January 2016

Developing Condition-Based Triggers for Bridge Deck Maintenance and Rehabilitation Treatments

Zhibo Zhang
Purdue University

Graduate School Form
30 Updated 12/26/2015

PURDUE UNIVERSITY
GRADUATE SCHOOL
Thesis/Dissertation Acceptance

This is to certify that the thesis/dissertation prepared

By Zhibo Zhang

Entitled

Developing Condition-Based Triggers for Bridge Maintenance and Rehabilitation Treatments

For the degree of Doctor of Philosophy

Is approved by the final examining committee:

Samuel Labi
Co-chair

Kumares C. Sinha
Co-chair

Jon Fricker

Thomas Morin

To the best of my knowledge and as understood by the student in the Thesis/Dissertation Agreement, Publication Delay, and Certification Disclaimer (Graduate School Form 32), this thesis/dissertation adheres to the provisions of Purdue University's "Policy of Integrity in Research" and the use of copyright material.

Approved by Major Professor(s): Samuel Labi and Kumares C. Sinha

Approved by: Dulcy Abraham 12/1/2016

Head of the Departmental Graduate Program Date

DEVELOPING CONDITION-BASED TRIGGERS FOR BRIDGE DECK MAINTENANCE AND REHABILITATION TREATMENTS

A Dissertation

Submitted to the Faculty

of

Purdue University

by

Zhibo Zhang

In Partial Fulfillment of the

Requirements for the Degree

of

Doctor of Philosophy

December 2016

Purdue University

West Lafayette, Indiana

To my beloved family

for their unconditional love and support

throughout my journey

ACKNOWLEDGEMENTS

First and foremost, my utmost appreciation and respect go to my major advisors, Professor Samuel Labi and Professor Kumares Sinha, for the time and effort they devoted to me and their invaluable advice and encouragement during my doctoral studies at Purdue University. Their scholarly direction greatly assisted me in this journey. My sincere gratitude also goes to my other committee members: Professor Jon Fricker, for his guidance and careful editing of the project report from which this dissertation was derived, and Professor Thomas Morin, for his assistance in the optimization methodology used in this dissertation. I also am grateful to Professor Fred Mannering, who served in my master's committee, for the advanced statistical techniques I acquired from his courses. I am very appreciative of the assistance of the experts at the Indiana Department of Transportation during my data collection efforts.

I sincerely acknowledge all my research group colleagues and friends in the Transportation Engineering area at Purdue. Without you, this journey would have been much less memorable and colorful: Dr. Qiang Bai, Dr. Matthew Volovski, Dr. Michelle Dojutrek, Dr. Bismark Agbelie, Dr. Jackeline Murillo Hoyos, Dr. Steve Lavrenz, Dr. Stephanie Everett, Dr. Mohammad Arman, Dr. Anwaar Ahmed, Dr. Wubeshet Woldemariam, Dr. Nathee Athigakunagorn, Ms. Eleni Bardaka, Mr. Tao Liao, Ms. Yu Qiao, Mr. Sikai Chen, Mr. Tariq Saeed, Mr. Saeed Alqadhi, Dr. Yu-Ting Hsu, Dr. Erdong Chen, Dr. Yingge Xiong, Dr. Yaotian Zou, Dr. Feng Zhu, Dr. Qing Ye, Mr. Xianyuan Zhan, Mr. Xinwu Qian, Mr. Yuntao Guo, Mr. Wenbo Zhang, Mr. Jian Wang, Mr. Anlan Li, and Mr. Peng Jiao.

Last but most certainly not least, I am eternally grateful to my parents, Mrs. Jianjie Gong and Mr. Qiang Zhang, who provided me with tremendous encouragement and strength, especially during the difficult times. I could not have succeeded in obtaining this honorable degree without their everlasting support and love.

It has been a long demanding journey, full of hard work and struggles, laughter and tears. But this amazing journey indeed has come to an end and it is time to say farewell. Thank you, Purdue University, for being my home for my first five years in the U.S! Best wishes to all the faculty members, staff, colleagues, and friends I made at Purdue. Thank you for being present in my life, all the time, all the way.

TABLE OF CONTENTS

Page

Page

LIST OF TABLES

Table Page

Table Page

Table Page

LIST OF FIGURES

Figure Page

Figure Page

Figure Page

ABSTRACT

Zhang, Zhibo. Ph.D., Purdue University, December 2016. Developing Condition-Based Triggers for Bridge Deck Maintenance and Rehabilitation Treatments. Major Professors: Samuel A. Labi and Kumares C. Sinha.

The bridges in the U.S. highway system suffer from deficiencies in both their structural condition and functionality. In an effort to improve the condition of bridges, highway agencies continually seek effective and efficient approaches to maintenance and rehabilitation (M&R) treatments for their bridges. However, one drawback to new approaches is that highway agencies have long relied on the subjective judgment of their engineers to determine the time or condition at which to implement the treatments as well as the types of treatments to be applied. The literature shows that previous researchers mainly focused on time-based M&R strategies, but there have been some efforts toward developing condition-based strategies, such as the Indiana Bridge Management System (IBMS). While IBMS and similar systems were laudable efforts, they also were developed on the basis of the judgment and experience of bridge management personnel and were not data-driven.

This dissertation proposes condition-based performance thresholds for bridge deck M&R treatments using data-driven analytical methods. The framework was developed for both deterministic and stochastic situations. Under the former, deterministic statistical models for bridge deterioration and costs were developed. The optimization framework was based on life-cycle agency and user costs, and its performance was demonstrated in this dissertation using data from state-owned bridges in the state of Indiana. Separate analyses were conducted with respect to different climate regions and highway functional classes. Sensitivity analysis was performed to investigate

the impacts of changes in the relative weights of agency and user costs and traffic volume on the outcome of the analyses. Under the stochastic situation, hazard-based duration models were developed to estimate the probability distribution of the time spent by a bridge deck in a given condition state. Stochastic life-cycle cost analysis was carried out by measuring and incorporating the uncertainty associated with each evaluation factor. The analysis outcomes from the stochastic analysis were found to be generally consistent with those of the deterministic situation.

On the basis of the analysis results, this dissertation recommended modifications to the existing decision tree (DTREE) currently used in the IBMS. The thresholds for specific deck overlay treatments were incorporated, and the logic flows of the existing DTREE were revised to eliminate redundancies and to address other issues. It is expected that this dissertation’s data-driven analysis and results will serve as a resource to bridge management practice by enhancing the decision-making process with respect to the condition-based timing of bridge deck M&R treatments.

CHAPTER 1. INTRODUCTION

1.1 Background

Bridges are one of the most important and visible components in a transportation system. Bridges save a significant amount of travel time and cost by providing crossings at critical locations and hence maintain the continuity of the transportation network (Markow et al., 2009). At the current time, the bridges in the U.S. highway system suffer from deficiencies in both their structural condition and functionality. According to National Bridge Inventory (NBI) data of 2014 (FHWA, 2014), approximately 24% of U.S. bridges are rated as either structurally deficient (SD) or functional obsolete (FO). Although the percentage of SD and FO bridges has been declining gradually 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) estimated that U.S. public agencies may need an annual investment of $20.5 billion to eliminate the backlog of deficient bridge work by 2028, while only $12.8 billion was actually spent in the year 2010 (FHWA, 2010). Given such circumstances, public agencies seek to maintain, rehabilitate, and reconstruct their bridges effectively and efficiently. Engineers have long relied on their experience and subjective judgment to decide when to preserve bridges and what treatments to undertake. In recent years, efforts have been made to approach bridge maintenance and repair decisions as a systematic and data-driven process.

Among the three main bridge components (i.e., deck, superstructure, and substructure), bridge decks have been investigated more substantially by both researchers and highway agencies for two primary reasons. First, the expenditures for the M&R treatments for decks are dominant in terms of the total M&R expenditures for a bridge.

Sinha et al. (2005) estimated the final needs for different bridge preservation treatments for bridges in Indiana during the horizon period 2006-2020 and found that, in 2002 constant dollars, the needs for bridge deck, superstructure, and substructure-related preservation were approximately 349 million dollars, 58 million dollars, and 17 million dollars, respectively. As can be seen, deck-related preservation needs accounted for more than 80% of the total needs. Decks are the most vulnerable bridge components compared to the superstructure and the substructure because decks are affected by both environmental factors and direct contact with traffic loading. Also, the design life of decks is shorter than the other two components (TRB, 2013). Decks necessarily require more maintenance treatments and more frequent replacements and consequently more expenditures. Due to the dominance of deck costs, improvements in M&R strategies for bridge decks could potentially lead to significant cost savings. Second, there are more candidate types and techniques of M&R treatments for decks than for superstructure and substructure (FHWA, 2011; Nevada DOT, 2008; INDOT, 2013). Hence, there is greater flexibility and room for an optimization process with respect to deck M&R strategies. Based on the above reasons, the scope of this dissertation focused on the bridge deck.

