiguous. For example, if confidence intervals were to be developed, the confidence intervals for some candidate triggers could possibly overlap. However, the small differences in EUACs among triggers could possibly be reflected by current practices. According to historical practices, the actual trigger condition varied a lot across different projects. A commonly used trigger was not found. This may to some extent indicate that the differences across candidate triggers may indeed not be significant enough; otherwise, the agency should have used one trigger significantly more often than the others. However, this is only a presumption that needs more evidence. In future studies, risks and uncertainties could be incorporated to further investigate the differences in EUACs for various trigger candidates.

Second, as indicated by INDOT engineers, Indiana started to use the polymeric overlays more aggressively only in recent years. Therefore, the databases did not contain enough polymeric overlay projects, and most of these projects had less than 10 years of condition data. Consequently, the effects of polymeric overlays on the deck, including performance jump and post-treatment effects, could not be studied as well as the LMC overlays, and some estimates had to be made. However, it was supposed that the estimates would not seriously impact the results. In the future, when more polymeric overlay data become available, new models could possibly be developed and the appropriate trigger results could be reexamined.

5. SUMMARY

The current study sought to establish appropriate performance thresholds for triggering bridge deck maintenance and rehabilitation activities. Statistical models were developed to describe bridge deck and wearing surface deterioration, and performance jump (condition improvement) due to deck overlays. The agency cost models for LMC and polymeric overlays took into account the pre-treatment deck condition, the impact of economies of scale, and the cost of maintenance of traffic (MoT). Two types of bridge user costs were incorporated, including travel time costs due to work zone delays, and the incremental vehicle operating costs (VOCs) during normal operations due to the increased roughness of the bridge deck surface.

A life-cycle cost analysis optimization framework was proposed. The analysis used data for bridges on the state-owned routes in Indiana. Various weights were assigned to the agency and user costs for a sensitivity analysis. Results indicated that different weighting would have an impact on the optimal trigger that leads to the lowest equivalent uniform annual cost (EUAC). For example, for NHS highways in Indiana central districts, the optimal trigger for LMC overlays should be at wearing surface (WS) condition = 5 if each dollar of agency cost is weighted at least 1.64 times as much as each dollar of user cost, or AC:UC > 1.64. Likewise, Trigger = 6 if 0.68 < AC:UC < 1.64, and Trigger = 7 if 0 ≤ AC:UC < 0.68. For the scenario where both polymeric overlay and LMC overlay were applied, polymeric overlay triggered at WS = 6 and LMC overlay triggered at WS = 5 was found to result in the

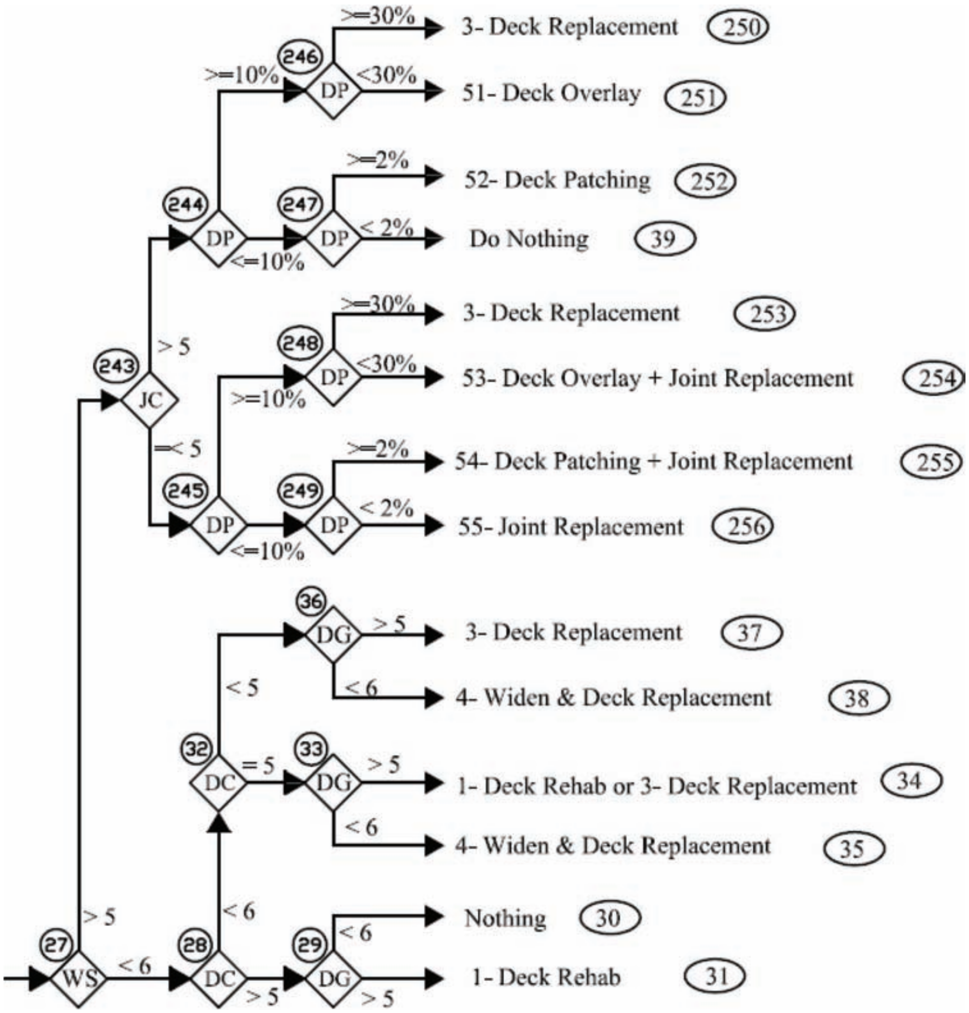

Figure 5.1 Partial decision tree (DTREE) for bridge deck M&R treatments in the Indiana Bridge Management System (IBMS) (Sinha et al., 2009).

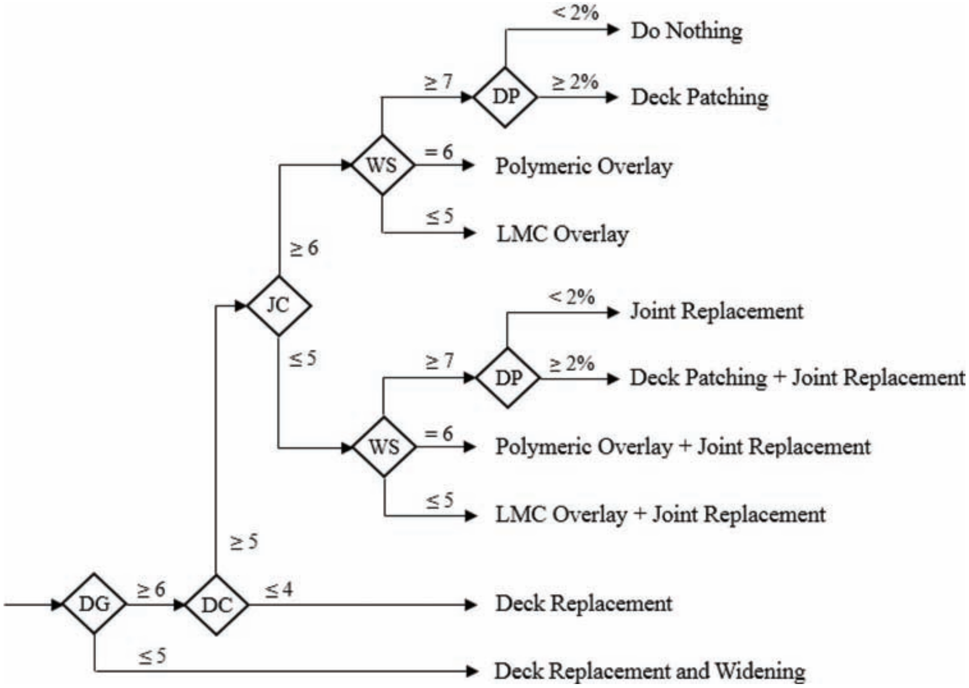

Figure 5.2 Modified partial decision tree (DTREE) for bridge deck M&R treatments in the Indiana Bridge Management System (IBMS).

lowest total EUAC, given AC:UC ≥ 1:1. In addition, the life-cycle condition-based deck M&R strategies based on different trigger results were proposed and presented.

On the basis of the results of the current study, some modifications are recommended to be made to the original DTREE used in the IBMS (Sinha et al., 2009), in order to incorporate the triggers for specific deck overlay treatments and simplify some redundancy of the flows in the DTREE.

Figure 5.1 presents part of the original DTREE that is related to deck M&R activities, where WS indicates wearing surface condition rating (0–9 integers), DC indicates deck condition rating (0–9 integers), DG indicates deck geometry rating (0–9 integers), JC indicates deck joint condition rating (0–9 integers), and DP indicates the proportion (%) of the sum of area that needs patching and already patched to the total deck area. Figure 5.2 is the proposed modified DTREE based on the current study.

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APPENDICES

APPENDIX A. ADDITIONAL LIFE-CYCLE COST ANALYSIS RESULTS

Appendix A presents the life-cycle cost analysis results for the other highway districts and functional classes, including central districts non-NHS, northern districts NHS and non-NHS, and southern districts NHS and non-NHS. It was found that the appropriate triggers vary between NHS and non-NHS, but remain consistent across highway districts. The Total EUAC values in all tables and figures used the weight of AC:UC=1:1 (i.e., Total EUAC = Agency EUAC + User EUAC).

TABLE A.1
Life-Cycle Agency and User EUAC Results for Central Districts, Non-NHS, LMC Overlays Only

Trigger	Do Nothing	WS = 5	WS = 6	WS = 7
Deck Service Life (years)	40	43	47	53
(Agency EUAC)/(Deck Area) ($/ft^2)	1.58	2.93	4.30	5.80
(User EUAC)/(Deck Area) ($/ft^2)	11.99	16.31	20.83	25.82
(Total EUAC)/(Deck Area) ($/ft^2)	13.57	19.24	25.13	31.62

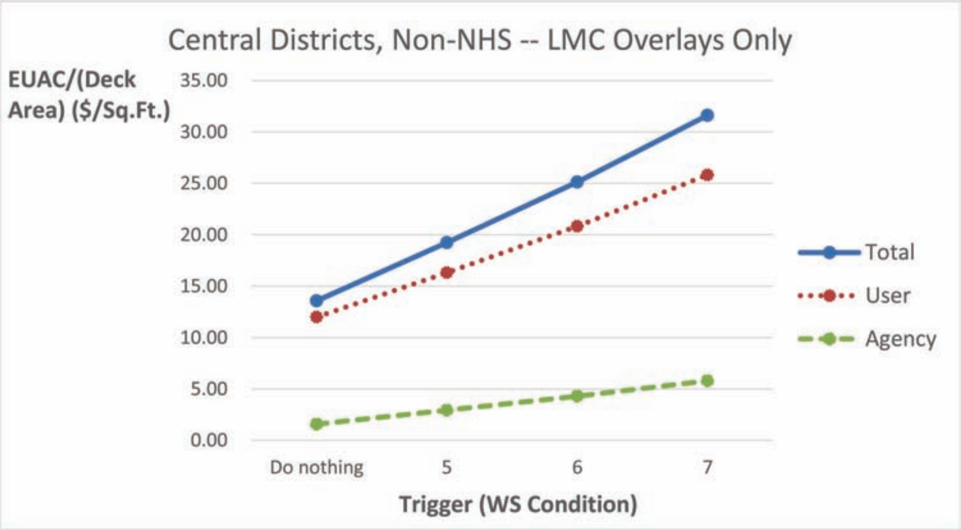


Figure A.1 Life-cycle agency and user EUAC results for central districts, non-NHS, LMC overlays only.

TABLE A.2
Life-Cycle Agency and User EUAC Results for Central Districts, Non-NHS, Polymeric and LMC Overlays

Trigger	Do Nothing	P8L7	P8L6	P8L5	P7L6	P7L5	P6L5
Deck Service Life (years)	40	45	45	41	47	41	47
(Agency EUAC)/(Deck Area) ($/ft^2)	1.58	7.20	5.48	4.18	5.05	4.03	3.34
(User EUAC)/(Deck Area) ($/ft^2)	11.99	27.63	21.85	17.17	21.18	16.90	15.68
(Total EUAC)/(Deck Area) ($/ft^2)	13.57	34.83	27.32	21.35	26.23	20.9	19.02

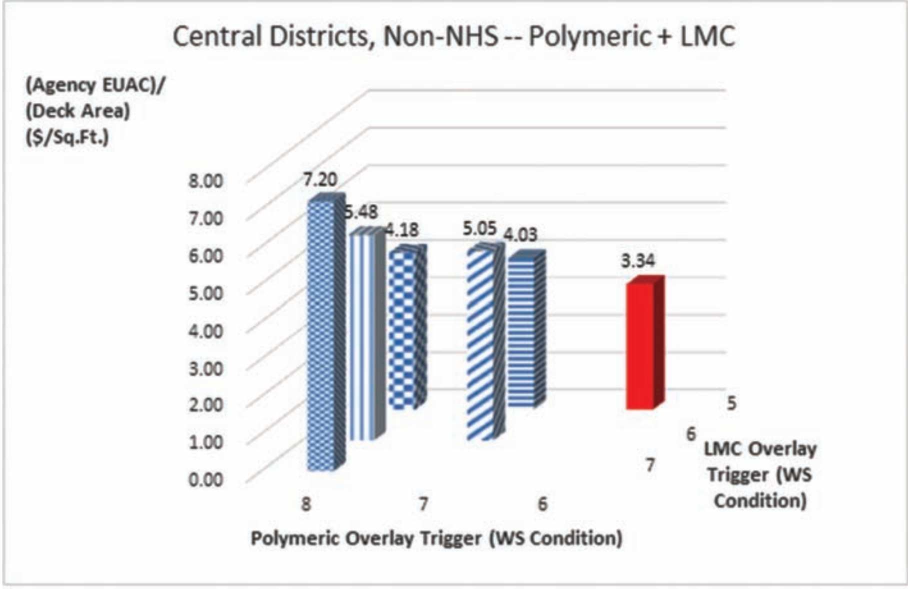


Figure A.2 Life-cycle agency EUAC results for central districts, non-NHS, polymeric and LMC overlays.

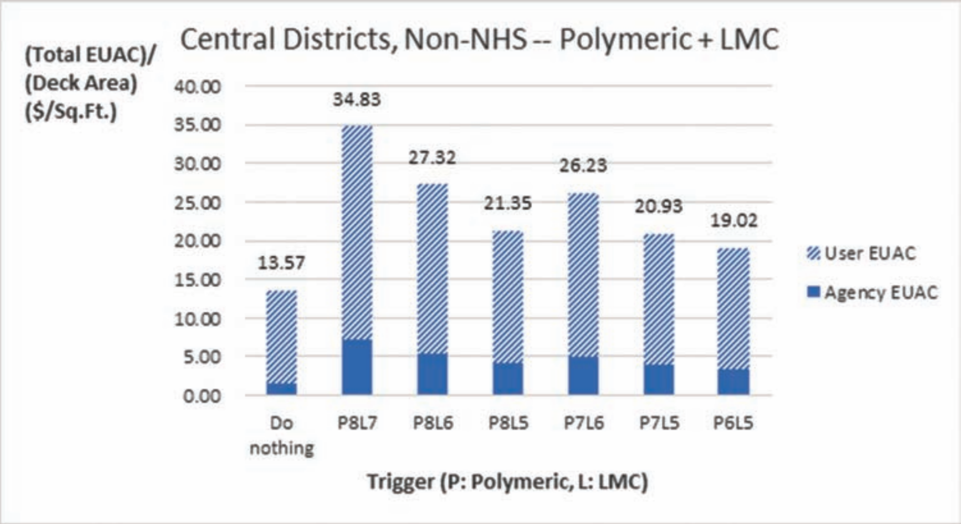


Figure A.3 Life-cycle total EUAC results for central districts, non-NHS, polymeric and LMC overlays.

TABLE A.3
Life-Cycle Agency and User EUAC Results for Northern Districts, NHS, LMC Overlays Only

Trigger	Do Nothing	WS = 5	WS = 6	WS = 7
Deck Service Life (years)	37	42	43	44
(Agency EUAC)/(Deck Area) ($/ft^2)	1.60	2.43	3.61	5.01
(User EUAC)/(Deck Area) ($/ft^2)	23.73	20.14	17.62	17.54
(Total EUAC)/(Deck Area) ($/ft^2)	25.33	22.57	21.23	22.55

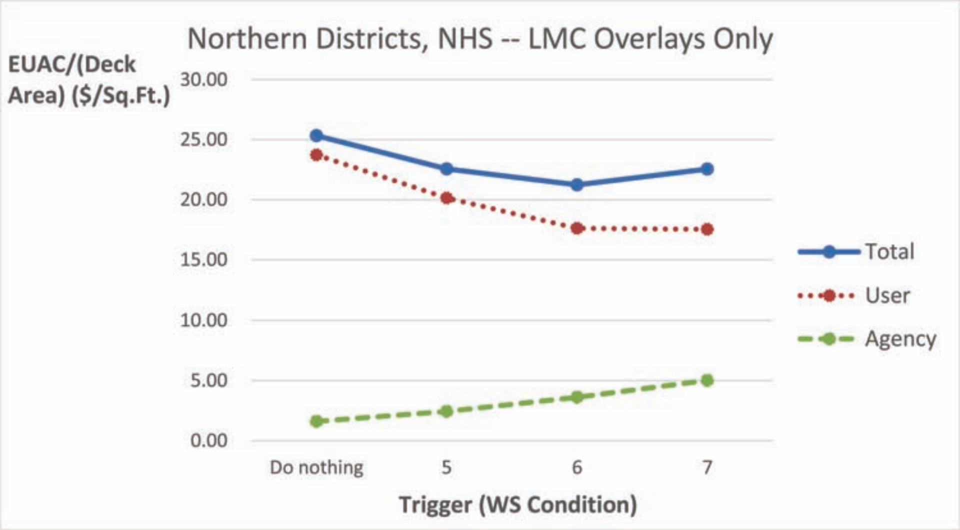


Figure A.4 Life-cycle agency and user EUAC results for northern districts, NHS, LMC overlays only.