According to an NCHRP survey (Krauss et al., 2009) of forty-one U.S. states, four Canadian provinces, and Puerto Rico, only twenty-two agencies reported using specific guidelines or procedures when selecting bridge deck treatments. Of those, only ten agencies had documented procedures or decision trees for this purpose. The rest used only visual evaluation, sometimes with supplementary tests, and then conducted internal consultations to determine the appropriate rehabilitation treatments. The survey results also revealed that the guidelines or thresholds developed by different states vary significantly.

FHWA’s Bridge Preservation Guide (FHWA, 2011) indicates that the objective of a good bridge deck preservation program is to employ cost-effective strategies and treatments to maximize the life of a bridge deck. Specifically, agencies seek to extend the service lives of their bridge decks as long as possible while maintaining the various structural elements of the bridges above certain levels to assure structural integrity and the safety and security of road users. At the same time, agencies seek to achieve these goals while minimizing the agency costs of repair or construction and the user costs. User costs typically include the incremental 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 timings or thresholds for M&R treatments to gain the “biggest bang for the buck” is the critical question highway agencies continually face.

1.2 Problem Statement

There is a trade-off between the condition (or service) level of a bridge deck that agencies want to achieve and the maintenance expenditure. Life-cycle maintenance expenditures depend on the frequency and intensity of the M&R treatments. In fact, a typical preservation strategy can be characterized by two extreme scenarios: a parsimonious scenario and an unrestrained scenario (Khurshid et al., 2010; Pasupathy et al., 2007). The parsimonious scenario is characterized by long periods between treatments and thus a lower frequency of them, which is likely to result in a lower life-cycle cost but a shorter service life and poorer condition. In contrast, the unrestrained scenario is characterized by shorter periods between M&R treatments, leading to a higher frequency of them. The unrestrained scenario would probably extend the service life of a bridge deck and provide road users a better surface quality, but its drawback would be incurring higher agency costs. Therefore, it can be hypothesized that, for each bridge deck M&R treatment type, there is a relationship between the condition level of the bridge deck at the time of the 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 M&R treatment, in other words, the condition level at which it should be implemented.

Two types of preservation strategies (or policies) have been adopted by agencies: time-based and condition-based. A time-based strategy is characterized by M&R treatments that are implemented at fixed time intervals during the deck service life. A condition-based strategy is characterized by M&R treatments that are triggered only if the condition of the bridge element (deck or wearing surface) reaches a certain threshold. The condition-based strategy therefore should be more reasonable and applicable in real practice compared to a time-based strategy, where it is possible that the bridge deck is still in good condition at the scheduled time threshold and actually does not need repairs or the deck may reach an unsatisfactory condition well before the scheduled time.

In terms of academic research, the literature review found very few projects that focused on developing triggers for individual deck treatments. Some researchers attempted to establish life-cycle M&R strategies; however, they were mostly time-based instead of condition-based. Also, they did not duly consider the issue of including user costs and only very seldom were risks or uncertainties incorporated into the analysis.

Therefore, given the fact that the current thresholds used by agencies are determined by expert opinion and considering the gaps in the existing research, there is a need to establish more rigorous condition-based triggers and M&R strategies for bridge deck treatments using data-driven approaches.

1.3 Study Objectives and Scope

Based on the aforementioned issues in the state of the practice and the gaps in the current academic studies, this dissertation developed condition-based performance threholds for commonly-used bridge deck M&R treatment types in state highway agencies using data-driven approaches. Furthermore, life-cycle condition-based strategies for deck M&R treatments were established on the basis of the performance threhold outcomes. These results have been implemented as updates in the IBMS bridge deck M&R strategies. In addition, risks and uncertainties were incorporated into the life-cycle analysis. The robustness of the developed thresholds was evaluated by comparing the results obtained from the deterministic analysis to the results of the stochastic analysis.

Apart from the major study objectives mentioned above, there are other affiliated intermediate results that could contribute to bridging the gap in the existing literature. Deck treatments trigger improvements in the deck condition rating; however, no statistical models regarding this effect (i.e., performance jump) were found in the existing literature. This dissertation therefore investigated the effects of individual bridge deck treatments on the deck condition rating. In addition, it is assumed that the performance trends and deterioration rates of a bridge deck and its wearing surface after an M&R treatment are likely to be different from those before it was implemented. This dissertation therefore investigated this situation by developing models that focus on the level of deterioratiobn before and after particular deck treatments.

In terms of the study scope, this dissertation only focused on M&R treatments for bridge decks because the majority of bridge M&R treatments are carried out on bridge decks and necessarily require more expenditures compared to other bridge components. The analysis in this dissertation was conducted at the project level instead of the network level because the performance thresholds were developed for the life cycle of individual bridges. This dissertation established condition-based thresholds and long-term strategies instead of time-based because the uncertainties that exist in practice can cause the time when the treatments are actually needed to deviate from the scheduled time. This dissertation carried out analyses with respect to both the deterministic situation and the stochastic situation. The results from the two situations were compared and hence provide a more comprehensive evaluation of the developed performance thresholds.

1.4 Organization of This Dissertation

Chapter 1 introduced the background, motivations, objectives, and scope of this dissertation. Chapter 2 presents a review of the literature pertaining to the development of bridge treatment thresholds and life-cycle strategies. Chapter 3 describes the framework for the deterministic situation, including optimization formulations, deterioration models, performance jump models, and cost models. Chapter 4 presents the results of the life-cycle cost analysis under the deterministic situation and proposes deck treatment triggers and long-term deck M&R strategies. Chapter 5 discusses the framework for the stochastic situation, including probabilistic deck deteriorarion models, uncertainties in terms of various factors, and optimization formuations with randomess incorporated. Chapter 6 presents the life-cycle cost analysis results under the stochastic situation. The findings are compared with those of the deterministic situation. Chapter 7 introduces an updated decision tree for deck treatment selection on the basis of the existing decision tree used in the IBMS. Chapter 8 concludes this dissertation by summarizing its findings, contributions, and limitations as well as future research recommendations.

CHAPTER 2. LITERATURE REVIEW

To clarify the various aspects and issues associated with bridge deck M&R scheduling, a review of the past research was carried out. This chapter presents the significant outcomes from past studies in order to shed more light on the existing methodologies used for bridge deck M&R 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 cost-effective M&R scheduling.

2.1 State of Practices of Bridge Deck M&R Treatments Selection

As indicated in Chapter 1, this dissertation focuses on condition-based scheduling rather than time-based scheduling. Time-based scheduling can be more useful in terms of budget planning and long-term M&R programming; however, when it comes to the implementation of these treatments in practice, condition-based decision-making is more applicable and reasonable. For example, 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 sources can cause the time when the treatments are actually needed to deviate from the time-based strategy schedule. Condition-based strategies, in contrast, are less sensitive to uncertainties because agencies can always implement the appropriate treatments at the pre-defined performance thresholds.

Information about condition thresholds for bridge treatments was mainly found in technical reports prepared by or for public agencies rather than in journal papers. Of the few resources, most of them were based on expert opinions expressed in surveys conducted of bridge engineers; and significant inconsistencies were found across the different sources. Information pertaining to specific states in the U.S. is summarized in the following sections.

2.1.1 Practices of Deck Treatment Selection of Selected U.S. and Canadian DOTs

An NCHRP study by Krauss et al. (2009) conducted a survey that was sent to all U.S. and Canadian departments of transportation (DOTs) regarding their guidelines for bridge deck treatment selection with respect to various deck conditions and deck materials. The study received a total of forty-nine responses from forty-one U.S. state DOTs, four Canadian provinces, and Puerto Rico.

Some general findings of the survey are as follows. 1) Twenty-two agencies (48%) reported using specific guidelines or procedures when they made decisions on selecting bridge deck treatments. Of those, only ten agencies (22%) had written procedures or had developed decision trees. Two agencies were in the process of developing decision trees; the remaining states used only visual evaluation, sometimes with supplementary tests, and conducted internal consultations to determine the appropriate rehabilitation approaches. 2) Thirty-three agencies (72%) reported deck condition as a suitable basis for treatment selection. Two of those specifically correlated topside and underside conditions. 3) All the agencies performed visual inspections, and some commonly-used supplementary inspection techniques included hammer or chain sounding, chloride measurement, and core sampling and strength testing. 4) Although guidelines were available, they were not mandatory and not necessarily used to make decisions in all cases. Some examples of guidelines from selected DOTs in the U.S. and Canada are presented in Table 2.1.

Table 2.2 presents a summary of 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 content of the provided information varied significantly across different DOTs.