TABLE A.4
Life-Cycle Agency and User EUAC Results for Northern Districts, NHS, Polymeric and LMC Overlays

Trigger	Do Nothing	P8L7	P8L6	P8L5	P7L6	P7L5	P6L5
Deck Service Life (years)	37	46	47	42	46	39	46
(Agency EUAC)/(Deck Area) ($/ft^2)	1.60	5.35	4.05	3.38	4.09	3.50	2.79
(User EUAC)/(Deck Area) ($/ft^2)	23.73	15.19	16.26	18.24	16.47	18.24	16.93
(Total EUAC)/(Deck Area) ($/ft^2)	25.33	20.54	20.30	21.61	20.55	21.74	19.72

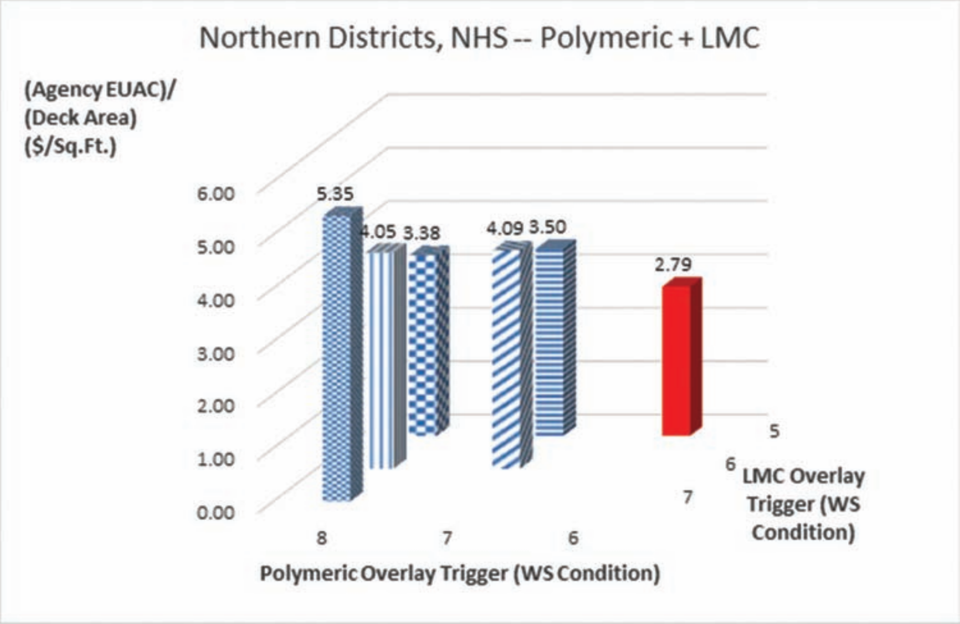


Figure A.5 Life-cycle agency EUAC results for northern districts, NHS, polymeric and LMC overlays.

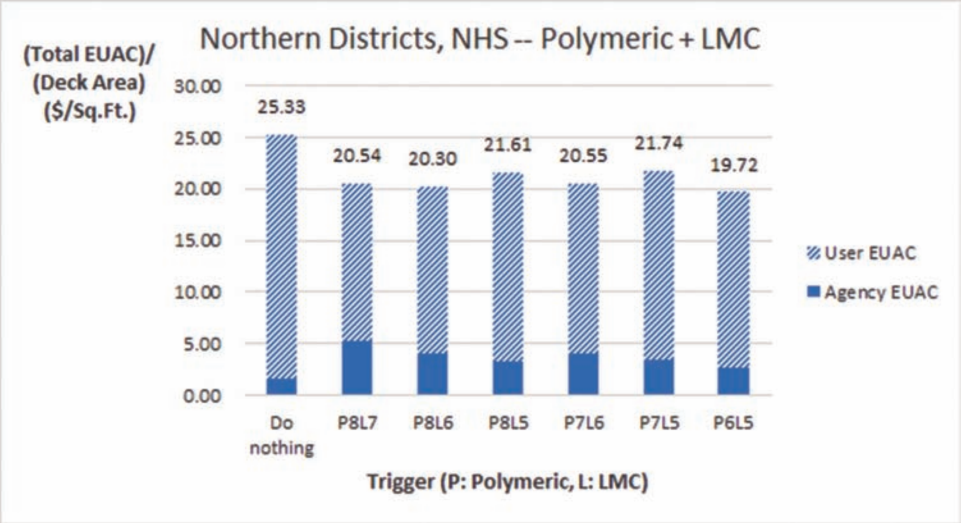


Figure A.6 Life-cycle total EUAC results for northern districts, NHS, polymeric and LMC overlays.

TABLE A.5
Life-Cycle Agency and User EUAC Results for Northern Districts, Non-NHS, LMC Overlays Only

Trigger	Do Nothing	WS = 5	WS = 6	WS = 7
Deck Service Life (years)	36	42	43	44
(Agency EUAC)/(Deck Area) ($/ft^2)	1.70	2.64	4.04	5.72
(User EUAC)/(Deck Area) ($/ft^2)	18.63	23.88	30.45	39.05
(Total EUAC)/(Deck Area) ($/ft^2)	20.32	26.53	34.50	44.77

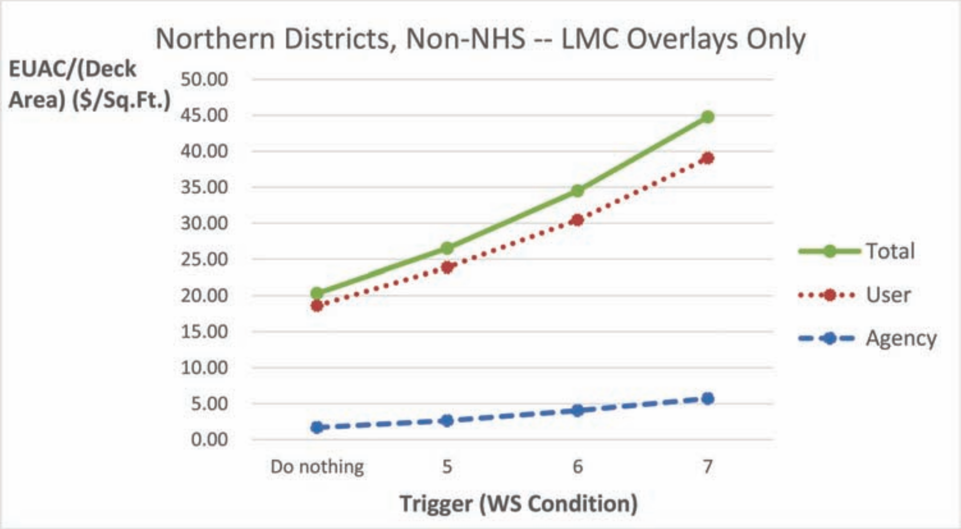


Figure A.7 Life-cycle agency and user EUAC results for northern districts, non-NHS, LMC overlays only.

TABLE A.6
Life-Cycle Agency and User EUAC Results for Northern Districts, Non-NHS, Polymeric and LMC Overlays

Trigger	Do Nothing	P8L7	P8L6	P8L5	P7L6	P7L5	P6L5
Deck Service Life (years)	36	46	47	42	46	39	46
(Agency EUAC)/(Deck Area) ($/ft^2)	1.70	5.99	4.46	3.62	4.49	3.78	3.02
(User EUAC)/(Deck Area) ($/ft^2)	18.63	37.06	29.33	23.77	29.79	24.39	22.70
(Total EUAC)/(Deck Area) ($/ft^2)	20.32	43.06	33.79	27.39	34.28	28.17	25.72

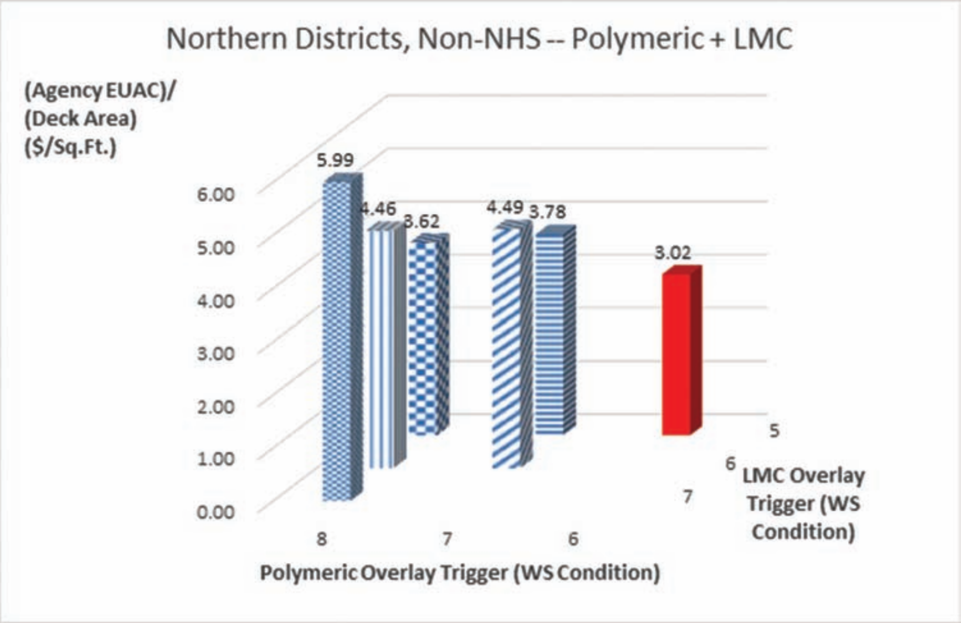


Figure A.8 Life-cycle agency EUAC results for northern districts, non-NHS, polymeric and LMC overlays.

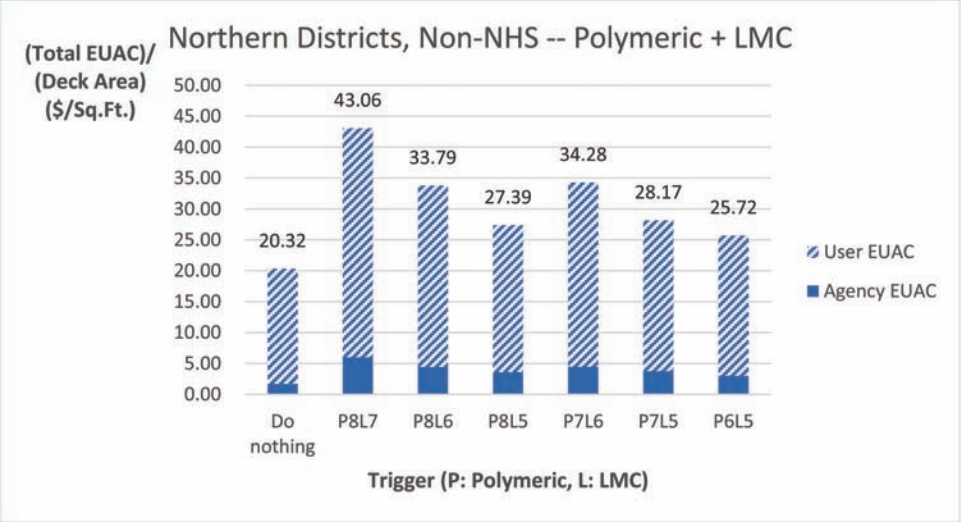


Figure A.9 Life-cycle total EUAC results for northern districts, non-NHS, polymeric and LMC overlays.

TABLE A.7
Life-Cycle Agency and User EUAC Results for Southern Districts, NHS, LMC Overlays Only

Trigger	Do Nothing	WS = 5	WS = 6	WS = 7
Deck Service Life (years)	39	43	47	53
(Agency EUAC)/(Deck Area) ($/ft^2)	1.55	2.57	3.65	4.85
(User EUAC)/(Deck Area) ($/ft^2)	25.34	21.79	18.98	17.75
(Total EUAC)/(Deck Area) ($/ft^2)	26.90	24.36	22.64	22.60

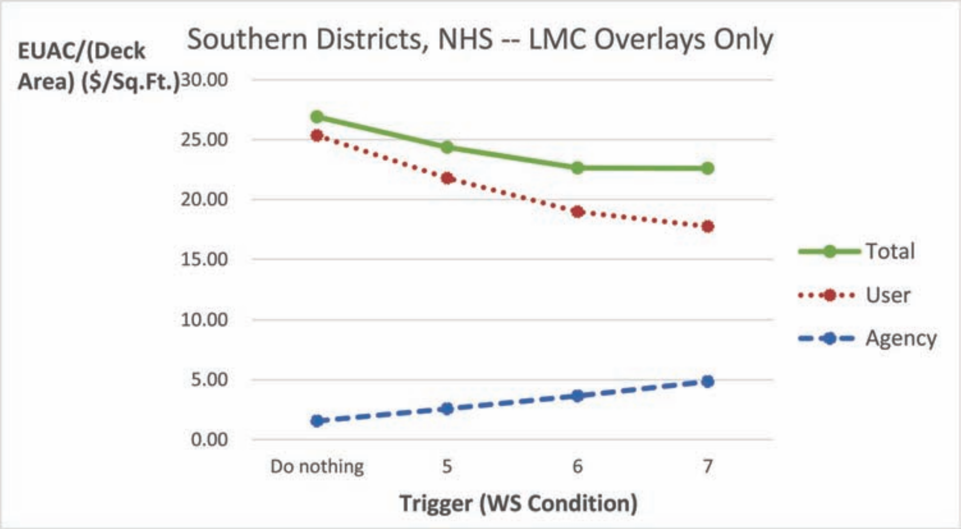


Figure A.10 Life-cycle agency and user EUAC results for southern districts, NHS, LMC overlays only.

TABLE A.8
Life-Cycle Agency and User EUAC Results for Southern Districts, NHS, Polymeric and LMC Overlays

Trigger	Do Nothing	P8L7	P8L6	P8L5	P7L6	P7L5	P6L5
Deck Service Life (years)	39	45	45	41	47	41	47
(Agency EUAC)/(Deck Area) ($/ft^2)	1.55	6.14	4.73	3.71	4.37	3.58	2.96
(User EUAC)/(Deck Area) ($/ft^2)	25.34	17.61	18.73	21.02	18.30	20.40	19.61
(Total EUAC)/(Deck Area) ($/ft^2)	26.90	23.75	23.46	24.73	22.66	23.98	22.57

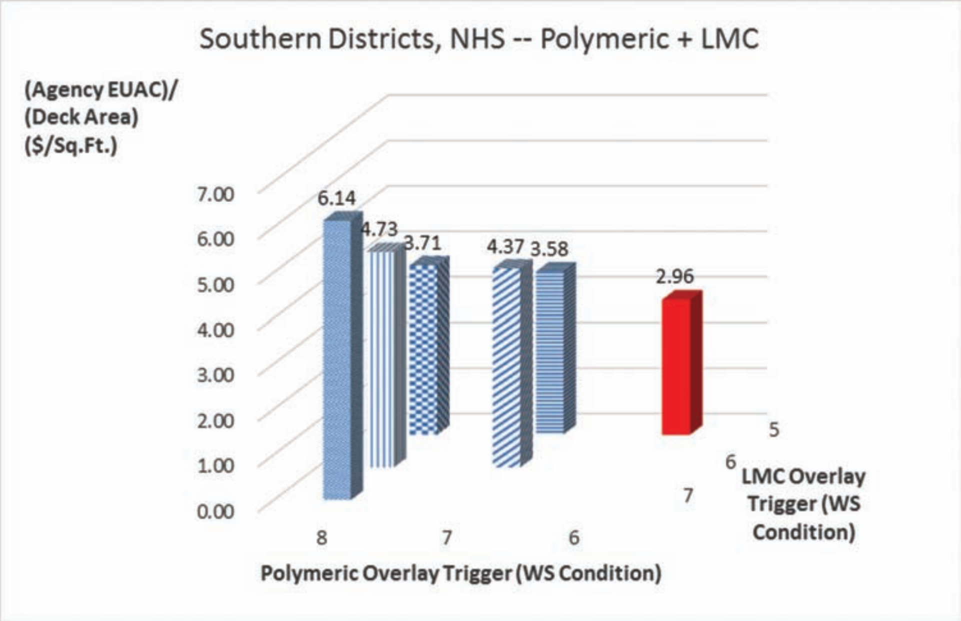


Figure A.11 Life-cycle agency EUAC results for southern districts, NHS, polymeric and LMC overlays.

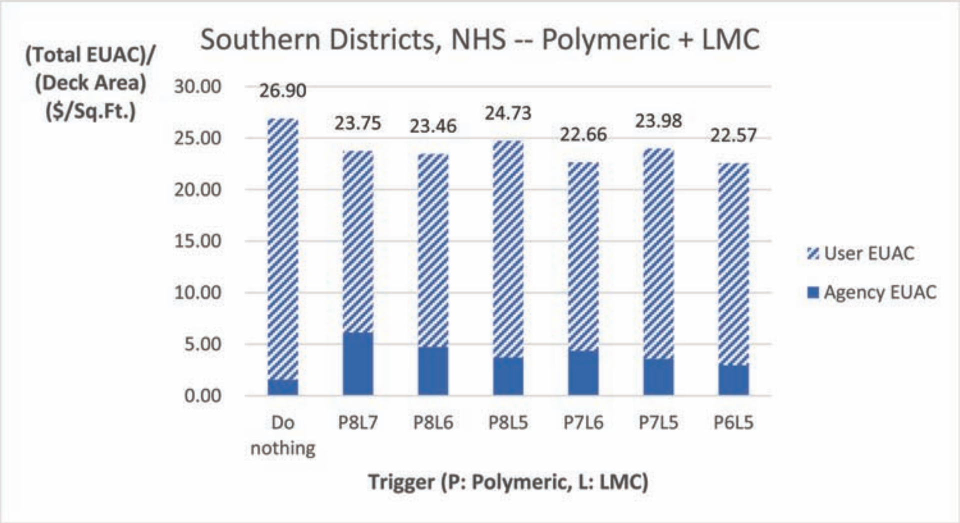


Figure A.12 Life-cycle total EUAC results for southern districts, NHS, polymeric and LMC overlays.

TABLE A.9
Life-Cycle Agency and User EUAC Results for Southern Districts, Non-NHS, LMC Overlays Only

Trigger	Do Nothing	WS = 5	WS = 6	WS = 7
Deck Service Life (years)	36	43	47	53
(Agency EUAC)/(Deck Area) ($/ft^2)	1.75	2.79	4.05	5.47
(User EUAC)/(Deck Area) ($/ft^2)	19.16	25.67	32.52	40.19
(Total EUAC)/(Deck Area) ($/ft^2)	20.91	28.46	36.57	45.65

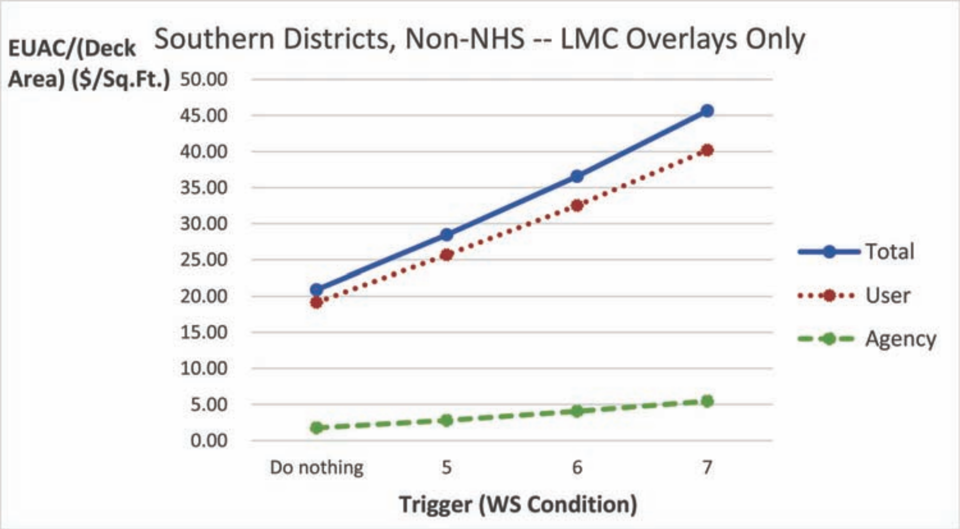


Figure A.13 Life-cycle agency and user EUAC results for southern districts, non-NHS, LMC overlays only.

TABLE A.10
Life-Cycle Agency and User EUAC Results for Southern Districts, Non-NHS, Polymeric and LMC Overlays

Trigger	Do Nothing	P8L7	P8L6	P8L5	P7L6	P7L5	P6L5
Deck Service Life (years)	36	45	45	41	47	41	47
(Agency EUAC)/(Deck Area) ($/ft^2)	1.75	6.82	5.20	4.00	4.79	3.86	3.21
(User EUAC)/(Deck Area) ($/ft^2)	19.16	42.90	34.06	26.94	33.03	26.49	24.63
(Total EUAC)/(Deck Area) ($/ft^2)	20.91	49.72	39.25	30.94	37.82	30.35	27.84

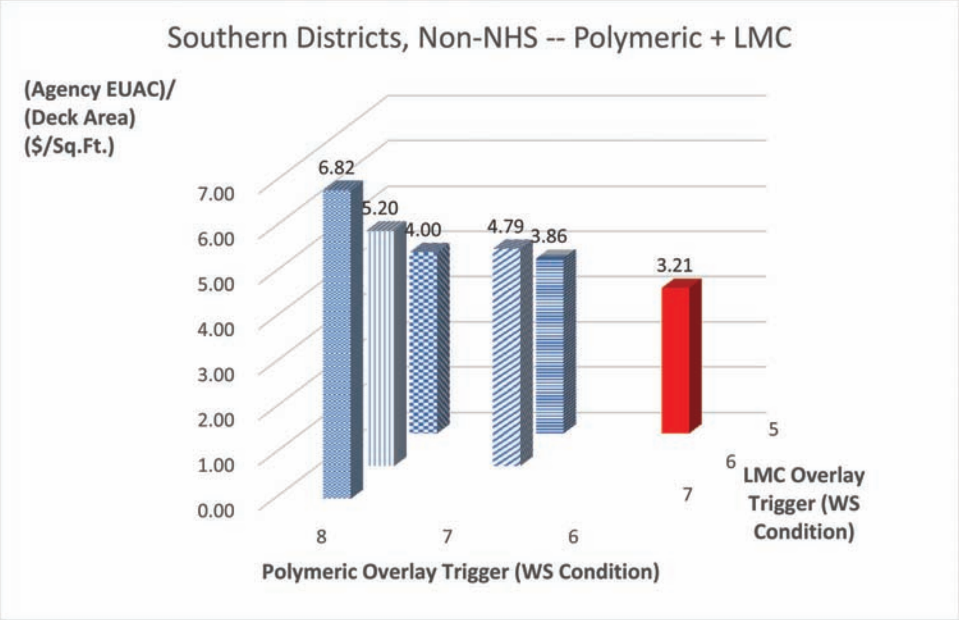


Figure A.14 Life-cycle agency EUAC results for southern districts, non-NHS, polymeric and LMC overlays.

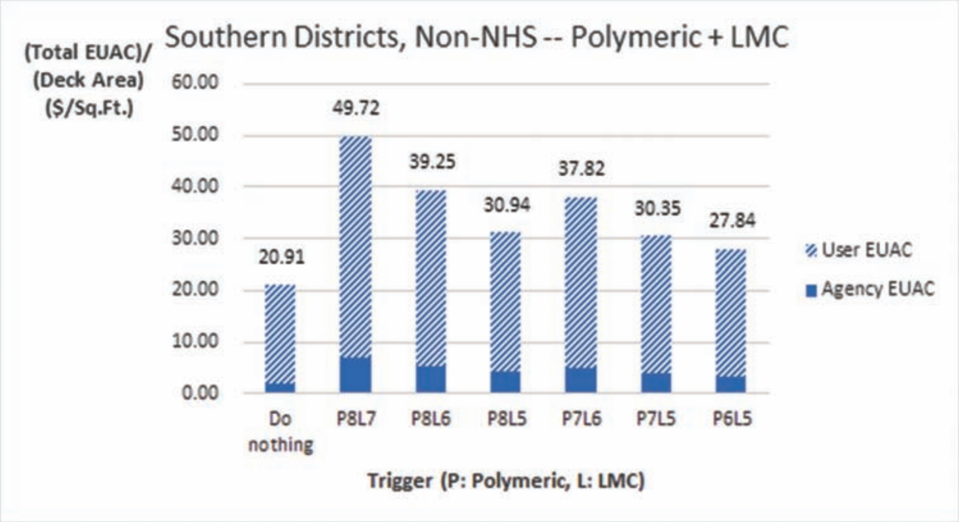


Figure A.15 Life-cycle total EUAC results for southern districts, non-NHS, polymeric and LMC overlays.

APPENDIX B. ADDITIONAL RECOMMENDED BRIDGE DECK LIFE-CYCLE M&R STRATEGIES (AC:UC=1:1)

Appendix B presents the recommended strategies for the other highway districts and functional classes, including central districts non-NHS, northern districts NHS and non-NHS, and southern districts NHS and non-NHS. The results presented herein were based on the weight of AC:UC=1:1. The summarized findings can be found in Section 4.3 (Zhang, 2016).

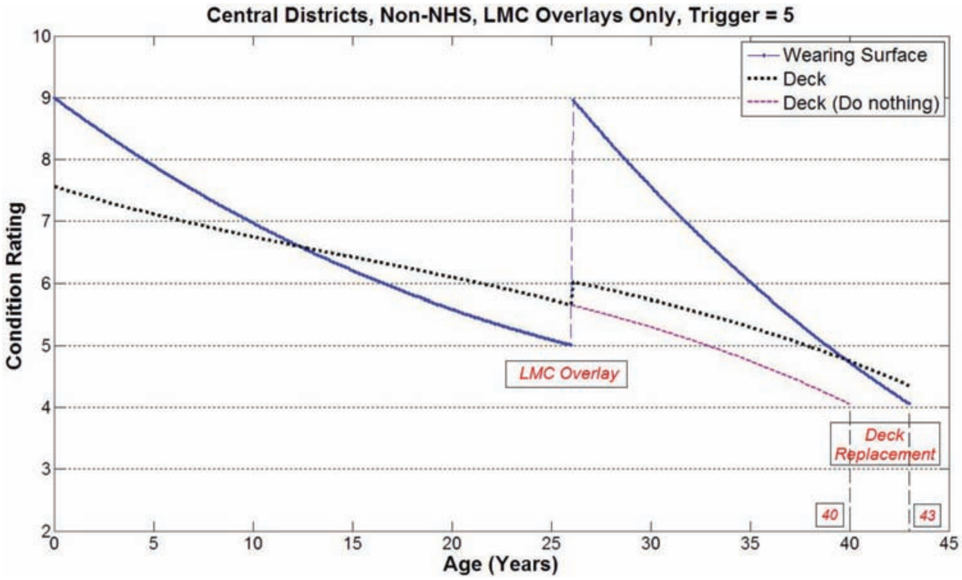


Figure B.1 Appropriate condition-based bridge deck M&R strategy for central districts, non-NHS, LMC overlays only.

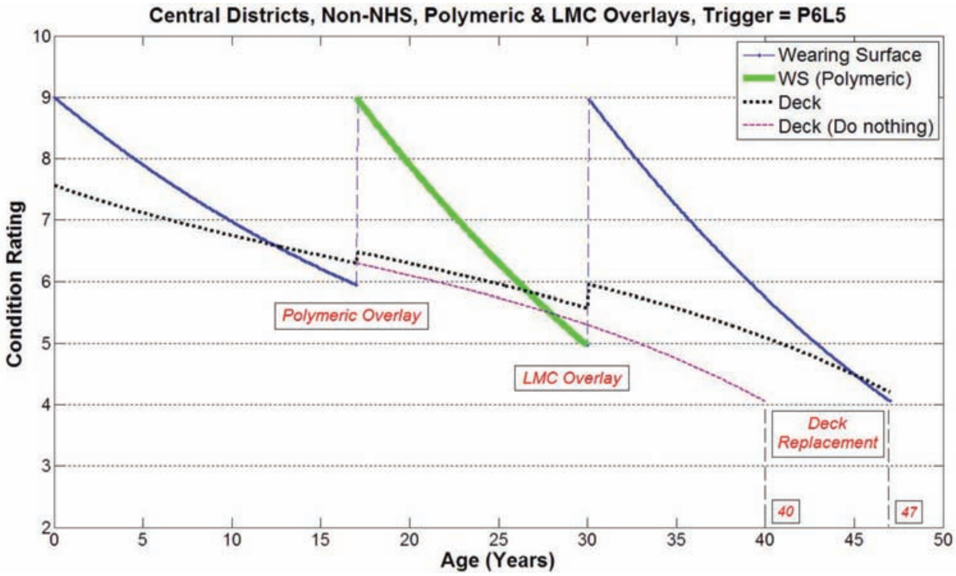


Figure B.2 Appropriate condition-based bridge deck M&R strategy for central districts, non-NHS, polymeric and LMC overlays.

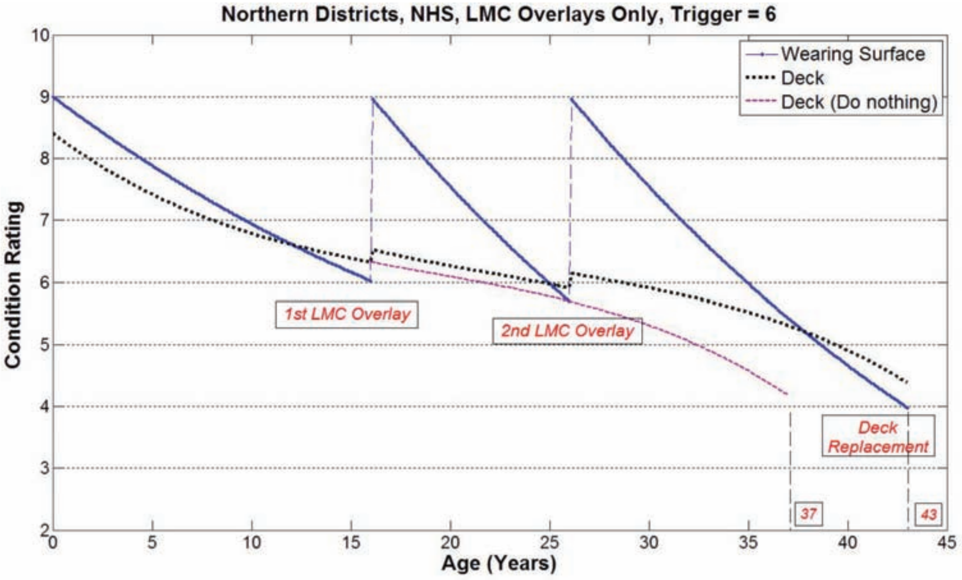


Figure B.3 Appropriate condition-based bridge deck M&R strategy for northern districts, NHS, LMC overlays only.

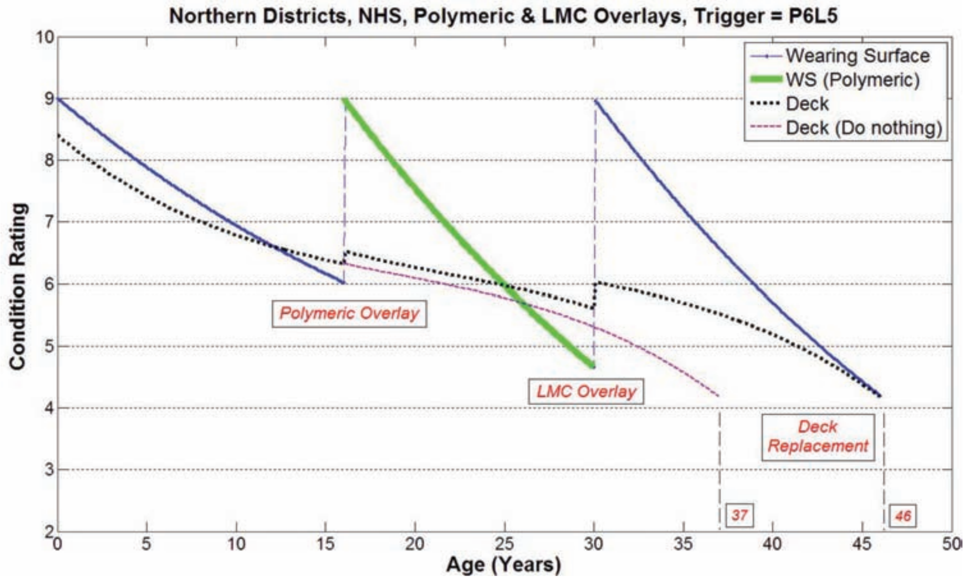


Figure B.4 Appropriate condition-based bridge deck M&R strategy for northern districts, NHS, polymeric and LMC overlays.