Table 2.1 Guidelines for Triggers for Bridge Deck Treatments from Selected DOTs (Source: Krauss et al., 2009)

DOT	**Guidelines for Triggers for Deck Treatments**
California	Full deck replacement is triggered if 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 is triggered when more than 35% of the deck requires patching.
Kansas	Decks with 3% to 10% distress: use a polymer overlay, 10% to 50% distress: use silica fume overlay, and over 50% distress: conduct further inspection of the deck.
Virginia	Full deck replacement is 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 is used for decks with extensive spalling and cracking; patching can be used 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. A polymer thin-bonded overlay may be used if the deck needs increased friction over a sealed surface.
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 2.2 Summary of Survey on Bridge Deck M&R Treatments' Expected Service Life, Unit Cost, Etc. (Source: 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

Notes: 1: Ultra high early cement with latex; 2: High early (Type III) cement with latex.

Krauss et al. (2009) also proposed guidelines for bridge deck repair selection based on their compilation of the responses from the survey, a literature review, and the experience of the research team. The authors considered four major types of repair actions: 1) do nothing, 2) maintenance (patching, crack repairs, concrete sealer), 3) protective overlay, and 4) structural rehabilitation (partial deck replacement, full depth deck replacement). The authors used various performance measures for the thresholds, which were intended to provide agencies with an overall or complete evaluation of the deck rather than using only the condition ratings, which are likely to be subjective. The performance measures included:

i. Deck Condition Rating and Percent of Distress: Evaluated the NBI condition rating of the deck, by the proportion of non-overlapping area of patches, spalls, delamination, and copper sulfate electrode (CSE) half-cell potentials more negative than -0.35V, and by an additional condition rating of the deck bottom surface (not in the NBI).

ii. Estimation of Time-to-Corrosion: The estimated time until sufficient chloride penetration takes place to initiate corrosion over a certain percentage of the reinforcing steel.

iii. Deck Surface Problems: surface scaling, poor drainage, abrasion loss, or skid resistance issues.

iv. Concrete Quality: Concrete durability (alkali silica reaction (ASR)/delayed Ettringite formation (DEF)/freeze-thaw) and strength problems.

The guidelines and performance thresholds suggested by Krauss et al. (2009) for concrete bridge deck M&R treatments are presented in Table 2.3.

Table 2.3 Suggested Guidelines of Bridge Deck Repair based on Various Performance Measures (Slightly revised from Krauss et al., 2009)

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

Notes:

1. % Distress includes non-overlapping area of patches, spalls, and delamination.
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 deck condition rating.
4. Condition rating of deck bottom surface by NBI condition rating scale.
5. Choose Do Nothing only if all conditions apply.
6. Surface scaling, poor drainage, abrasion loss, or skid resistance issues.
7. Concrete durability and strength problems.

2.1.2 Practices of Bridge Deck M&R in Indiana

Indiana began developing its own bridge management system (IBMS) in the 1980s. Gion et al. (1992) published the first edition of the user's manual for the implementation of IBMS, which was based on a series of previous research reports by the Joint Highway Research Project (JHRP) at Purdue University (Sinha et al., 1988; Saito and Sinha 1989a & 1989b; Jiang and Sinha 1989a). A decision tree module named DTREE was 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 treatments. Part of the updated DTREE is presented in Figure 2.1 as an illustration. WS indicates the wearing surface condition rating (0-9 integers), DC indicates the deck condition rating (0-9 integers), DG indicates the deck geometry rating (0-9 integers), JC indicates the deck joint condition rating (0-9 integers), and DP indicates the proportion of the sum of the area that needs patching and already patched to the total deck area. The complete DTREE is presented in Appendix E of this dissertation.

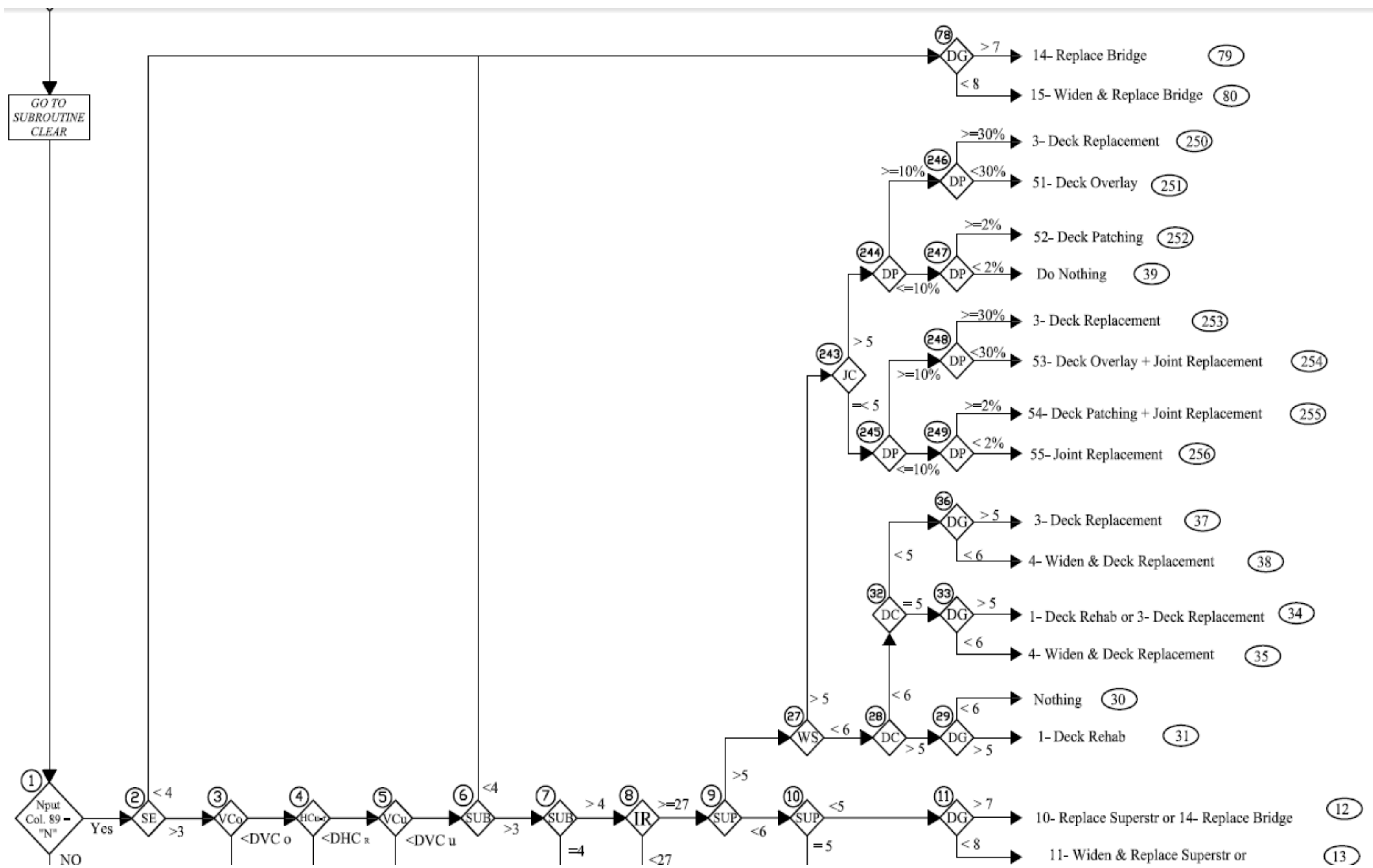


Figure 2.1 Partial DTREE for NHS Bridges in IBMS (Sinha et al., 2009)

The above thresholds were based on the expert opinion of INDOT bridge engineers. It should be noted that these experience-based judgments may not lead to the highest cost-effectiveness theoretically. The developed performance thresholds are as follows (Sinha et al., 2009):

For all bridges:

If (WS > 5), check joint condition (JC)

If (JC > 5), check for deck patching (DP)

If (JC ≤ 5), replace joint

For NHS bridges:

If 2 ≤ DP ≤ 10%, carry out patching

If 10% < DP < 30%, carry out deck overlay

If DP ≥ 30%, carry out deck replacement

For non-NHS bridges:

If 2 ≤ DP ≤ 15%, carry out patching

If 15% < DP < 30%, carry out deck overlay

If DP ≥ 30%, carry out deck replacement

In the INDOT Bridge and Culvert Preservation Initiative (BCPI) policy statement (INDOT, 2014), the commonly-used bridge preventive maintenance and corrective maintenance treatments in Indiana were listed (Table 2.4), and the condition-based candidate criteria for the election of treatments were established (Table 2.5). However, these candidate criteria represent the lower bounds or upper bounds of the performance measures, meaning that they do not necessarily represent the optimal performance thresholds.

Table 2.4 Preventive Deck Treatments Performance Criteria (INDOT, 2014)

Preventive Treatments	**Deck Condition Rating**	**Implementation Cycle (years)**
Cleaning/Flushing Bridge Decks	> 4	1
Cleaning Deck Drains	> 4	1
Cleaning Joints	> 4	1
Deck Sealing	> 5	1

Table 2.5 Corrective Deck Treatments Performance Criteria (INDOT, 2014)

Corrective Treatments	**Deck Condition Rating**	**Other Criteria**
Deck Patching (shallow/deep)	> 4	D/SS > 4; and maximum 10% deck patching
Joint Repair/Replacement	< 6	WS/D/SS [1] > 4
Thin Deck Overlay (e.g. Polymeric Overlay)	> 5	D/SS > 4; and maximum 10% deck patching
Latex Modified Concrete (LMC) Overlay	> 3	D/SS > 5; and maximum 15% deck patching
Deck Crack Sealing	> 5	D/SS > 5

Note: WS = Wearing Surface; D = Deck; SS = Superstructure and Substructure

In the current Indiana Design Manual (INDOT, 2013), the thresholds and effects of some of the bridge rehabilitation treatments are briefly described. It is noted that the thresholds for the LMC overlay are different from what is stated in the IBMS manual. INDOT is currently updating the Indiana Design Manual to resolve this inconsistency.

- Patching: The area that needs patching can be estimated by sounding or NDT techniques. Deck patching alone as a treatment is only moderately successful as it generally extends the deck service life from one to three years.
- Latex-modified Concrete (LMC) overlay: LMC bridge deck overlays have been successfully used by INDOT since the 1970s. An 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 each must have a bridge inspection rating of 5 or higher and the need for partial depth patching must be less than 15%. If the extent of full-depth patching exceeds 35%, consideration should be given to deck replacement. An LMC overlay typically protects the bridge deck for 15 ± 5 years. The variation depends on the quality of the overlay placement, the amount of truck traffic, and the use of winter salting. An LMC overlay is placed in a thickness of 1¾ inches after 1/4 inch of the deck is removed, thereby producing a net 1½-inch increase in deck grade. The grade can be adjusted by adding an HMA wedge on each

approach. Using an overlay over an existing overlay is not allowed. Any existing overlay should be milled off the deck prior to other preparation work.

- Polymeric overlay: This flexible overlay consists of an epoxy polymer combined with a special aggregate. The wearing surface, deck, superstructure, and substructure each must 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.

Frosch et al. (2013) provided INDOT with an enhanced evaluation and selection toolbox for bridge deck protective systems. The authors recommended LMC overlays where more extensive damage is observed. Also, because LMC overlays provide a relatively longer service life, they recommended their use on more critical bridges as both preventive maintenance and a rehabilitation. Thin polymer overlays were suggested for situations where quick installations are necessary or where a thin protective system is needed. A thin polymer overlay also was recommended as a preventive maintenance system on a new bridge deck. However, the authors did not provide any numerical thresholds or strategies regarding when or under what conditions the overlay should be applied.

2.2 Types of Bridge Deck M&R Treatments

Each state in the U.S. has its own commonly-used M&R treatments for bridge decks. Even the deck treatment categories are different across the states. Some typical categories include preventive maintenance, corrective maintenance, routine maintenance, rehabilitation, preservation, and replacement. Because the total number of deck M&R treatment types can be enormous, this section selected three representative sources to demonstrate the typical types of deck M&R treatments and how they are categorized.

In the FHWA Bridge Preservation Guide (2011), deck treatments are grouped as deck preventive maintenance (including cyclical treatments and condition-based treatments) and deck rehabilitation. Table 2.6 presents the categorization structure and some typical treatment types in each category. It is noted that FHWA (2011) regards deck overlay as condition-based preventive maintenance while deck rehabilitation only includes partial and complete deck replacement.

Table 2.6 Deck M&R Treatments and Categories (Source: FHWA, 2011)

Bridge Deck Preservation		
Preventive Maintenance		**Rehabilitation**
Cyclical Treatments	**Condition-based Treatments**	
Deck washing/cleaning	Thin bonded polymer system overlays	Partial deck replacement
Concrete deck sealing with waterproofing penetrating sealant	Asphalt overlays with waterproof membrane	Complete deck replacement
	Rigid overlays such as silica fume and latex modified	
	Sealing or replacing leaking joints	
	Installing deck cathodic protection systems	
	Electrochemical chloride extraction	

In the INDOT Bridge and Culvert Preservation Initiative (BCPI) policy statement (INDOT, 2014), deck M&R treatments are categorized as preventive maintenance and corrective maintenance. Preventive maintenance in the BCPI is defined as “specific treatments that are scheduled on a fixed cycle that are intended to maintain a structure at its current level and prevent or reduce deterioration.” This category is similar to the cyclical treatment category in FHWA (2011). Corrective maintenance in the BCPI is defined as “specific treatments that are condition-driven, intended to correct defects and prevent or reduce deterioration.” These treatments are referred to as rehabilitation in the Indiana Design Manual (INDOT, 2013). Table 2.7 presents the combined information from INDOT (2013) and INDOT (2014) above regarding the types of deck M&R treatments and their categories. It is noted that deck replacement is not included in the deck M&R categories in Indiana.

Table 2.7 Deck M&R Treatments and Categories (Source: INDOT, 2013 and 2014)

Preventive Treatments	Cleaning/Flushing Bridge Decks
	Cleaning Deck Drains
	Cleaning Joints
	Deck Sealing
Corrective Treatments (Rehabilitation)	Deck Patching (shallow/deep)
	Joint Repair/Replacement
	Thin Deck Overlay (e.g. Polymeric Overlay)
	Latex Modified Concrete (LMC) Overlay
	Deck Crack Sealing
	Epoxy Resin Injection
	Low Viscosity Sealant for Crack Repair
	Concrete Overlay
	Cathodic Protection
	Deck Drainage Improvements
	Upgrade Bridge Railings
	Upgrade Guardrail-to-Bridge-Railing Transitions
	Joint Elimination
	Concrete Sealants
	Corrosion Inhibitors
	Prefabricated Bridge Deck

The practices of Nevada DOT (NDOT), also were studied. NDOT does not separate the treatments into preventive or corrective categories. Instead, they are all included under deck rehabilitation techniques. The treatments are presented in Table 2.8.

Table 2.8 Deck M&R Treatments and Categories (Source: NDOT, 2008)

Bridge Deck Rehabilitation
Patching
Polymer Concrete Overlay
Resin Overlay
Waterproof Membrane/Asphalt Overlay
Epoxy-Resin Injection
Crack Sealant
Silane Seal
Joint Rehabilitation and Replacement
Upgrade/Retrofit Bridge Rails
Approach Slabs

Based on the three sources, some commonly-used deck M&R treatments were found to include, but are not limited to, polymer overlay, latex-modified overlay, deck patching, concrete deck sealing, joint repair and replacement, and deck cleaning. These treatments are considered as the candidate treatments in the analyses conducted in subsequent chapters.

2.3 Analytical Approaches for Bridge Deck M&R Scheduling

Although the bridge deck M&R condition thresholds used in practice are largely based on expert opinion, a large number of research studies have attempted to develop optimal strategies for bridge deck maintenance and repair treatments. However, most of these studies aimed at establishing only the optimal strategy for the entire life cycle of the bridge deck rather than considering optimal performance thresholds for particular deck 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 deck deterioration modeling, the effects of bridge deck M&R treatments (i.e., performance jump), bridge agency cost models, and user cost issues.

2.3.1 Optimization of Bridge Deck M&R Strategy

A number of studies attempted to establish an optimal strategy for bridge deck maintenance, repair, rehabilitation, and reconstruction treatments. Many of them carried out multi-objective optimization, which included, but was not limited to, the following objective functions: maximizing a condition index, maximizing a safety or reliability index, and minimizing life-cycle costs. The constraints included, but were not limited to, the bounds of the condition index, the safety and reliability index, and the budgetary considerations. Various optimization techniques have been used, such as genetic algorithm (GA), ε-constraint method, and shuffled frog leaping (SFL). Some of the studies focused on project-level or facility-level optimization while others conducted analysis with respect to a network of bridges. There were also studies that addressed a general infrastructure management policy that can be applied to bridge management. Some of the above 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 strategies for concrete bridge decks. Case studies were conducted to apply the tool to various state DOTs. An issue with their study was that some fundamental data used for the analysis, such as the deterioration rates, the effectiveness of MR&R treatments, and the unit costs, were based on questionnaire surveys of state DOTs. The subjectivity in those important data may have severely compromised the reliability of the analysis results.

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

Miyamoto et al. (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 using a multi-objective GA in which the objective functions were the 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 the condition, safety level, and cost.

Neves et al. (2006a & 2006b) used two performance indicators: the condition index (0 to 3, resulting from visual inspection) and the safety index (measure of load-carrying capacity resulting from structural analysis). A multi-objective GA was used to solve the optimization problem and the Latin hypercube sampling technique was used to compute the temporal evolution of performance indicators and cost. The timing for application of silane (a preventive maintenance action in the U.K.) and the safety index threshold for deck reconstruction were determined using the concepts of Pareto solutions and dominated solutions.