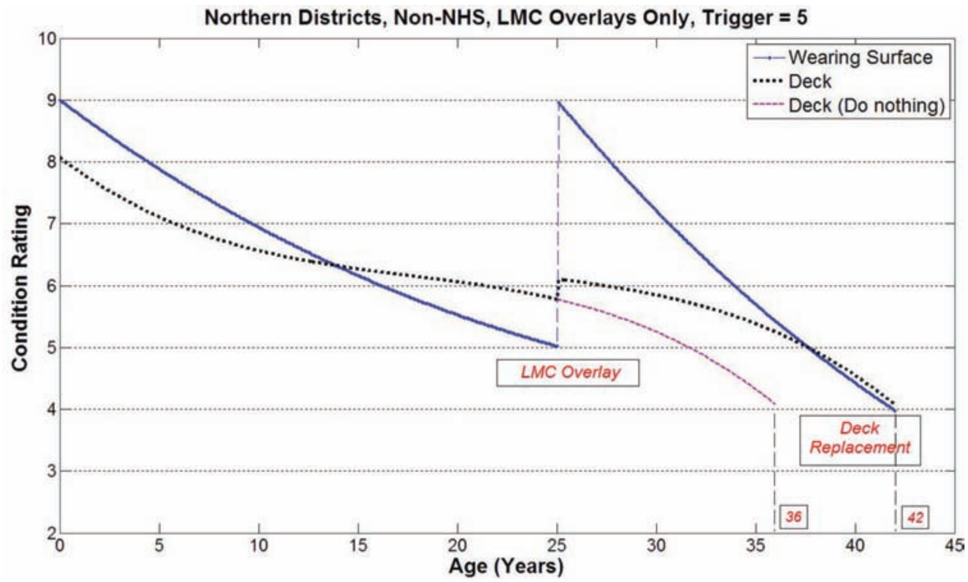


Figure B.5 Appropriate condition-based bridge deck M&R strategy for northern districts, non-NHS, LMC overlays only.

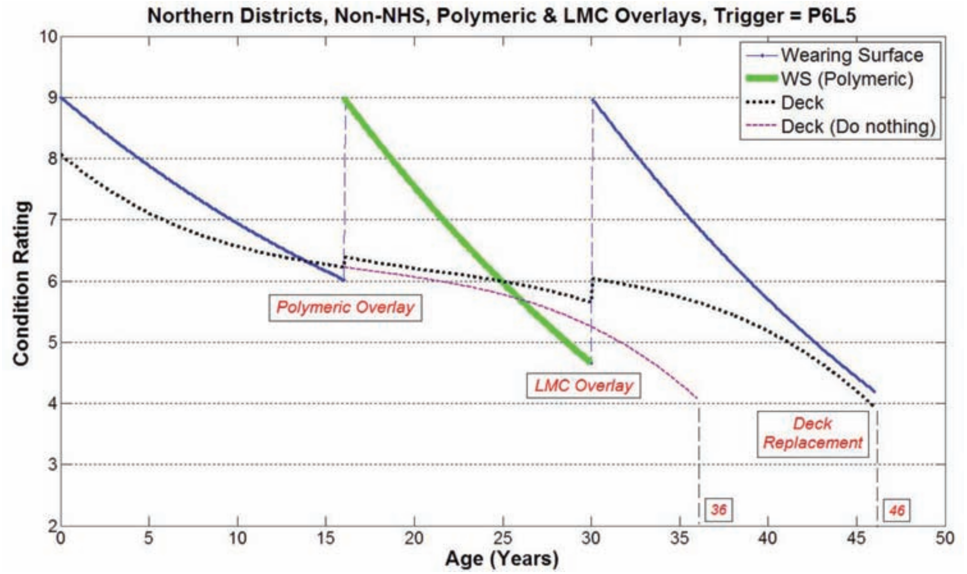


Figure B.6 Appropriate condition-based bridge deck M&R strategy for northern districts, non-NHS, polymeric and LMC overlays.

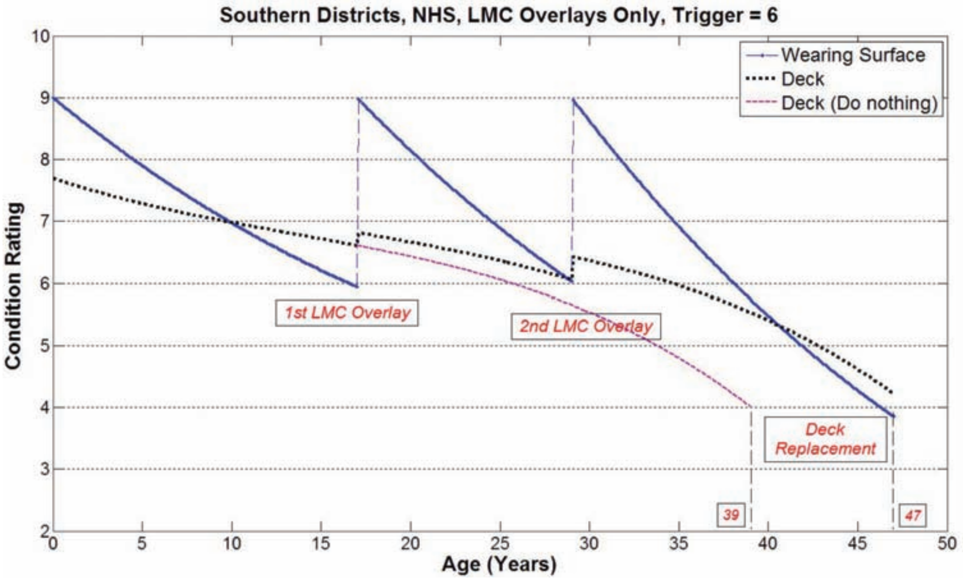


Figure B.7 Appropriate condition-based bridge deck M&R strategy for southern districts, NHS, LMC overlays only.

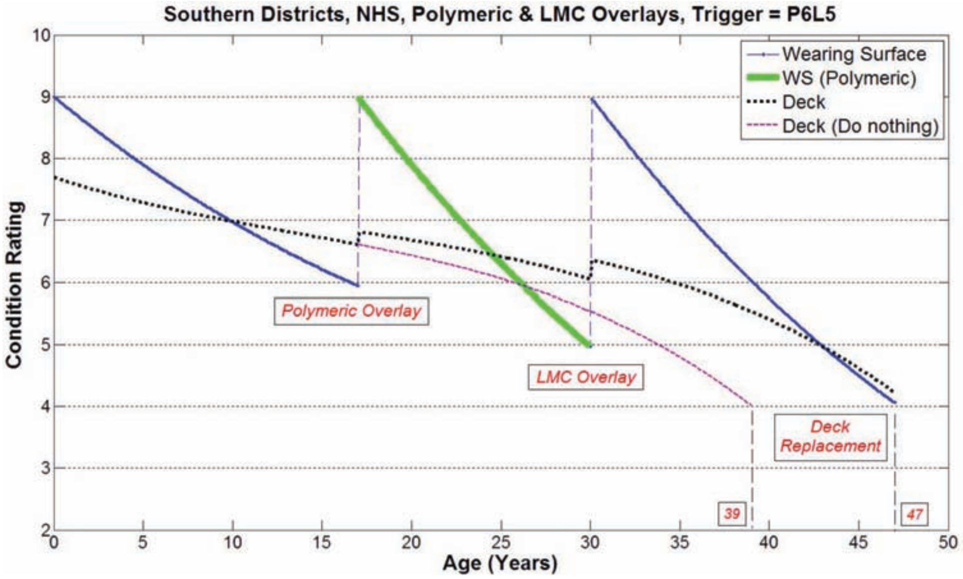


Figure B.8 Appropriate condition-based bridge deck M&R strategy for southern districts, NHS, polymeric and LMC overlays.

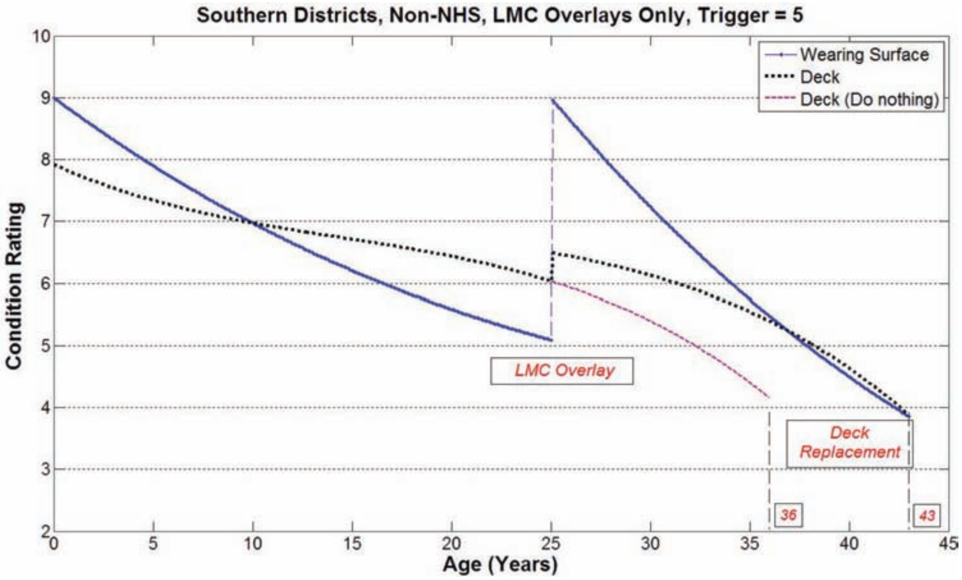


Figure B.9 Appropriate condition-based bridge deck M&R strategy for southern districts, non-NHS, LMC overlays only.

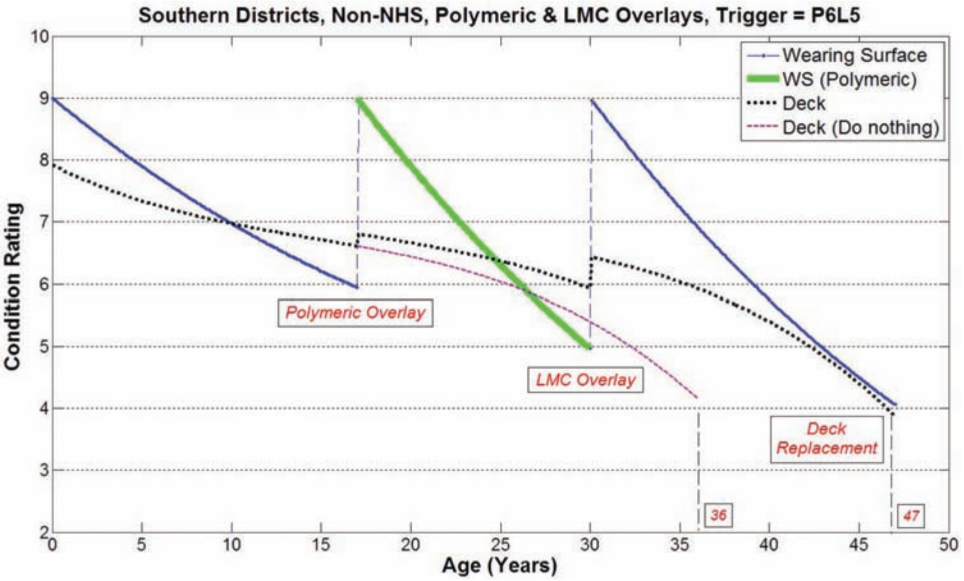


Figure B.10 Appropriate condition-based bridge deck M&R strategy for southern districts, non-NHS, polymeric and LMC overlays.

APPENDIX C. ADDITIONAL EXAMPLES OF CANDIDATE DECK LIFE-CYCLE M&R STRATEGIES (POLYMERIC + LMC OVERLAYS)

Appendix C presents some other examples of strategies for central districts NHS that are found to be not most cost-effective based on the analysis of the current study, including P7L5, P7L6, P8L5, and P8L7. However, these strategies can still serve as candidate strategies. If any factors or parameters, such as unit costs or deterioration rates, are updated in the future, it is possible that one of the candidate strategies would become the new cost-effective strategy (Zhang, 2016).

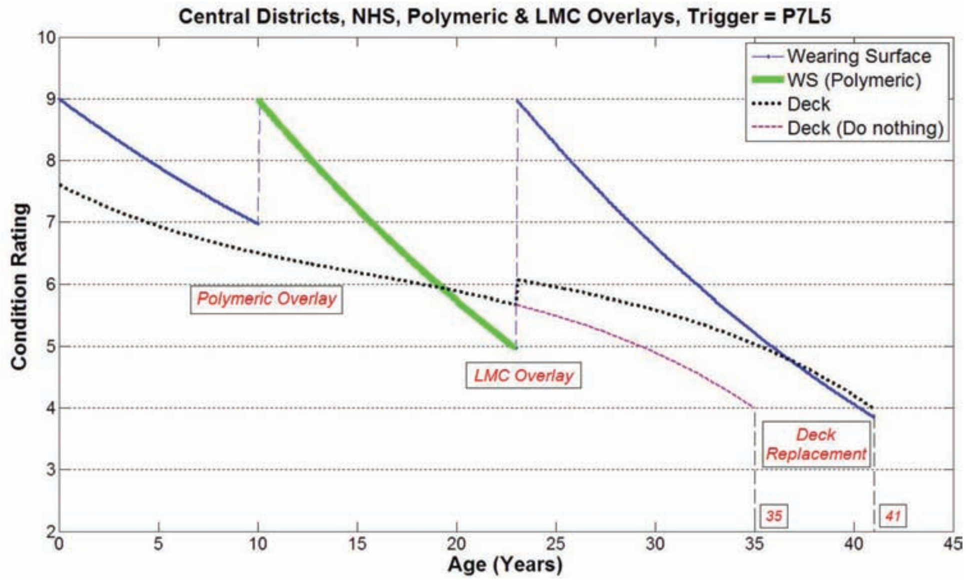


Figure C.1 Profile of other candidate deck M&R strategies for central districts, NHS, polymeric and LMC overlays (Trigger = P7L5).

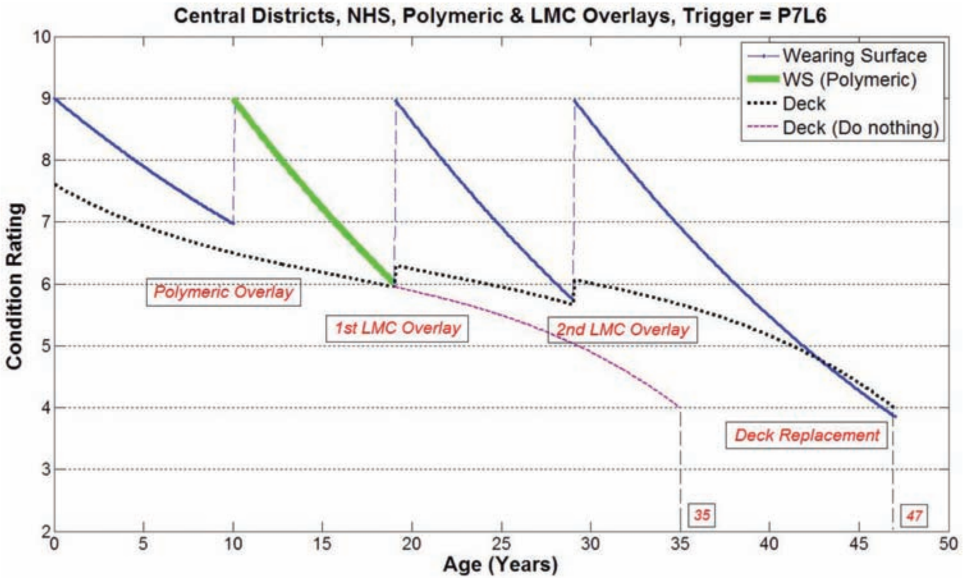


Figure C.2 Profile of other candidate deck M&R strategies for central districts, NHS, polymeric and LMC overlays (Trigger = P7L6).

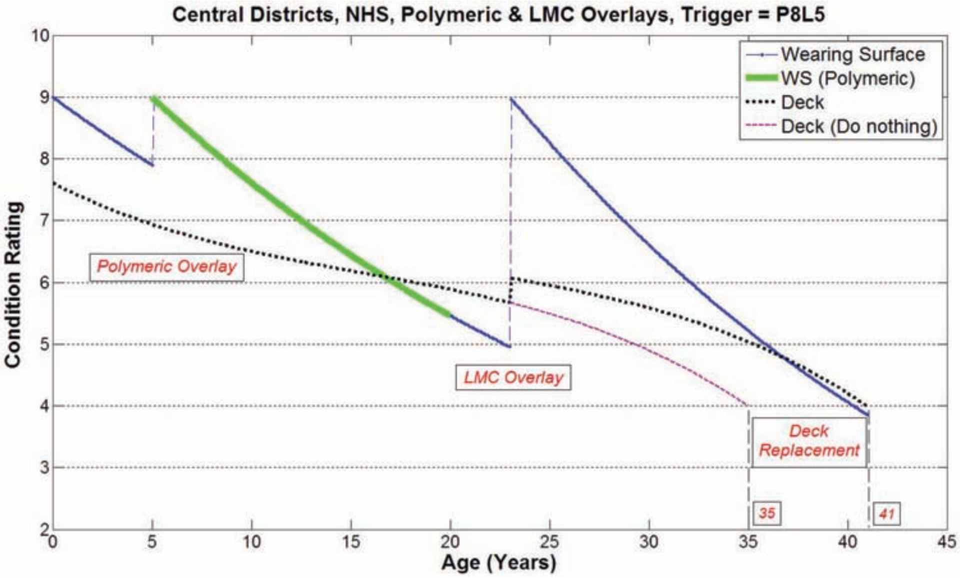


Figure C.3 Profile of other candidate deck M&R strategies for central districts, NHS, polymeric and LMC overlays (Trigger = P8L5).