Elbehairy et al. (2006) introduced a model for integrated project-level and network-level decisions on bridge deck repairs, and two evolutionary-based optimization algorithms (GA and 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 et al. (2007) developed a software package tool named Multi-Objective Optimization System (MOOS) which made 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 treatments in the long term by selecting from an array of scoping and timing alternatives. The bridge-level model separated the fixed and variable costs of treatments and duly considered treatments whose life-cycle benefit exceeded their initial variable costs, which was one of the features that made this tool different from Pontis.

Bai et al. (2013) proposed a method that evaluated the network performance of candidate project portfolios before employing a multi-attribute utility function. Then, the optimal portfolio with the best network performance was identified. The authors indicated that their method effectively incorporated decision-makers' preferences into the decision-making process, 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 in terms of raw performance measures.

Apart from the above literature, there were a number of studies that did not focus on bridge management, but the methodology framework they designed for general infrastructure or for pavements could be easily applied to bridges. Some of these 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 treatment profiles. The nonlinear cost-effectiveness optimality was solved using mixed-integer nonlinear programming. Lamptey et al. (2005) documented several sets of alternative pavement design and preservation strategies (both condition-based and time-based) through life-cycle cost analysis. Lamptey et al. (2008) presented a case study for optimization of the combination of preventive maintenance treatments and timings to be implemented in a resurfacing life-cycle. Bai et al. (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 the traditional NSGA II.

Ben-Akiva et al. (1993) developed the Latent Markov Decision Process (LMDP), which took into account the uncertainties in facility condition prediction and the random measurement errors in facility condition measurement. This 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 incorporating 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 the inspection and M&R costs. The study showed once 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 the open-loop control scheme), which ignores the feedback from the actual condition. The difference in the performance was more significant when the actual deterioration rate deviated more from the initially expected deterioration rate. Guillaumot et al. (2003) and Durango and Madanat (2008) further extended the previous studies by integrating the LMDP and the AC schemes, that is, both accounted for the uncertainty in measuring the facility condition and allowed for feedback from the actual condition to update the deterioration expectations.

2.3.2 Bridge Deck Deterioration Modeling

Bridge deck deterioration models, or performance prediction models, are the basis of life-cycle assessment of bridge decks (Zayed et al., 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 and stochastic, have been studied extensively. Deterministic models are 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 of the deterministic models use regression techniques, 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 and Sinha, 1989b). Also, as the bridge condition rating is typically expressed as an integer scale from 0 - 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 extensively used in the field of bridge management to provide prediction of bridge condition deterioration (Jiang et al., 1987; Cesare et al., 1992; Madanat and Wan Ibrahim, 1995). All the state-of-the-art bridge management systems (BMSs), such as AASHTOWare™ Bridge Management software (BrM) (formerly Pontis) (Gutkowski and Arenella, 1998), BRIGIT (Hawk, 1995), and IBMS (Sinha et al., 2009), adopted the Markov-chain models to predict the performance of bridge components and networks.

Transitions are stochastic in nature because the existence of various unobserved factors and the presence of measurement errors make infrastructure deterioration unpredictable with certainty (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 of 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 on which it is based: 1) state independence (i.e., future bridge condition depends only on the present condition and is not related to past conditions); 2) constant inspection period (i.e., bridge inspections are conducted at predetermined and fixed time intervals) (Morcous, 2006). Many research studies have shown the impacts of violating these assumptions. Madanat et al. (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, which resulted in unequally spaced condition data in terms of time, and found that such variation in the inspection period may lead to a 22% error in estimating the deck service life. It is worth mentioning that although state independence seems to be a strict condition, many studies (Morcous, 2006; Mishalani and Madanat, 2002; Madanat et al., 1997) showed, using actual data, that the null hypothesis of the 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 transition probabilities. Bulusu and Sinha (1997) used two approaches, one based on the Bayesian approach and the other using a binary probit model. Expert opinion were combined with observed data through the Bayesian approach. Their binary probit model used a zero/one indicator variable for the condition switching state and 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 the nonnegative integer response variable (count data), and also the negative binomial regression model, which is a generalization of the Poisson model that relaxes the assumption that the mean is equal to the variance. Another limitation of the Markov approach is that it does not recognize the latent nature of infrastructure deterioration (Madanat et al., 1995) because deterioration is an unobservable entity whose manifestation results in observable distresses (Ben-Akiva and Ramaswamy, 1993). Madanat 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 deterioration. Mishalani and Madanat (2002) used the time-based stochastic duration model to estimate the probability density function of the duration it takes an infrastructure facility before it steps out of a particular condition state, given a set of explanatory variables. Mauch and Madanat (2001) observed that it is possible for the discrete-time state-based models, such as Markov chain, to attain the transition probabilities from the probability density function of the duration model, and vice versa.

2.3.3 Effects of Bridge Deck M&R Treatments on Deterioration Process

Although much research has been conducted on bridge deterioration modeling, the basic premise is that no major rehabilitation treatments are implemented within the analysis period. The Markov chain model, for example, requires that the condition either stay at the current state or transfers to some lower state, implying the absence of rehabilitation treatments 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 treatments on the deterioration process. Two possible effects brought about by the treatments are: a) major rehabilitation treatments (e.g. deck overlay) may raise the deck condition by certain levels (e.g., from deck condition rating of 5 to 6 or 7); and b) minor rehabilitation or maintenance (e.g., 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 studies) are assumed. For example, Lee and Kim (2007) developed “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 2.9 presents their results.

Hong and Hastak (2007) developed the average improvements of the deck NBI condition rating after M&R treatments based on survey responses they received from 28 U.S. state DOTs (presented in Table 2.10). However, there were limitations to the results: 1) responses were based on expert opinions only, 2) there was inconsistency across different DOTs, and 3) the pre-treatment condition was not included as a factor of the improvement.

Table 2.9 Recovering Effect Value of M&R Treatments (Lee and Kim, 2007)

Effect / Treatments	Damage Types							
	Micro-crack	Mode-rate crack	Macro-crack	Rebar corro-sion	Punching/ cavitation	Exfoli-ation/ pothole	Leakage/ efflore -scence	Maxi-mum 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

Table 2.10 Average Improvement of Deck Condition Rating (NBI Scale) after M&R Treatments Based on Survey Results (Hong and Hastak, 2007)

M&R Treatments	**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 overlay	3.17
Increased slab thickness and cover	1.86
Attaching additional girders	0.92
Concrete overlay or high density overlay	2.17

Liu et al. (1997) assumed some simple “impacts” of maintenance treatments on the degree of deterioration, which are presented in Table 2.11. The “deterioration degree” was defined by the authors on a scale of 0 (new deck) to 1 (structural failure level). Four maintenance methods were recommended by the authors with respect to different deterioration degree intervals.

Table 2.11 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

Elbehairy et al. (2006) estimated the impacts of “light, medium, and extensive” repair options on bridge deck condition ratings, as shown in Table 2.12.

Table 2.12 Impact of Repair Option on Bridge Deck Condition (Elbehairy et al., 2006)

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

The updated IBMS Manual (Sinha et al., 2009) provides a detailed table showing the effects of various repair treatments and their combinations on the deck condition, superstructure condition, substructure condition, wearing surface condition, and service life. This table is a good reference, but again, its limitations could include that it was based on expert opinions and it did not take into account the effect of pre-treatment condition. Also, some of the included repair treatments are general, such as deck rehabilitation and superstructure rehabilitation. Table 2.13 extracts the information from the IBMS Manual for some of the deck treatments only.

Table 2.13 Improvement in Condition Rating (NBI Scale) and Extension of Service Life due to Deck M&R Treatments (Sinha et al., 2009)

Treatments	**Improvement in Condition Rating and Service Life**		
	Deck	Wearing Surface	Service Life (years)
Deck rehab	1	3	15
Deck replacement	9	9	20

2.3.4 Bridge Agency Cost Models and User Cost Issues

The estimation of agency costs and user costs is necessary for bridge life-cycle cost analysis. With regard to agency costs, studies have been conducted to either build statistical cost models or develop average costs for different treatments, using historical data. These cost models may need to be updated frequently, however, considering the improvements in technology and changes in materials costs and labor costs. With regard to user cost, debate has existed regarding whether to include this cost category, what types of user cost to include, and what the weight between user cost and agency cost should be. 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, component rehabilitation costs, component 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 et al. (2005) investigated INDOT bridge contract data and developed comprehensive cost models for various bridge work types, including deck rehabilitation, deck replacement, 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 the risks incorporated and the agency and user costs included. However, this study did not provide any actual cost models or cost information but rather only the implementation of the framework through some hypothetical examples. There were 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 variations 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 et al. (2013) collected cost data for 52 steel box girder bridges in Korea and built cost estimation models.