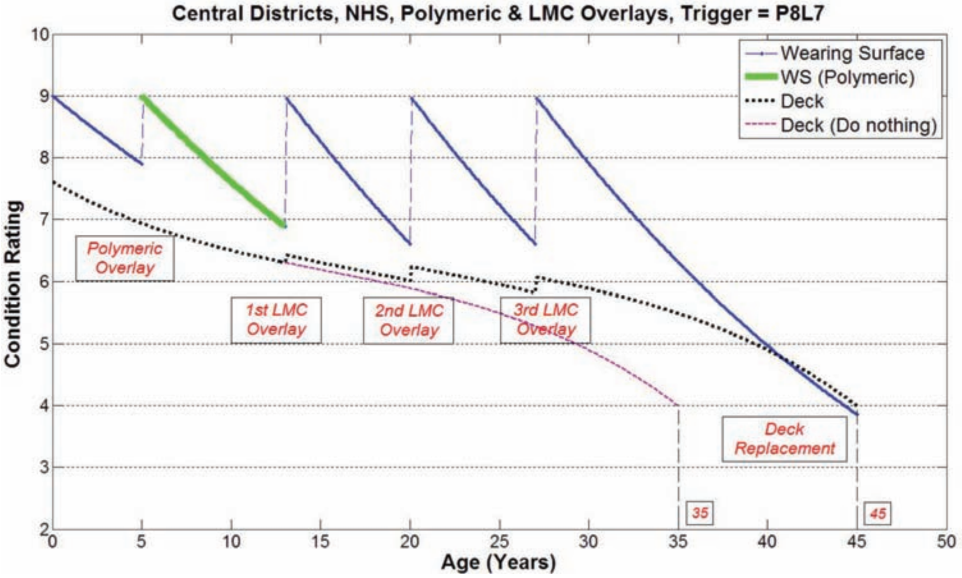


Figure C.4 Profile of other candidate deck M&R strategies for central districts, NHS, polymeric and LMC overlays (Trigger = P8L7).

APPENDIX D. ADDITIONAL SENSITIVITY ANALYSIS RESULTS

Appendix D presents the sensitivity analysis for the other highway districts and functional classes, including northern districts non-NHS, central districts NHS and non-NHS, and southern districts NHS and non-NHS. The Total EUAC values in the table for traffic volume sensitivity analysis are based on the weight of AC:UC=1:1. The findings of the sensitivity analysis has been discussed in Section 4.4 (Zhang, 2016).

TABLE D.1
Sensitivity Analysis for Weights between Agency and User Costs for Northern Districts, Non-NHS, LMC Overlays Only

		Trigger			
	Weight (AC:UC)	**Do Nothing**	**WS = 5**	**WS = 6**	**WS = 7**
(Total EUAC) / (Deck Area) ($/ft^2)	1:1	20.32	26.53	34.50	44.77
	2:1	11.01	14.59	19.27	25.24
	4:1	6.35	8.62	11.66	15.48
	6:1	4.80	6.62	9.12	12.23
	8:1	4.02	5.63	7.85	10.60
	10:1	3.56	5.03	7.09	9.62

TABLE D.2
Sensitivity Analysis for Weights between Agency and User Costs for Northern Districts, Non-NHS, Polymeric and LMC Overlays

		Trigger						
	Weight (AC:UC)	**Do Nothing**	**P8L7**	**P8L6**	**P8L5**	**P7L6**	**P7L5**	**P6L5**
(Total EUAC) / (Deck Area) ($/ft^2)	1:1	20.32	43.06	33.79	27.39	34.28	28.17	25.72
	2:1	11.01	24.53	19.12	15.50	19.38	15.97	14.37
	4:1	6.35	15.26	11.79	9.56	11.94	9.87	8.70
	6:1	4.80	12.17	9.35	7.58	9.45	7.84	6.81
	8:1	4.02	10.63	8.12	6.59	8.21	6.83	5.86
	10:1	3.56	9.70	7.39	5.99	7.47	6.22	5.29

TABLE D.3
Sensitivity Analysis for Traffic Volume for Northern Districts, Non-NHS, LMC Overlays Only

		Trigger			
	Traffic (ADT)	**Do Nothing**	**WS = 5**	**WS = 6**	**WS = 7**
	2,000	5.92	8.06	10.94	14.56
(Total EUAC) / (Deck Area) ($/ft^2)	5,000	12.26	16.18	21.30	27.84
	10,000	22.82	29.73	38.57	49.99
	20,000	43.95	56.81	73.11	94.27

TABLE D.4
Sensitivity Analysis for Traffic Volume for Northern Districts, Non-NHS, Polymeric and LMC Overlays

		Trigger						
	Traffic (ADT)	**Do Nothing**	**P8L7**	**P8L6**	**P8L5**	**P7L6**	**P7L5**	**P6L5**
(Total EUAC) / (Deck Area) ($/ft^2)	2,000	5.92	14.38	11.10	9.00	11.23	9.30	8.17
	5,000	12.26	26.99	21.08	17.09	21.37	17.60	15.89
	10,000	22.82	48.01	37.71	30.57	38.26	31.44	28.76
	20,000	43.95	90.05	70.97	57.53	72.05	59.10	54.50

TABLE D.5
Sensitivity Analysis for Weights between Agency and User Costs for Central Districts, NHS, LMC Overlays Only

		Trigger			
	Weight (AC:UC)	**Do Nothing**	**WS = 5**	**WS = 6**	**WS = 7**
(Total EUAC) / (Deck Area) ($/ft^{2})	1:1	19.11	17.83	17.09	17.50
	2:1	10.45	10.26	10.47	11.32
	4:1	6.12	6.47	7.16	8.23
	6:1	4.67	5.21	6.05	7.20
	8:1	3.95	4.58	5.50	6.68
	10:1	3.52	4.20	5.17	6.37

TABLE D.6
Sensitivity Analysis for Weights between Agency and User Costs for Central Districts, NHS, Polymeric and LMC Overlays

		Trigger						
	Weight (AC:UC)	**Do Nothing**	**P8L7**	**P8L6**	**P8L5**	**P7L6**	**P7L5**	**P6L5**
(Total EUAC) / (Deck Area) ($/ft^{2})	1:1	19.11	18.73	17.99	18.47	17.34	17.96	16.73
	2:1	10.45	12.55	11.45	11.14	10.95	10.83	9.90
	4:1	6.12	9.46	8.17	7.47	7.75	7.27	6.49
	6:1	4.67	8.44	7.08	6.25	6.69	6.08	5.35
	8:1	3.95	7.92	6.54	5.64	6.16	5.49	4.78
	10:1	3.52	7.61	6.21	5.27	5.84	5.13	4.44

TABLE D.7
Sensitivity Analysis for Traffic Volume for Central Districts, NHS, LMC Overlays Only

		Trigger			
	Traffic (ADT)	**Do Nothing**	**WS = 5**	**WS = 6**	**WS = 7**
	2,000	6.53	6.83	7.47	8.52
(Total EUAC) / (Deck Area) ($/ft^{2})	5,000	13.64	13.05	12.91	13.60
	10,000	25.51	23.42	21.97	22.06
	20,000	49.23	44.15	40.09	38.99

TABLE D.8
Sensitivity Analysis for Traffic Volume for Central Districts, NHS, Polymeric and LMC Overlays

		Trigger						
	Traffic (ADT)	**Do Nothing**	**P8L7**	**P8L6**	**P8L5**	**P7L6**	**P7L5**	**P6L5**
(Total EUAC) / (Deck Area) ($/ft^{2})	2,000	6.53	9.76	8.49	7.82	8.06	7.61	6.81
	5,000	13.64	14.83	13.86	13.84	13.31	13.46	12.42
	10,000	25.51	23.28	22.82	23.88	22.06	23.21	21.77
	20,000	49.23	40.19	40.74	43.95	39.56	42.72	40.46

TABLE D.9
Sensitivity Analysis for Weights between Agency and User Costs for Central Districts, Non-NHS, LMC Overlays Only

		Trigger			
	Weight (AC:UC)	**Do Nothing**	**WS = 5**	**WS = 6**	**WS = 7**
(Total EUAC) / (Deck Area) ($\$/\text{ft}^2$)	1:1	13.57	19.24	25.13	31.62
	2:1	7.58	11.09	14.72	18.71
	4:1	4.58	7.01	9.51	12.26
	6:1	3.58	5.65	7.78	10.10
	8:1	3.08	4.97	6.91	9.03
	10:1	2.78	4.56	6.39	8.38

TABLE D.10
Sensitivity Analysis for Weights between Agency and User Costs for Central Districts, Non-NHS, Polymeric and LMC Overlays

		Trigger						
	Weight (AC:UC)	**Do Nothing**	**P8L7**	**P8L6**	**P8L5**	**P7L6**	**P7L5**	**P6L5**
(Total EUAC) / (Deck Area) ($\$/\text{ft}^2$)	1:1	13.57	34.83	27.32	21.35	26.23	20.93	19.02
	2:1	7.58	21.02	16.40	12.76	15.64	12.48	11.18
	4:1	4.58	14.11	10.94	8.47	10.35	8.26	7.26
	6:1	3.58	11.81	9.12	7.04	8.58	6.85	5.95
	8:1	3.08	10.66	8.21	6.32	7.70	6.14	5.30
	10:1	2.78	9.96	7.66	5.89	7.17	5.72	4.91

TABLE D.11
Sensitivity Analysis for Traffic Volume for Central Districts, Non-NHS, LMC Overlays Only

		Trigger			
	Traffic (ADT)	**Do Nothing**	**WS = 5**	**WS = 6**	**WS = 7**
(Total EUAC) / (Deck Area) ($\$/\text{ft}^2$)	2,000	8.07	11.76	15.57	19.77
	5,000	17.80	24.99	32.48	40.73
	10,000	34.03	47.05	60.65	75.65
	20,000	66.48	91.18	117.00	145.50

TABLE D.12
Sensitivity Analysis for Traffic Volume for Central Districts, Non-NHS, Polymeric and LMC Overlays

		Trigger						
	Traffic (ADT)	**Do Nothing**	**P8L7**	**P8L6**	**P8L5**	**P7L6**	**P7L5**	**P6L5**
(Total EUAC) / (Deck Area) ($\$/\text{ft}^2$)	2,000	8.07	22.15	17.30	13.47	16.51	13.18	11.82
	5,000	17.80	44.58	35.03	27.41	33.71	26.90	24.55
	10,000	34.03	81.96	64.59	50.64	62.36	49.77	45.77
	20,000	66.48	156.7	123.7	97.11	119.7	95.50	88.20

TABLE D.13

Sensitivity Analysis for Weights between Agency and User Costs for Southern Districts, NHS, LMC Overlays Only

		Trigger			
	Weight (AC:UC)	**Do Nothing**	**WS = 5**	**WS = 6**	**WS = 7**
(Total EUAC) / (Deck Area) (\$/ft^2)	1:1	26.90	24.36	22.64	22.60
	2:1	14.23	13.47	13.15	13.73
	4:1	7.89	8.02	8.40	9.29
	6:1	5.78	6.20	6.82	7.81
	8:1	4.72	5.30	6.03	7.07
	10:1	4.09	4.75	5.55	6.63

TABLE D.14

Sensitivity Analysis for Weights between Agency and User Costs for Southern Districts, NHS, Polymeric and LMC Overlays

		Trigger						
	Weight (AC:UC)	**Do Nothing**	**P8L7**	**P8L6**	**P8L5**	**P7L6**	**P7L5**	**P6L5**
(Total EUAC) / (Deck Area) (\$/ft^2)	1:1	26.90	23.75	23.46	24.73	22.66	23.98	22.57
	2:1	14.23	14.94	14.09	14.22	13.51	13.78	12.76
	4:1	7.89	10.54	9.41	8.97	8.94	8.68	7.86
	6:1	5.78	9.08	7.85	7.22	7.42	6.98	6.23
	8:1	4.72	8.34	7.07	6.34	6.65	6.13	5.41
	10:1	4.09	7.90	6.60	5.81	6.20	5.62	4.92

TABLE D.15

Sensitivity Analysis for Traffic Volume for Southern Districts, NHS, LMC Overlays Only

		Trigger			
	Traffic (ADT)	**Do Nothing**	**WS = 5**	**WS = 6**	**WS = 7**
(Total EUAC) / (Deck Area) (\$/ft^2)	2,000	6.11	6.48	7.05	8.02
	5,000	12.93	12.35	12.17	12.81
	10,000	24.31	22.13	20.69	20.77
	20,000	47.06	41.69	37.73	36.71

TABLE D.16

Sensitivity Analysis for Traffic Volume for Southern Districts, NHS, Polymeric and LMC Overlays

		Trigger						
	Traffic (ADT)	**Do Nothing**	**P8L7**	**P8L6**	**P8L5**	**P7L6**	**P7L5**	**P6L5**
(Total EUAC) / (Deck Area) (\$/ft^2)	2,000	6.11	9.29	8.08	7.48	7.64	7.24	6.48
	5,000	12.93	14.03	13.13	13.14	12.57	12.73	11.76
	10,000	24.31	21.93	21.53	22.58	20.78	21.89	20.56
	20,000	47.06	37.74	38.35	41.46	37.21	40.20	38.16

TABLE D.17
Sensitivity Analysis for Weights between Agency and User Costs for Southern Districts, Non-NHS, LMC Overlays Only

		Trigger			
	Weight (AC:UC)	**Do Nothing**	**WS = 5**	**WS = 6**	**WS = 7**
(Total EUAC) / (Deck Area) (\$/ft^2)	1:1	20.91	28.46	36.57	45.65
	2:1	11.33	15.63	20.31	25.56
	4:1	6.54	9.21	12.18	15.51
	6:1	4.95	7.07	9.47	12.16
	8:1	4.15	6.00	8.12	10.49
	10:1	3.67	5.36	7.31	9.49

TABLE D.18
Sensitivity Analysis for Weights between Agency and User Costs for Southern Districts, Non-NHS, Polymeric and LMC Overlays

		Trigger						
	Weight (AC:UC)	**Do Nothing**	**P8L7**	**P8L6**	**P8L5**	**P7L6**	**P7L5**	**P6L5**
(Total EUAC) / (Deck Area) (\$/ft^2)	1:1	20.91	49.72	39.25	30.94	37.82	30.35	27.84
	2:1	11.33	28.27	22.22	17.47	21.31	17.10	15.53
	4:1	6.54	17.54	13.71	10.74	13.05	10.48	9.37
	6:1	4.95	13.97	10.87	8.49	10.30	8.27	7.32
	8:1	4.15	12.18	9.45	7.37	8.92	7.17	6.29
	10:1	3.67	11.11	8.60	6.69	8.10	6.51	5.68

TABLE D.19
Sensitivity Analysis for Traffic Volume for Southern Districts, Non-NHS, LMC Overlays Only

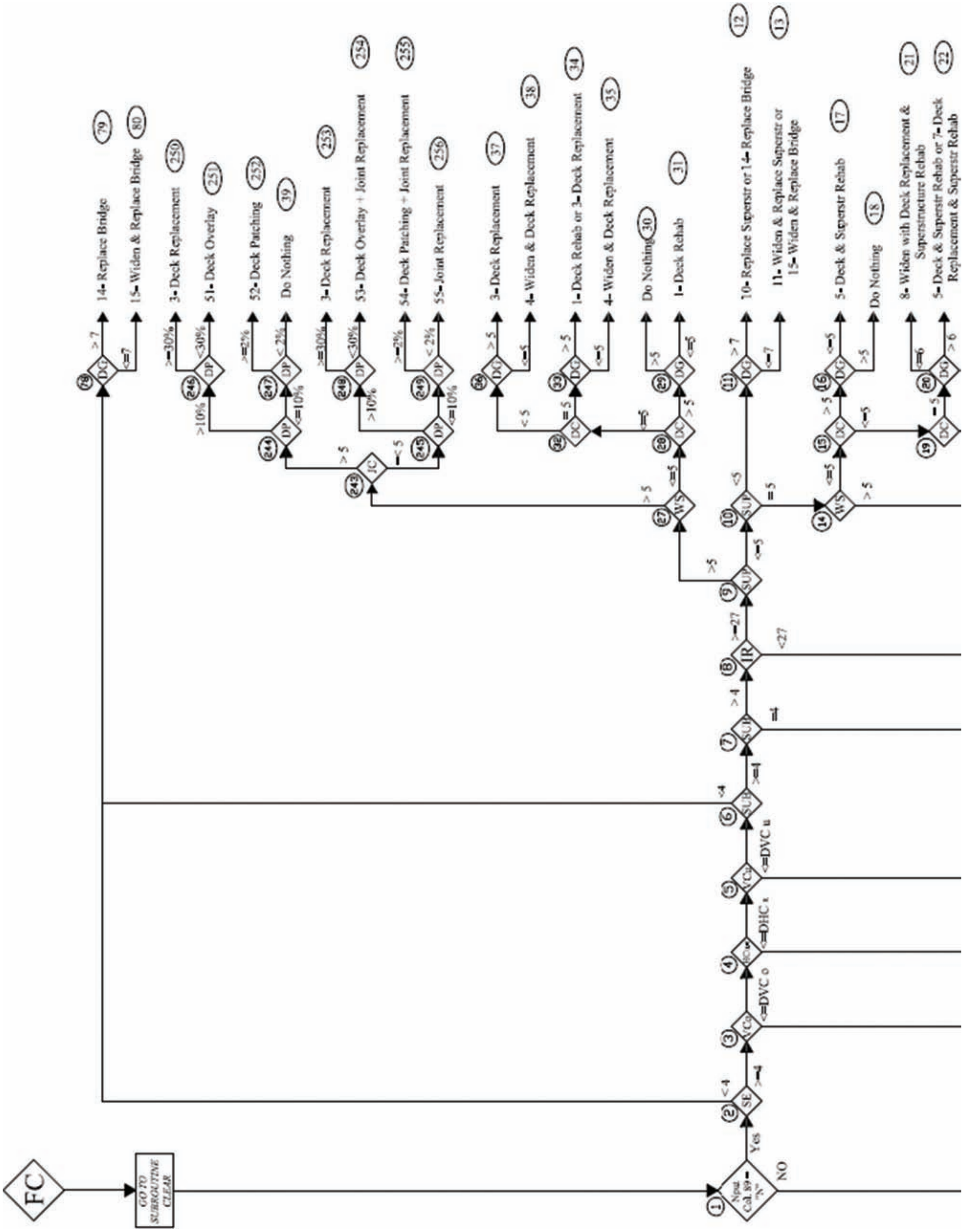
		Trigger			
	Traffic (ADT)	**Do Nothing**	**WS = 5**	**WS = 6**	**WS = 7**
(Total EUAC) / (Deck Area) (\$/ft^2)	2,000	7.90	11.02	14.47	18.34
	5,000	17.12	23.38	30.12	37.68
	10,000	32.49	43.97	56.20	69.91
	20,000	63.23	85.14	108.37	134.37

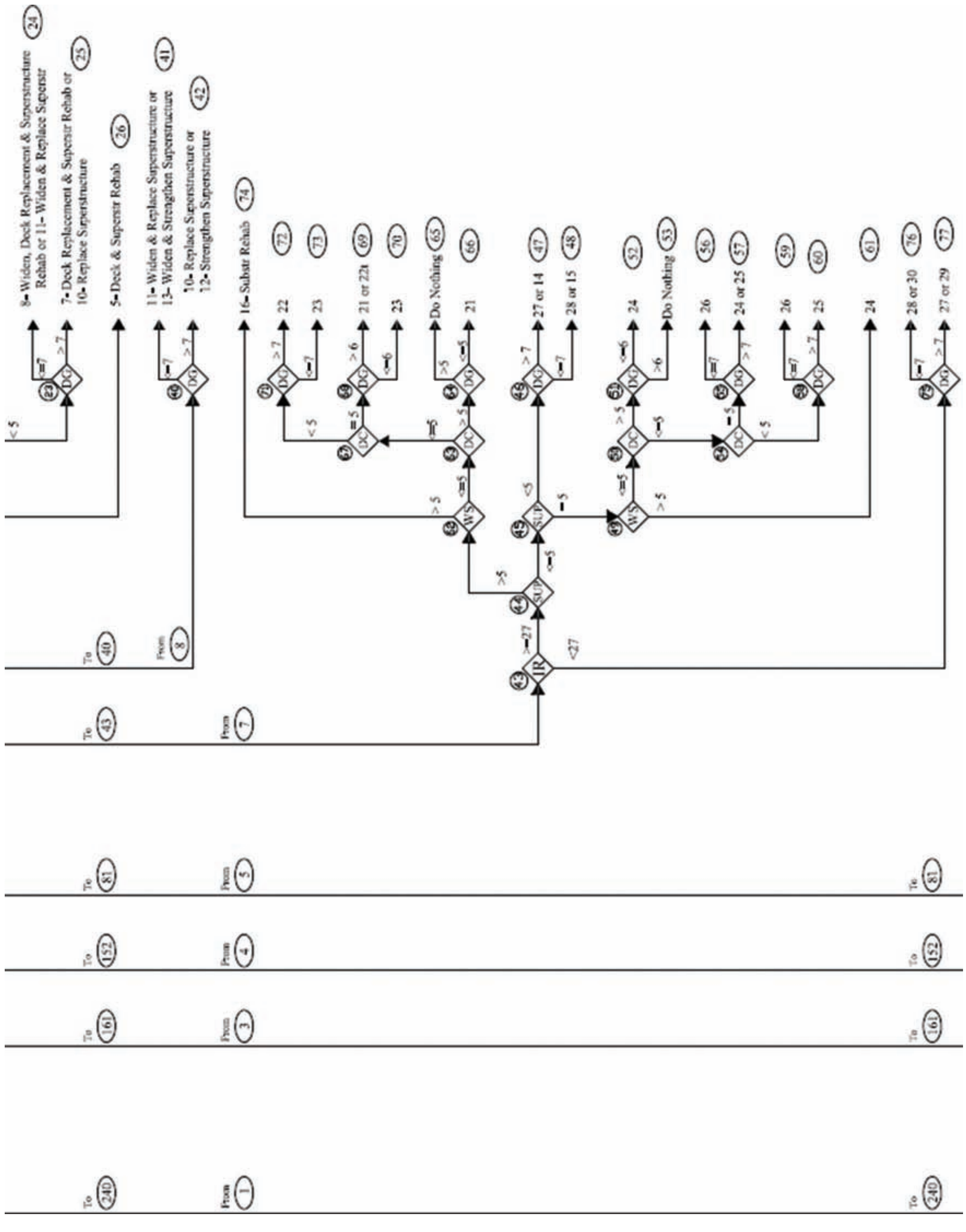
TABLE D.20
Sensitivity Analysis for Traffic Volume for Southern Districts, Non-NHS, Polymeric and LMC Overlays

		Trigger						
	Traffic (ADT)	**Do Nothing**	**P8L7**	**P8L6**	**P8L5**	**P7L6**	**P7L5**	**P6L5**
(Total EUAC) / (Deck Area) (\$/ft^2)	2,000	7.90	20.56	16.11	12.64	15.38	12.35	11.11
	5,000	17.12	41.21	32.50	25.60	31.27	25.10	22.96
	10,000	32.49	75.62	59.81	47.21	57.76	46.34	42.71
	20,000	63.23	144.4	114.4	90.42	110.7	88.84	82.22

APPENDIX E. IBMS DTREE FOR NHS AND NON-NHS BRIDGES

DTREE for NHS Bridges




8- Widen, Deck Replacement & Superstructure Rehab or 11- Widen & Replace Superstr
24
7- Deck Replacement & Superstr Rehab or 10- Replace Superstructure
25
5- Deck & Superstr Rehab
26
11- Widen & Replace Superstructure or 13- Widen & Strengthen Superstructure
41
10- Replace Superstructure or 12- Strengthen Superstructure
42
16- Substr Rehab
74
22
72
23
73
21 or 22t
69
23
70
Do Nothing
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21
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47
28 or 15
48
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52
Do Nothing
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57
26
59
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61
28 or 30
76
27 or 29
77
< 5
23
DG
<=7
> 7
40
DG
<=7
> 7
71
DG
> 7
<=7
67
DC
= 5
< 5
68
DG
> 6
<=6
63
DC
> 5
<=5
64
DG
>5
<=5
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WS
> 5
<=5
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DG
> 7
<=7
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SUP
<5
=5
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SUP
>5
<=5
43
IR
>=27
<27
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WS
<=5
> 5
50
DC
> 5
<=5
51
DG
<=6
>6
54
DC
=5
< 5
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DG
<=7
> 7
58
DG
<=7
> 7
75
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To
40
From
8
To
43
From
7
To
81
From
5
To
81
To
152
From
4
To
152
To
161
From
3
To
161
To
240
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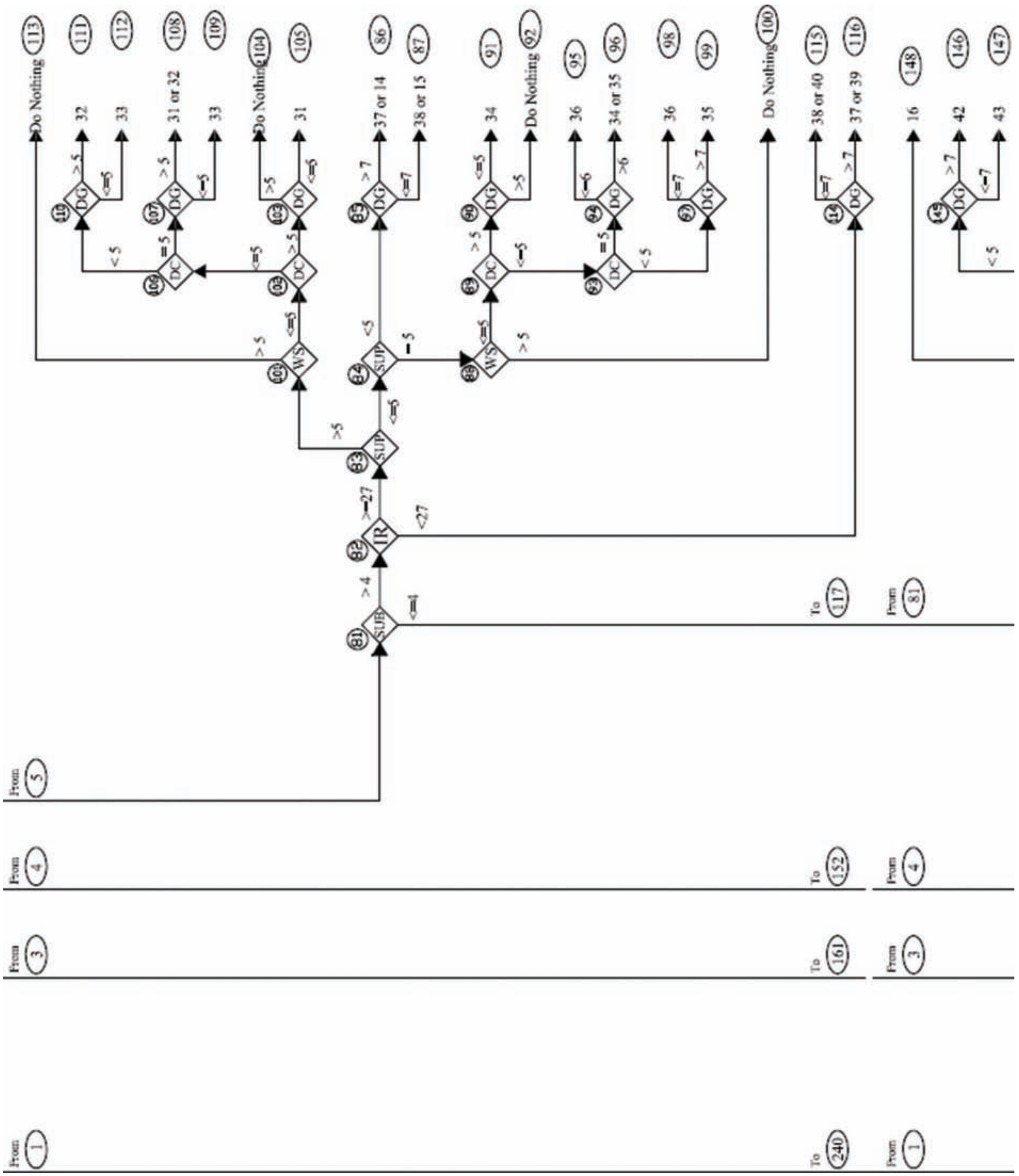
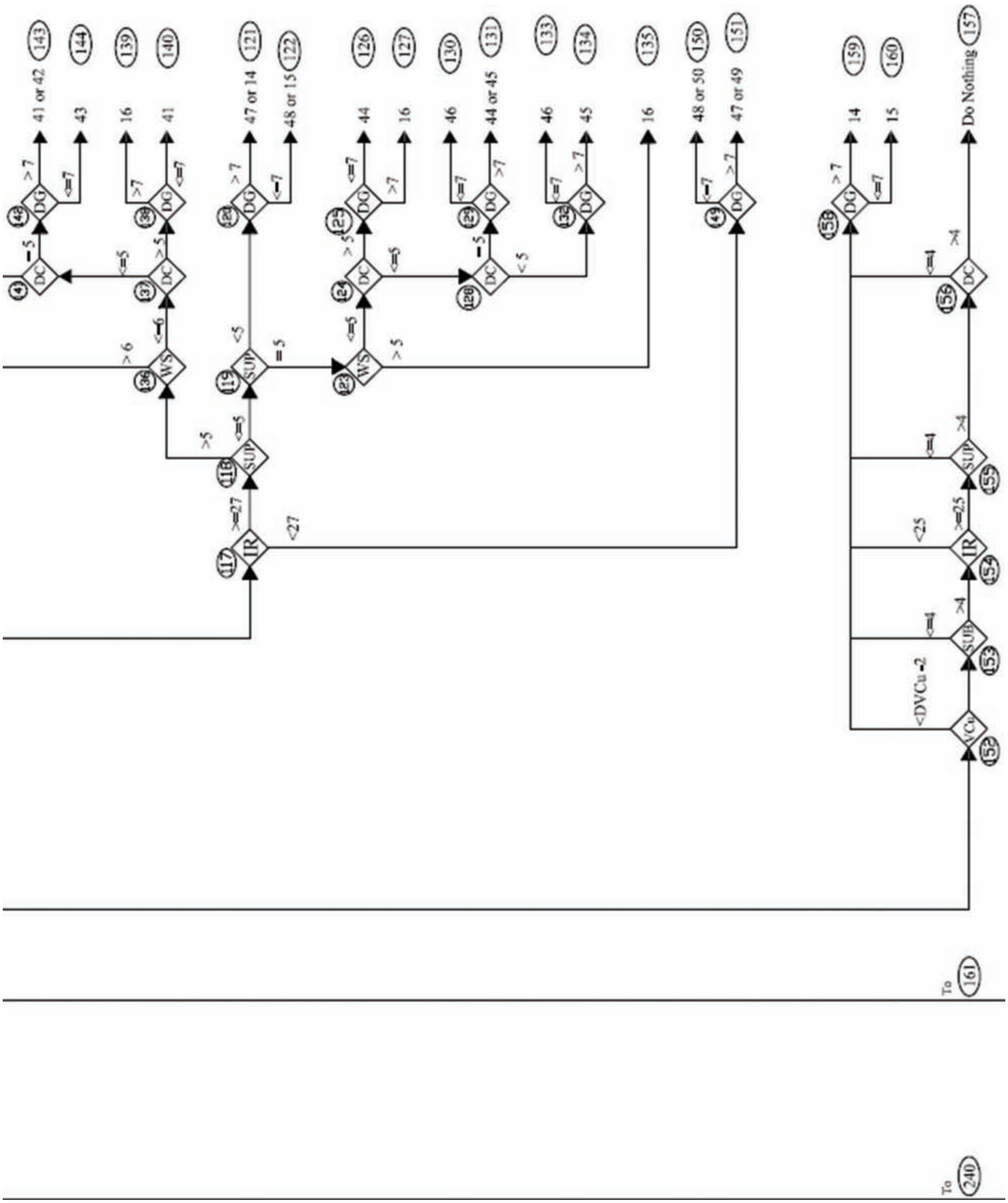
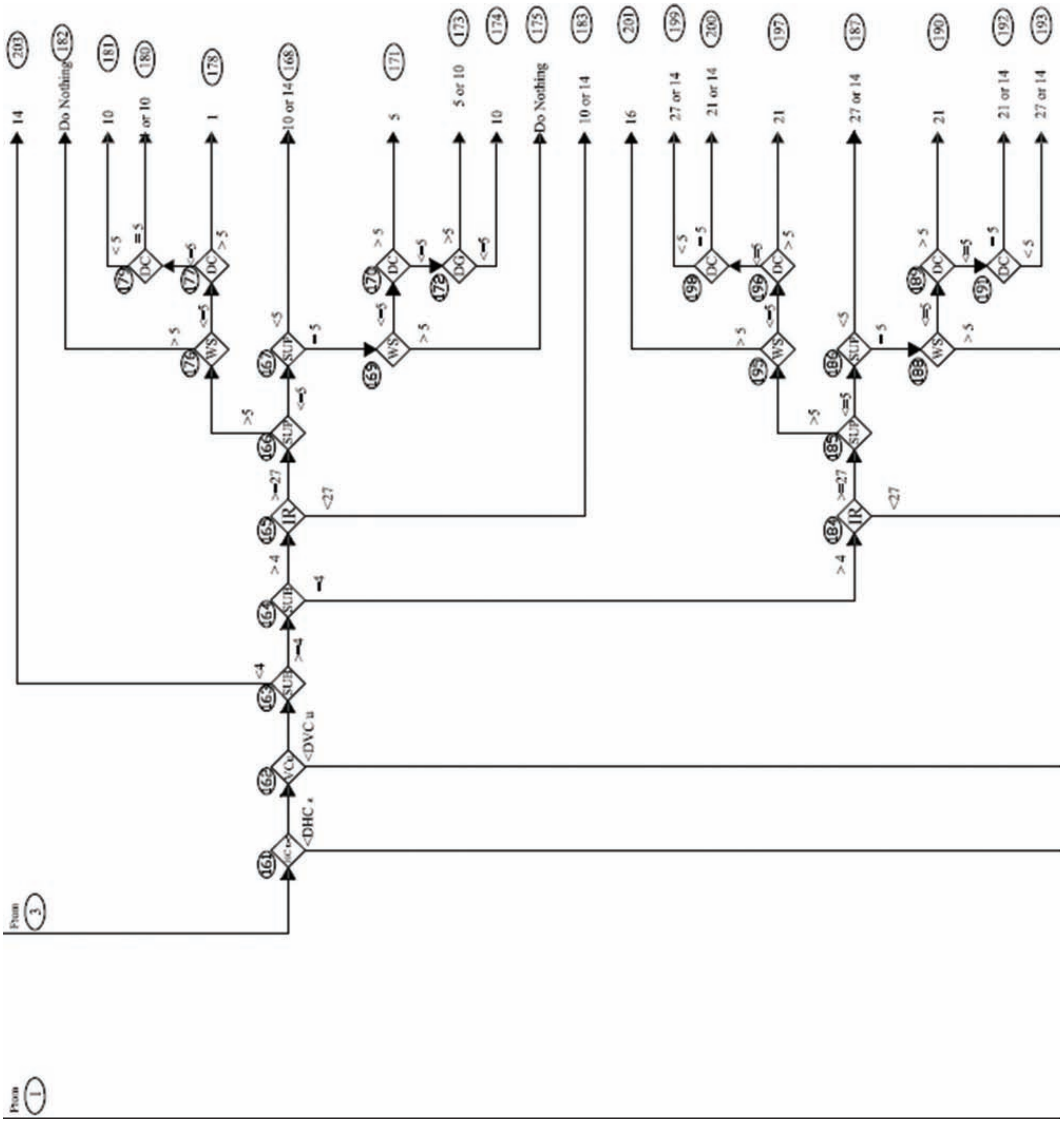
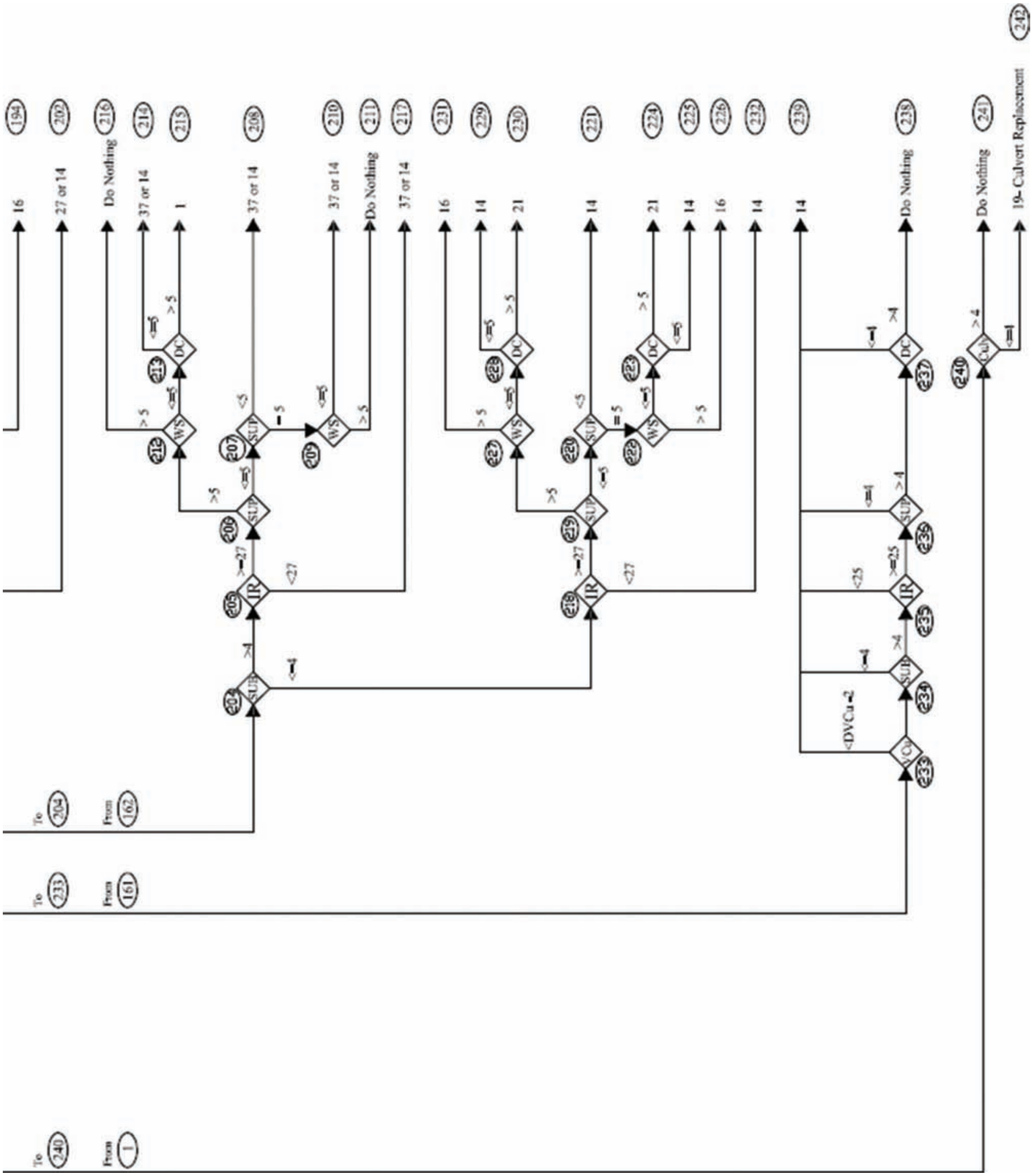
1
To
240