2.3.4.2 Bridge User Cost

The most typical bridge user costs include travel time costs due to work zone delays, VOC, and safety costs for possible accidents incurred at work zones due to bridge M&R treatments. 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 challenge to the implementation of life-cycle cost analysis. One reason for this situation is that the typically large magnitude of the user costs often substantially exceed the agency costs, especially in project locations where there are high traffic volumes.

FHWA (2002) further stated that there could be several reasons for an agency's reluctance to include user cost as an evaluation factor, such as the difficulty in valuing the travel time delay, the significant randomness of crash rates, and the uncertainty that exists about the factors leading to VOC. In addition, unlike agency costs, user costs do not actually debit agency budgets. It can be challenging to justify assigning a specific dollar value of user costs to make them comparable with the actual agency cost figures.

The calculation of user cost has been examined by a number of studies. However, only a few studies focused on bridge user cost only. Son and Sinha (1997) considered several types of user costs that are unique to bridges, including user cost due to bridge weight limits, vertical clearance limits, and deck width. Bai et al. (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 limitations into the calculation for bridge user costs.

2.4 Chapter Summary

Based on the review of the state of practice, few agencies have established specific guidelines for triggering bridge deck treatments. These guidelines are largely on the basis of expert opinion, which suffers from subjectivity and inconsistency.

In terms of the academic research, very little literature was found that focused on developing triggers for individual deck treatments. Some of the studies attempted to establish life-cycle M&R strategies; however, they were mostly time-based instead of condition-based. In reality, a condition-based approach is more reasonable and applicable. It is true that if uncertainties are not taken into account, time-based and condition-based strategies make no difference; but when uncertainties are included, these two approaches may yield very different results. In fact, very few studies incorporated uncertainties into their analyses. In addition, the issues of user cost were seldom discussed in the past studies. Generally, although some studies developed sophisticated theoretical frameworks, their case studies were too simplified to help solve real problems. These research gaps are addressed in the subsequent chapters of this dissertation.

CHAPTER 3. METHODOLOGY FOR THE DETERMINISTIC SITUATION

This chapter discusses the proposed framework for developing optimal bridge deck M&R triggers under deterministic situations, which in this chapter does not take into account randomness. Bridge deck and wearing surface deterioration models, performance jump models, and cost models adopt the regression technique without random effects or random parameters. Such deterministic methods are intuitive in terms of concepts and can be readily applied by highways agencies or other researchers. The framework for the stochastic situation is discussed in Chapter 5 of this dissertation.

3.1 Optimization of Life-Cycle Costs under the Deterministic Situation

The optimization framework in this dissertation is based on life-cycle costs and benefits. The objective is to minimize the weighted sum of the 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 threshold level is expected to influence the life-cycle deterioration trend of the bridge deck and wearing surface and, subsequently, the frequency of treatment applications. It thus affects the service life of the deck and the agency costs and user costs incurred over the life cycle. There are typically upper and lower bounds on the treatment thresholds, which are based on historical data and expert opinion in this dissertation.

The formulation of the optimization problem is as follows:

Objective function:

$$\min_{T_p, T_l, T_r} \sum_{t=1}^{L} \left[(AC_t + wUC_t) \cdot \frac{1}{(1+r)^t} \right] \cdot \frac{r(1+r)^L}{(1+r)^L - 1} \tag{3.1}$$

where AC_t and UC_t are the agency costs and user costs incurred in year t; w is the weight for user costs; T_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 Eq. 3.1,

$$AC_t = I_{mt}C_m + I_{pt}C_p + I_{lt}C_l + I_{rt}C_r \tag{3.2}$$

$$UC_t = VOC_t + I_{wt}TTC_w \tag{3.3}$$

$$L = f_L(T_p, T_l, T_r) \tag{3.4}$$

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;

L is a function of T_p, T_l, and T_r.

In Eq. 3.2,

$$C_p(T_p, q_p) = u_p(T_p, q_p) \cdot q_p \tag{3.5}$$

$$C_l(T_l, q_l) = u_l(T_l, q_l) \cdot q_l \tag{3.6}$$

$$C_m(q_m) = u_m(q_m) \cdot q_m \tag{3.7}$$

$$C_r(q_r) = u_r(q_r) \cdot q_r \tag{3.8}$$

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);

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 Eq. 3.3,

$$VOC_t = f_V(T_t, WS_t) \tag{3.9}$$

$$WS_t = f_W(A_w, PJ_w, O_w) \tag{3.10}$$

$$TTC_w = f_T(ADT, D, MoT) \tag{3.11}$$

where:

the 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 Eq. 3.4,

$$L = f_L(T_p, T_l, T_r) = f_D^{-1}(T_r) \tag{3.12}$$

$$DK_t = f_D(A_d, PJ_d, O_d) \tag{3.13}$$

where:

deck service life (L), which 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, which 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:

$$T_{pl} \le T_p \le T_{pu} \tag{3.14}$$

$$T_{ll} \le T_l \le T_{lu} \tag{3.15}$$

$$I_{pt} = 1 \text{ if } WS_t = T_p \tag{3.16}$$

$$I_{lt} = 1 \text{ if } WS_t = T_l \tag{3.17}$$

$$I_{rt} = 1 \text{ if } DK_t = T_r \tag{3.18}$$

$$I_{mt} + I_{pt} + I_{lt} + I_{rt} = 1, \ \forall t, \ \ for \ I_{mt}, I_{pt}, I_{lt}, I_{rt} \in \{0,1\} \tag{3.19}$$

$$I_{wt} = 1 \text{ if } I_{pt} + I_{lt} + I_{rt} = 1, \ \forall t \tag{3.20}$$

Where, in constraints Eq. 3.14 and Eq. 3.15, 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. 3.16, Eq. 3.17, and Eq. 3.18 mean that costs for p, l, and r are incurred only when these treatments are triggered; constraint Eq. 3.19 means that for any given year t, only one type of treatment among m, p, l, and r is implemented; constraint Eq. 3.20 means that costs for work zone delays are incurred only when p, l, or r is implemented.

Considering that the mathematical formulations 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 Figure 3.1, Figure 3.2, and Figure 3.3, are created to better illustrate and explain all the parameters and variables, and the overall ideas of this optimization problem. Figure 3.1 shows how the deck condition and wearing surface condition change with the implementation of treatments, and Figure 3.2 and Figure 3.3 show the agency costs and the user costs incurred throughout the bridge deck service life.

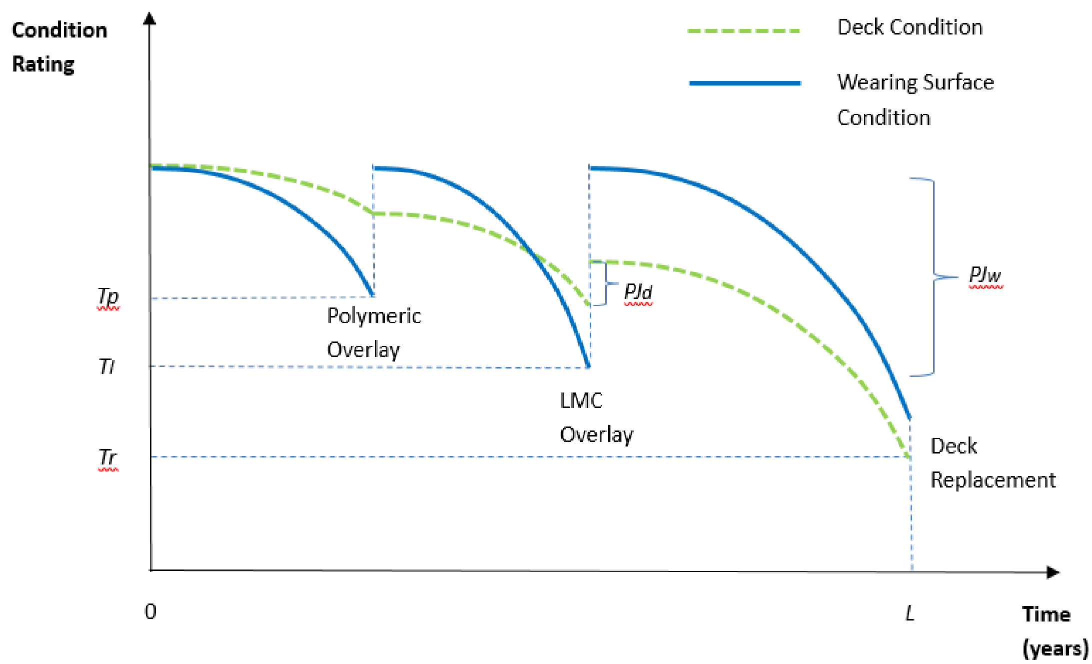


Figure 3.1 Illustration of Change in Deck and Wearing Surface Deterioration due to M&R Treatments