From 5
From 4
From 3
From 1
To 117
To 152
To 161
To 240
From 81
From 4
From 3
From 1
SUB
> 4
<=1
IR
>=27
<27
SUP
> 5
<=5
WS
DC
DG
Do Nothing
113
32
111
33
112
31 or 32
108
109
104
31
105
37 or 14
86
38 or 15
87
34
91
92
36
95
34 or 35
96
98
35
99
100
38 or 40
115
37 or 39
116
16
148
42
146
43
147


41 or 42
143
43
144
16
139
41
140
47 or 14
121
48 or 15
122
44
126
16
127
46
130
44 or 45
131
46
133
45
134
16
135
48 or 50
150
47 or 49
151
14
159
15
160
Do Nothing
157
DC
DG
> 7
<=7
= 5
<=5
WS
> 6
<=6
SUP
< 5
= 5
> 5
IR
>=27
<27
>=25
<25
SUB
>4
<=4
VCu
<DVCu -2
To 161
To 240


From 1
From 3
161 DHC
<DHC
162 VCu
<DVC u
163 SUP
<4
>=4
164 SUP
=4
>4
165 IR
>=27
<27
166 SUP
>5
<=5
167 SUP
<5
=5
176 WS
>5
<=5
177 DC
<=5
>5
179 DC
<5
=5
169 WS
<=5
>5
170 DC
>5
<=5
172 DG
>5
<=5
14
203
Do Nothing
182
10
181
5 or 10
180
1
178
10 or 14
168
5
171
5 or 10
173
10
174
Do Nothing
175
10 or 14
183
16
201
27 or 14
199
21 or 14
200
21
197
27 or 14
187
21
190
21 or 14
192
27 or 14
193
184 IR
>=27
<27
>4
185 SUP
>5
<=5
186 SUP
<5
=5
188 WS
<=5
>5
189 DC
>5
<=5
191 DC
=5
<5
195 WS
>5
<=5
196 DC
<=5
>5
198 DC
<5
=5



To 204
From 162
To 233
From 161
To 240
From 1
SUP
IR
WS
DC
VCu
Culv
<DVCu=2
>4
<=4
>=27
<27
>5
<=5
<5
=5
>=25
<25
=1
16
27 or 14
Do Nothing
37 or 14
1
21
14
19- Culvert Replacement
194
202
216
214
215
208
210
211
217
231
229
230
221
224
225
226
232
239
238
241
242
204
205
206
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212
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228
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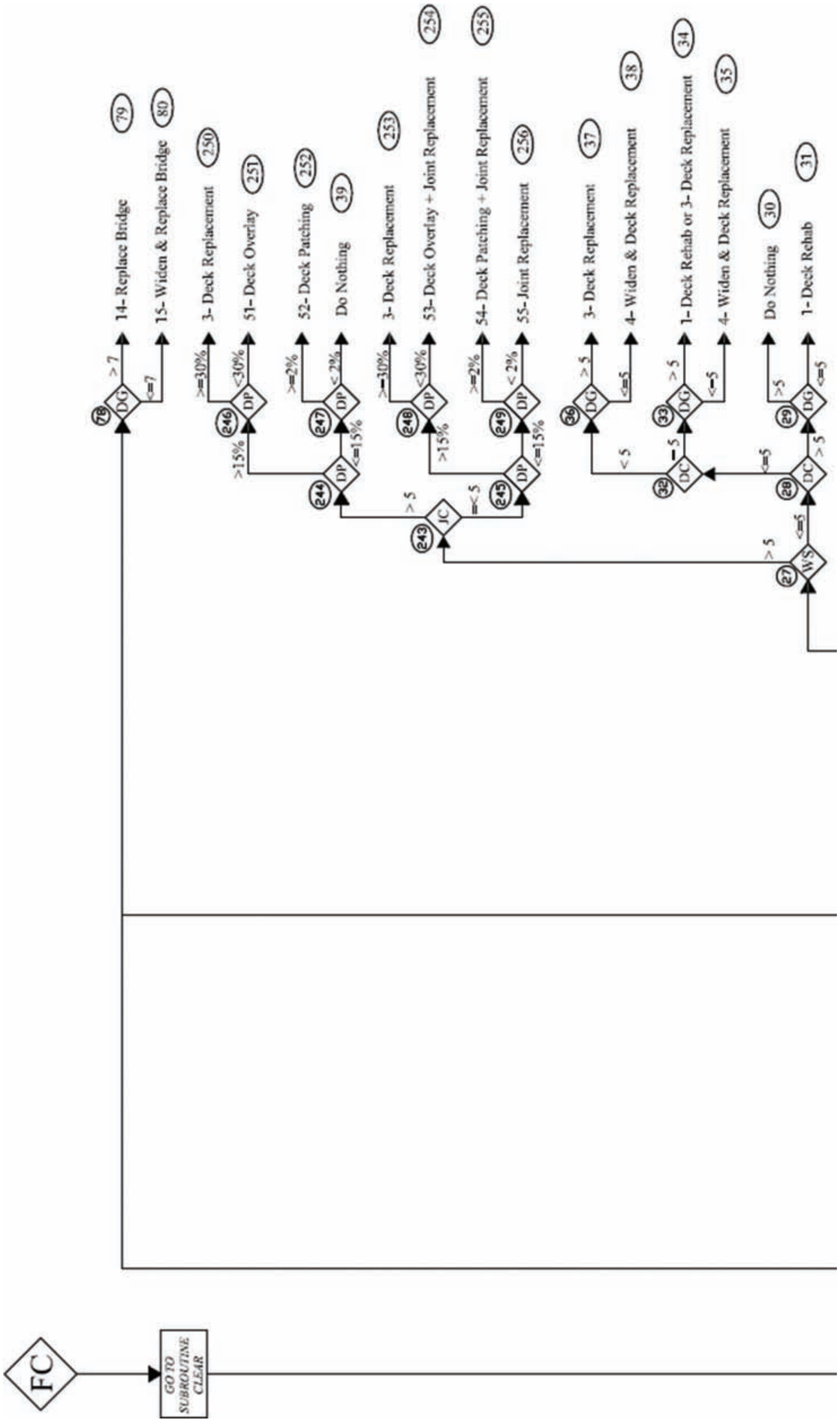
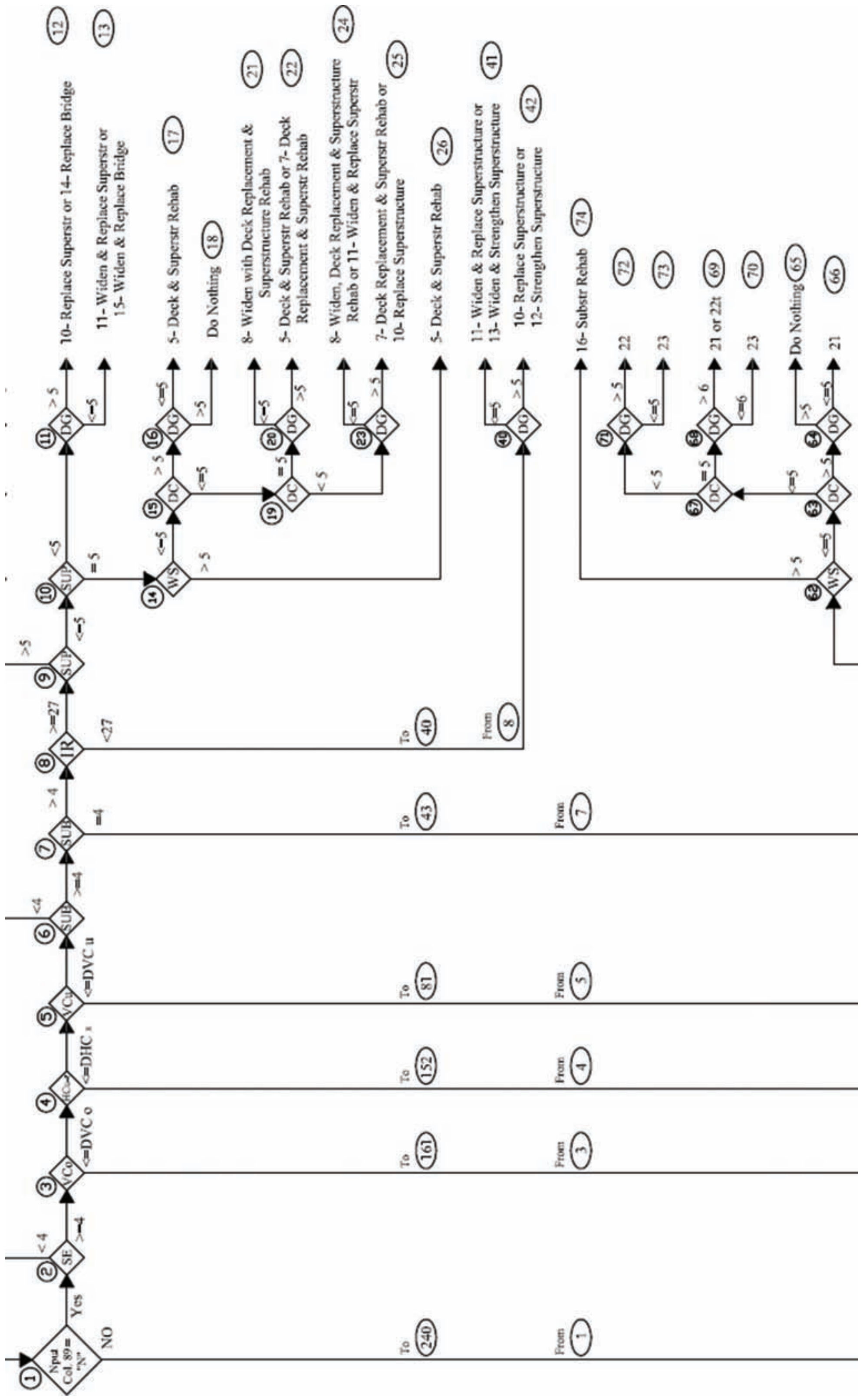
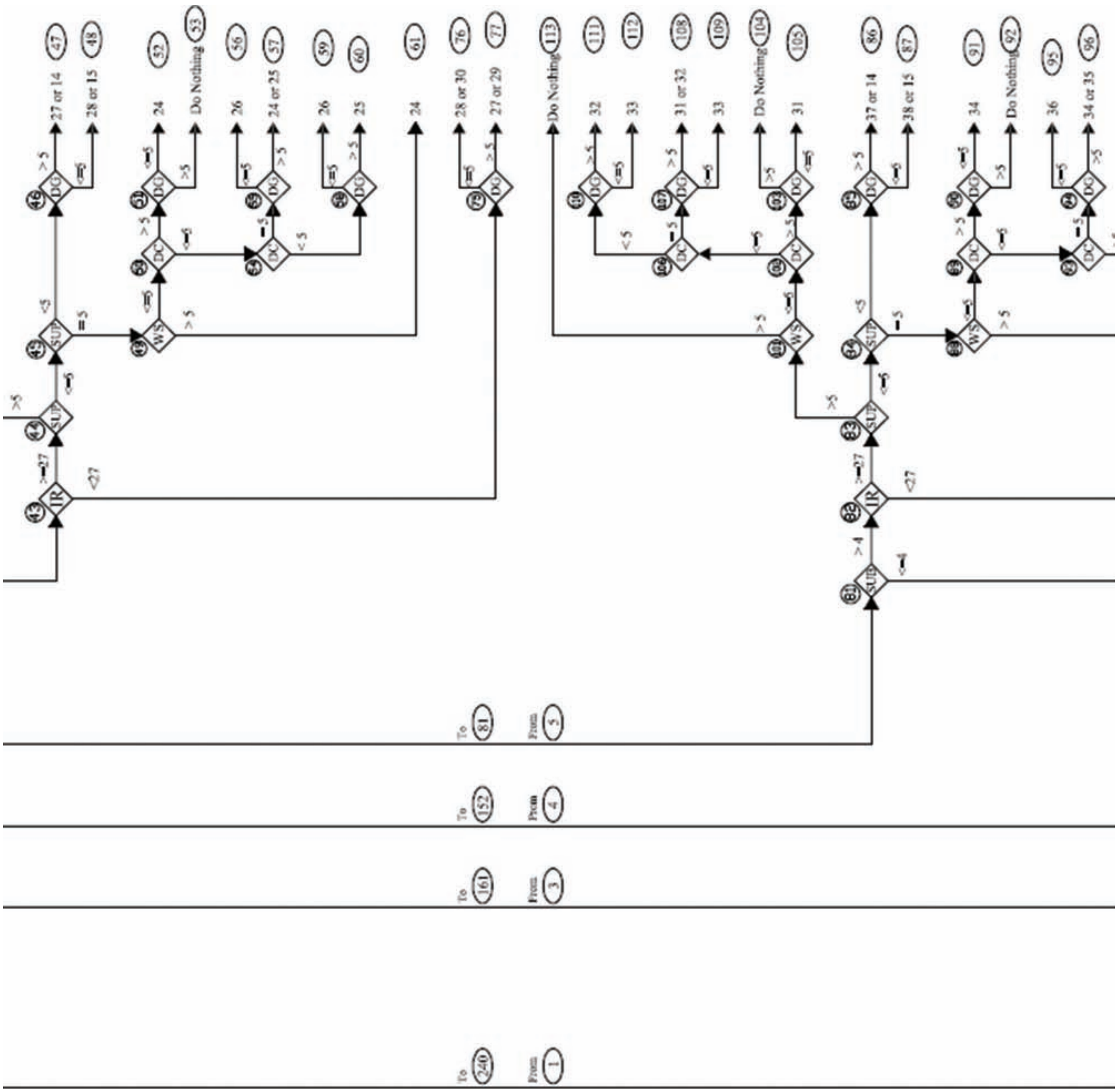
234
235
236
237
240