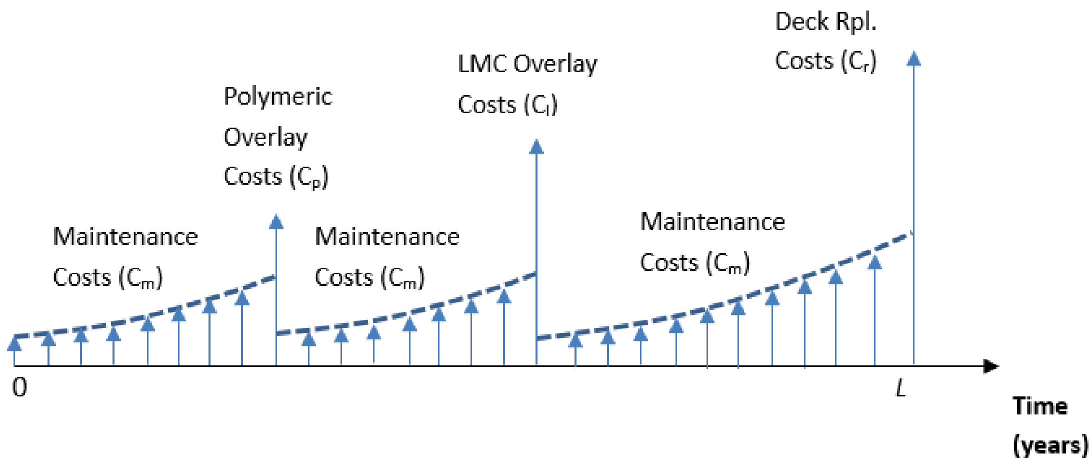


Figure 3.2 Illustration of Agency Costs Incurred through Deck Service Life

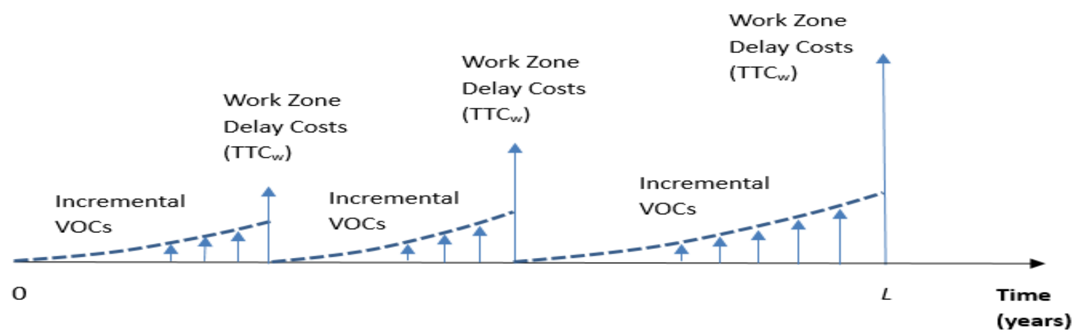


Figure 3.3 Illustration of User Costs Incurred through Deck Service Life

It should be noted that Figure 3.1, Figure 3.2, and Figure 3.3 present only one example scenario of the life-cycle M&R strategies (i.e., one polymeric overlay followed by another LMC overlay before deck replacement). The figures only serve to provide a conceptual illustration so the magnitudes may be exaggerated or reduced. In Figure 3.3, the incremental VOCs refer to the additional VOCs during normal operations caused by increasing deck surface roughness (i.e., the total VOCs minus the base VOCs associated with a new wearing surface).

3.2 Deterioration Models for Bridge Deck and Wearing Surface

Because this dissertation 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 treatments, including LMC overlays and polymeric overlays. 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, which is likely to slow down the deterioration process of the deck.

3.2.1 Models for Bridge Deck

In this chapter, deterministic models using linear regression are used. The general form is:

$$y_i = \beta_0 + \beta_1 x_{1i} + \cdots + \beta_p x_{pi} + \varepsilon_i \tag{3.21}$$

where y_i is the *i*th observation of the response variable *y*, x_{pi} is the *i*th observation of the *p*th 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*, indicating that the disturbance terms are approximately normally distributed, the variance of the disturbance term is independent across observations, disturbance terms are not autocorrelated, and the regressors are exogenous.

To model deck deterioration using the deterministic model, 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:

$$DCR = \beta_0 + \beta_1 AGE + \beta_2 AGE^2 + \beta_3 AGE^3 + \boldsymbol{\beta X} + \boldsymbol{\varepsilon} \tag{3.22}$$

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

In this dissertation, the model results from an INDOT project (Moomen et al., 2015) that used the same methodology are used for the case study in Chapter 4. The statistical variables used for modeling deck deterioration are presented in Table 3.1.

Table 3.1 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)

ANOVA test results suggested that separate deck models should be developed for different climate regions and different highway functional classes in Indiana because bridges in cold and warm regions tend to have different deterioration rates due to the impact of the freeze-thaw cycles and the use of chemicals for winter deicing treatments. Also, bridges in different highway classes have different design standards as well as different traffic volumes and percentages of heavy vehicles.

Specifically, six deterioration models were developed in this dissertation for bridge decks on NHS and non-NHS highways in the cold (northern), moderate (central), and warm (southern) climate regions of Indiana. The climate statistics, such as annual average temperature, annual precipitations, freeze index, and freeze-thaw cycles, are similar within each defined climate region. The results are presented in Table 3.2. A plot of the model for bridge decks on NHS highways in the northern region of Indiana is presented in Figure 3.4.

Table 3.2 Deck Deterioration Models by Climate Region and Functional Class (Source: Moomen et al., 2015)

Climate Region	**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	$DCR = 8.05846 - 0.14617 \cdot AGE + 0.00663 \cdot AGE^2 - 0.00015219 \cdot AGE^3 - 0.00098333 \cdot LENGTH + 0.43363 \cdot DECKPROT - 0.06043 \cdot FRZINDX - 0.14681 \cdot ADTT$

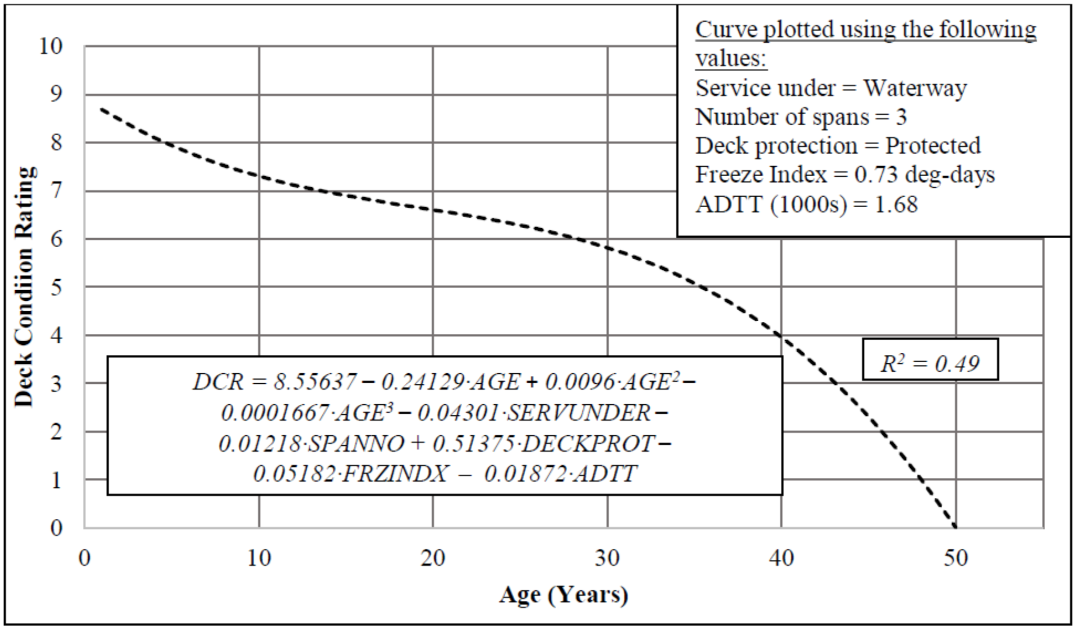


Figure 3.4 Illustration of Deck Model for Northern Region, NHS
(Source: Moomen et al., 2015)

3.2.2 Models for Bridge Wearing Surface

The deterioration models for the bridge wearing surface adopted a polynomial form similar to that of decks. For the purpose of the case study, which uses data from Indiana in Chapter 4, the models for the wearing surface presented in this section were provided by INDOT. 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 because age has been proven to be the most significant factor that affects deterioration of the wearing surfaces. Other factors were taken into account by using different categories, such as climate region categories, wearing surface type categories, and initial deck condition categories. Separate wearing surface models were developed under each combination of categories. Specifically, for a particular category,

$$WSCR = \beta_0 + \beta_1 AGE + \beta_2 AGE^2 + \beta_3 AGE^3 + \varepsilon \tag{3.23}$$

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

The results of the wearing surface models are presented in Table 3.3, where the codes in each category are as follows. For the climate regions, *C* refers to the cold climate region in the northern part of Indiana, *M* refers to the moderate climate region in the central part of Indiana, and *W* refers to the warm climate region in the southern part of Indiana. For the type of wearing surface, the codes follow the NBI guidelines (i.e., 1 refers to monolithic concrete (concurrently placed with structural deck), 3 refers to latex-modified concrete or similar additive, 6 refers to bituminous, and 9 refers to all other types. Finally, for the initial deck condition, the codes follow the NBI 0-9 deck condition rating scale, where the initial deck condition refers to the deck condition when the new wearing surface is placed.