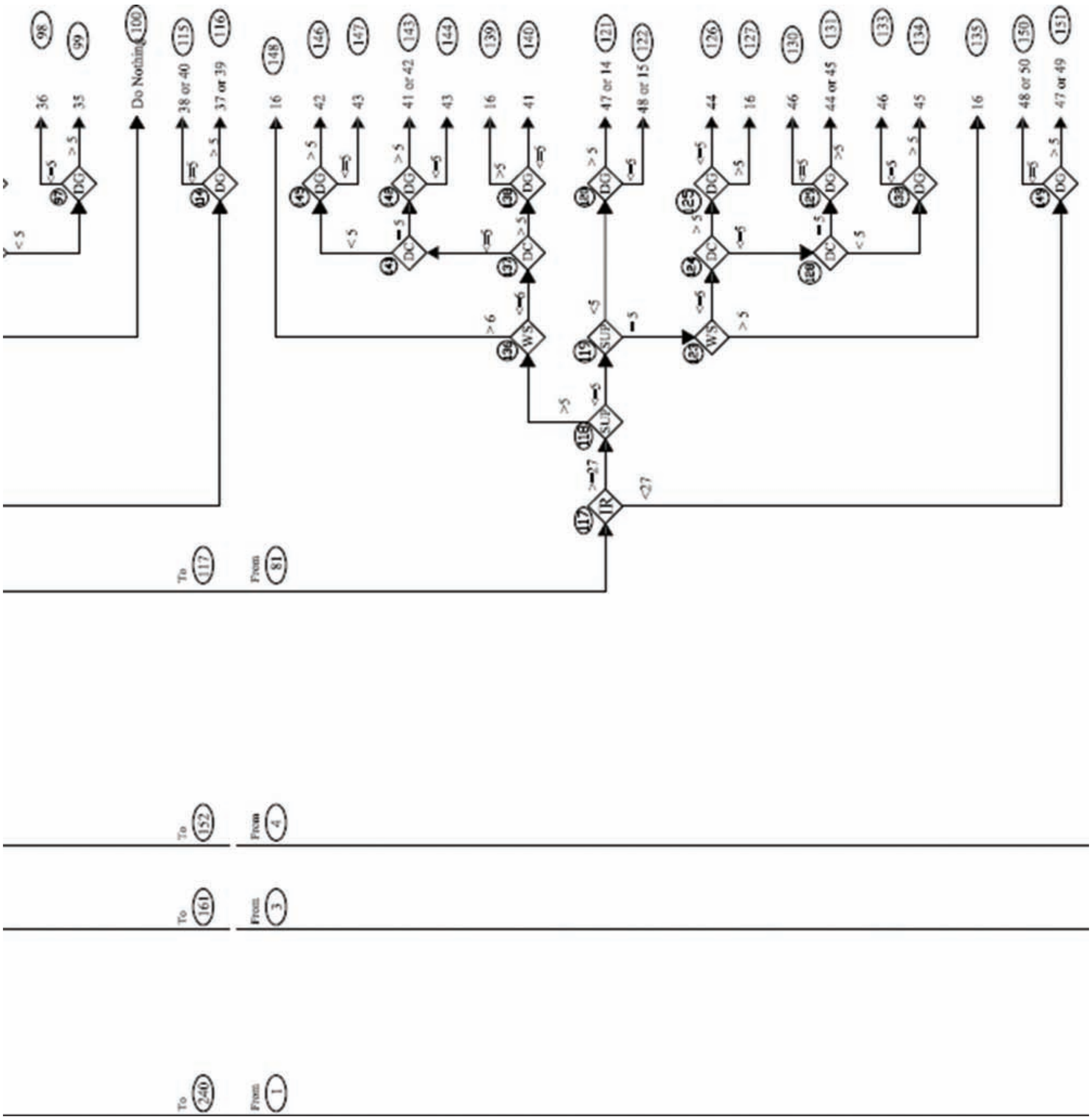
DTREE for Non-NHS Bridges




1
Npd Col. 89= "N"
Yes
NO
To 240
From 1
2
SF
< 4
>=4
3
VCo
<=DVC o
To 161
From 3
4
HC
<=DHC
To 152
From 4
5
VCu
<=DVC u
To 81
From 5
6
SUB
<4
>=4
7
SUB
> 4
=4
To 43
From 7
8
IR
>=27
<27
To 40
From 8
9
SUP
>5
<=5
10
SUP
<5
= 5
11
DG
> 5
<=5
10- Replace Superstr or 14- Replace Bridge
12
11- Widen & Replace Superstr or 15- Widen & Replace Bridge
13
14
WS
<=5
> 5
15
DC
> 5
<=5
16
DG
<=5
>5
5- Deck & Superstr Rehab
17
Do Nothing
18
19
DC
= 5
< 5
20
DG
<=5
> 5
8- Widen with Deck Replacement & Superstructure Rehab
21
5- Deck & Superstr Rehab or 7- Deck Replacement & Superstr Rehab
22
23
DG
<=5
> 5
8- Widen, Deck Replacement & Superstructure Rehab or 11- Widen & Replace Superstr
24
7- Deck Replacement & Superstr Rehab or 10- Replace Superstructure
25
5- Deck & Superstr Rehab
26
40
DG
<=5
> 5
11- Widen & Replace Superstructure or 13- Widen & Strengthen Superstructure
41
10- Replace Superstructure or 12- Strengthen Superstructure
42
16- Substr Rehab
74
62
WS
> 5
<=5
63
DC
> 5
<=5
64
DG
>5
<=5
Do Nothing
65
21
66
67
DC
= 5
< 5
68
DG
> 6
<=6
21 or 22t
69
23
70
71
DG
> 5
<=5
22
72
23
73



27 or 14
47
28 or 15
48
24
52
Do Nothing
53
26
56
24 or 25
57
26
59
25
60
24
61
28 or 30
76
27 or 29
77
Do Nothing
113
32
111
33
112
31 or 32
108
33
109
Do Nothing
104
31
105
37 or 14
86
38 or 15
87
34
91
Do Nothing
92
36
95
34 or 35
96
DG
SUP
WS
DC
IR
>5
<=5
=5
<5
>=27
<27
>4
<=4
To
81
From
5
To
152
From
4
To
161
From
3
To
240
From
1

98
99
100
115
116
148
146
147
143
144
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122
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127
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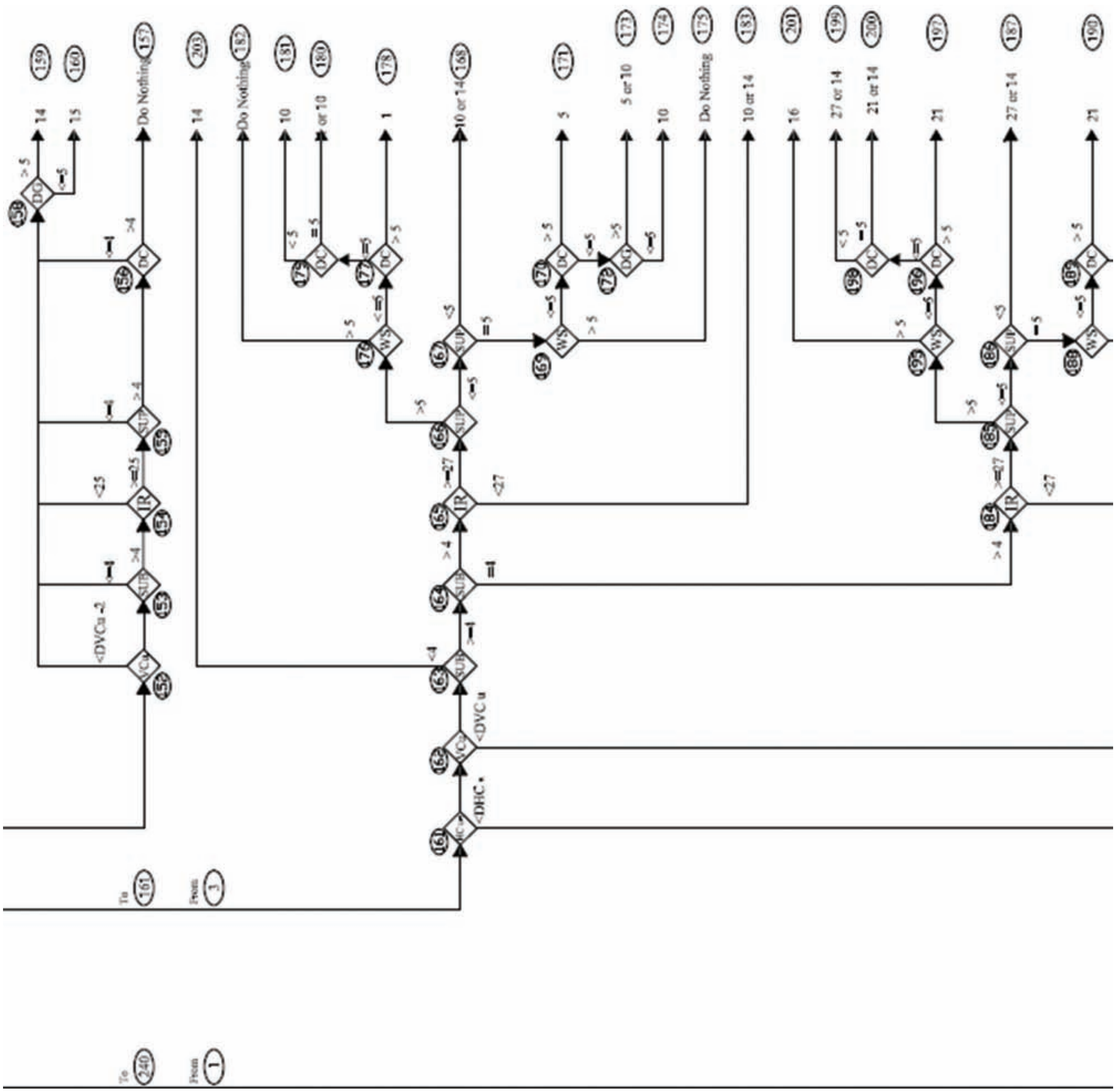
131
133
134
135
150
151
36
33
Do Nothing
38 or 40
37 or 39
16
42
43
41 or 42
43
16
41
47 or 14
48 or 15
44
16
46
44 or 45
46
45
16
48 or 50
47 or 49
DG
DC
WS
SUF
IR
< 5
>= 5
> 5
> 6
<5
>= 27
<27
117
To 117
From 81
To 152
From 4
To 161
From 3
To 240
From 1


To 240
From 1
To 161
From 3
<DHC
<DVCu
<DVCu -2
Do Nothing
10 or 14
5 or 10
27 or 14
21 or 14
16
21
14
15
10
5
1
159
160
157
203
182
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171
173
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201
199
200
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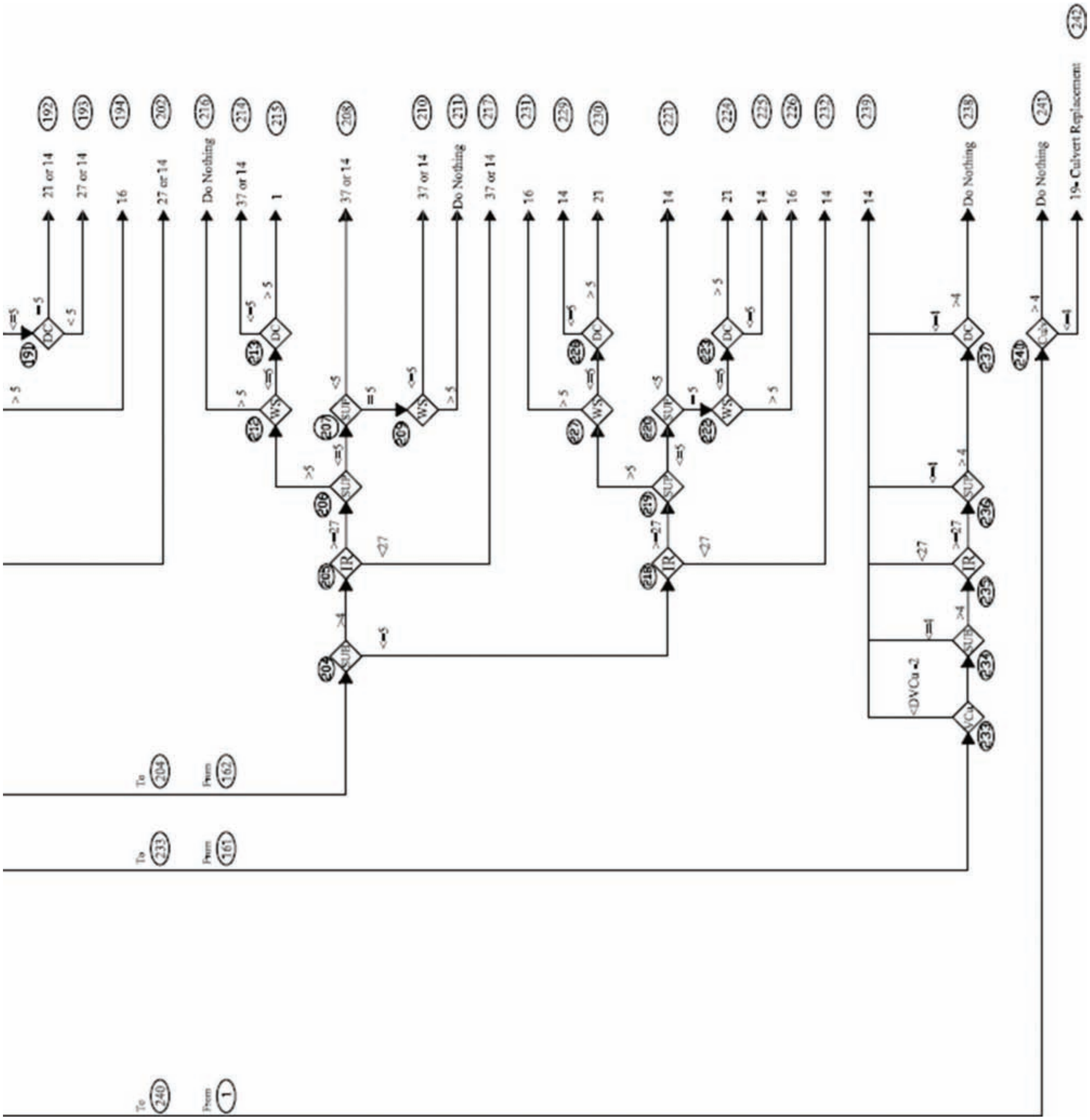
187
190



192
193
194
202
216
214
215
208
210
211
217
231
229
230
221
224
225
226
232
239
238
241
242
21 or 14
27 or 14
16
27 or 14
Do Nothing
37 or 14
1
37 or 14
37 or 14
Do Nothing
37 or 14
16
14
21
14
21
14
16
14
14
Do Nothing
Do Nothing
19- Culvert Replacement
DC
WS
SUF
IR
DVCu
To
From
204
162
233
161
240
1
<DVCu-2

About the Joint Transportation Research Program (JTRP)

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

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

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

Further information about JTRP and its current research program is available at: http://www.purdue.edu/jtrp

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