Table 3.3 Wearing Surface Deterioration Models by Climate Region, Initial Deck Condition, and Type of Wearing Surface (Source: INDOT)

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

3.3 Performance Jump Models

Performance jump was defined in this dissertation 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 (i.e., the lower the condition rating before the treatment, the greater the performance jump typically will be). The following sections discuss the performance jump effects caused by two commonly-used deck overlays: LMC overlay and polymeric overlay. Statistical models were developed using the historical data.

3.3.1 Latex-Modified Concrete (LMC) Overlay

According to the Indiana Design Manual (INDOT, 2013), a 1¾ inch thick LMC overlay is placed after 1/4 inch of the deck is removed, producing a net 1½-inch grade increase. Therefore, an LMC overlay can improve the overall 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 investigations 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, meaning that he triggers mainly could have been based on experience-based judgment, which does not necessarily lead to optimal timing.

Figure 3.5 presents the distribution of the change in the 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 was 380. The most frequent five scenarios were 7-7, 6-7, 6-6, 5-7, and 6-8. The reason why the deck condition did not improve after the LMC overlay (e.g., 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 was removed and replaced, the overall rating of the deck did not change much (i.e., there was not enough improvement to qualify for an increase to 8).

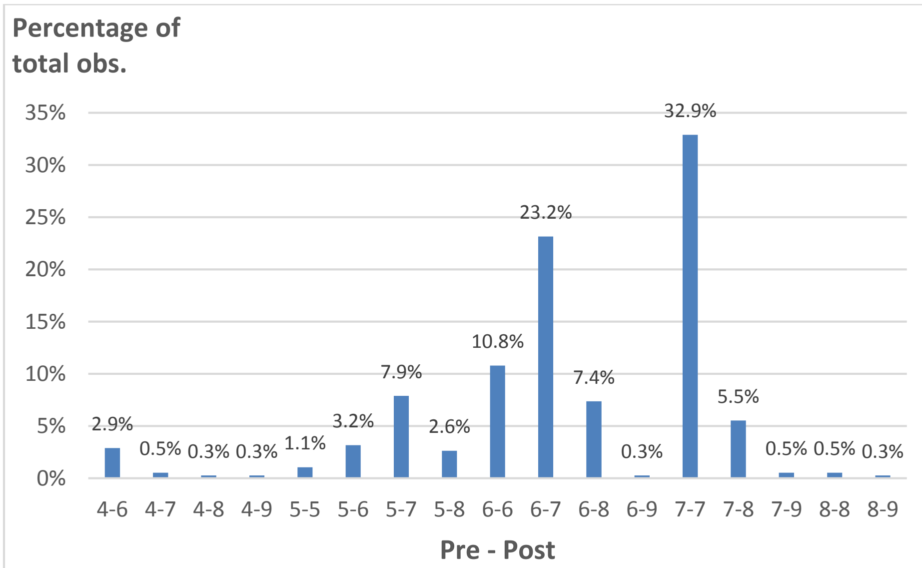


Figure 3.5 Distribution of Pre- and Post- LMC Overlay Deck Condition Change

A statistical model was developed to capture the effect of the pre-treatment deck condition on the performance jump. The model with the best fit had the independent variable as a natural logarithm transformation:

$$PJ_{Deck} = 8.9145 - 4.4686 \times \ln(PreDeck) \qquad (3.24)$$

where PJ_{Deck} is the performance jump of the deck condition due to the LMC overlay, and $\ln(PreDeck)$ is the natural logarithm of the deck condition prior to the implementation of the LMC overlay, where $PreDeck \in \{4,5,6,7,8\}$. Table 3.4 presents the details of the estimated model.

Table 3.4 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			

It was 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 has an inverse effect on the performance jump (i.e., the higher (lower) the pre-treatment deck condition, the smaller (greater) the performance jump will be).

The effect of LMC overlays on the wearing surface condition also was investigated because the trigger of LMC overlay is primarily based on the wearing surface condition rather than the deck condition. Figure 3.6 presents the distribution of the historical trigger values in terms of wearing surface condition for LMC overlay. The total number of observations is 66.

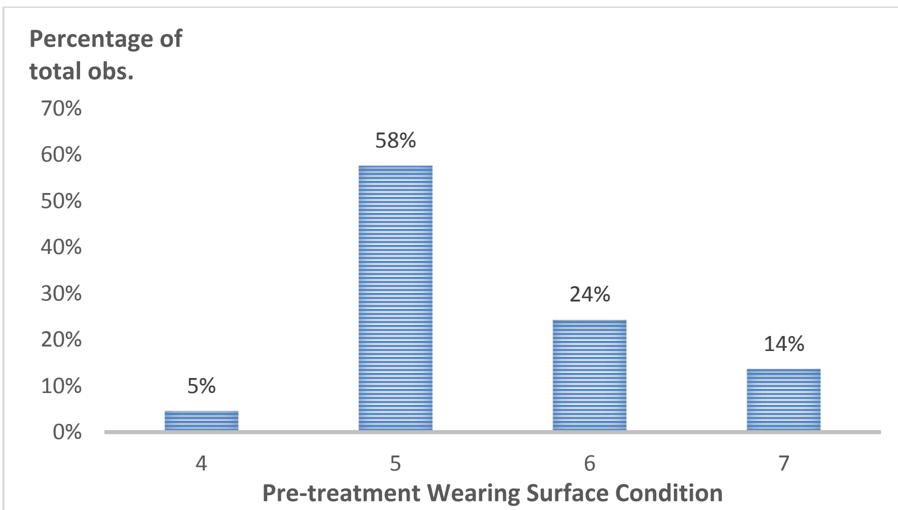


Figure 3.6 Distribution of the Pre-LMC-Overlay Condition of the Wearing Surface

It can be seen that the majority of LMC overlays were carried out when the pre-treatment wearing surface condition was 5, and nearly 25% of them were carried out at 6. These historical data represent the actual practices, not necessarily the optimal choices. With regard to 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 this dissertation, it is assumed that the wearing surface condition returns to 9 after an LMC overlay.

3.3.2 Polymeric Overlay

Polymeric overlays (or polymer overlays) were seldom used by INDOT until recent years. Therefore, the observations in the INDOT databases were inadequate to build statistical models. According to INDOT experts, the 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 can result in moderate improvement to the deck. Polymeric overlays can also be applied to new decks as preventive maintenance rather than rehabilitation.

Based on the limited number of observations, the trigger values of the wearing surface condition for a 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 an LMC overlay, it was assumed that the wearing surface condition returns to 9 after a polymeric overlay.

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 stated in the Indiana Design Manual (INDOT, 2013), 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 an LMC overlay, the post-treatment deck performance used the same deterioration curves shown in 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 was considered using the wearing surface models under the 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".

3.4.2 Polymeric Overlay

For a polymeric overlay, the effect on the extension of the 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 had similar characteristics (climate region, functional class, ADT, truck percentage, etc.) to the bridge in question and had not experienced overlays were sorted out. The average time that these bridges stayed at certain conditions were determined (e.g., condition 8 for t_1 years, 7 for t_2 years, and 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 problem of small samples, significant variation was found. The best estimate that could be made from the data was that polymeric overlay could extend the deck service life for approximately five to eight 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 the post-treatment wearing surface performance, the same method as for an LMC overlay in Section 3.4.1 was used.

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 an LMC overlay was not only for the LMC wearing surface itself, but also for the hydrodemolition and deck patching typically included in LMC overlay contracts, which are the preparation work for the LMC overlay, as well as the 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. In addition, the unit cost of a construction work is often affected by the economies of scale (i.e., the greater the deck area (overlay area), the lower the unit cost).

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

$$\ln(UCL) = \beta_0 + \beta_1 \cdot PreDeck + \beta_2 \cdot \ln(DeckArea) + \varepsilon \tag{3.25}$$

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 3.5. 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 was calculated as \$62.81/ft^2, and the sample standard deviation was \$44.47/ft^2, which is quite large given the sample mean.

Table 3.5 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			

Figure 3.7 illustrates the LMC overlay unit cost model results, including the raw data points and the fitted curves. The models for different pre-treatment deck conditions are plotted separately.

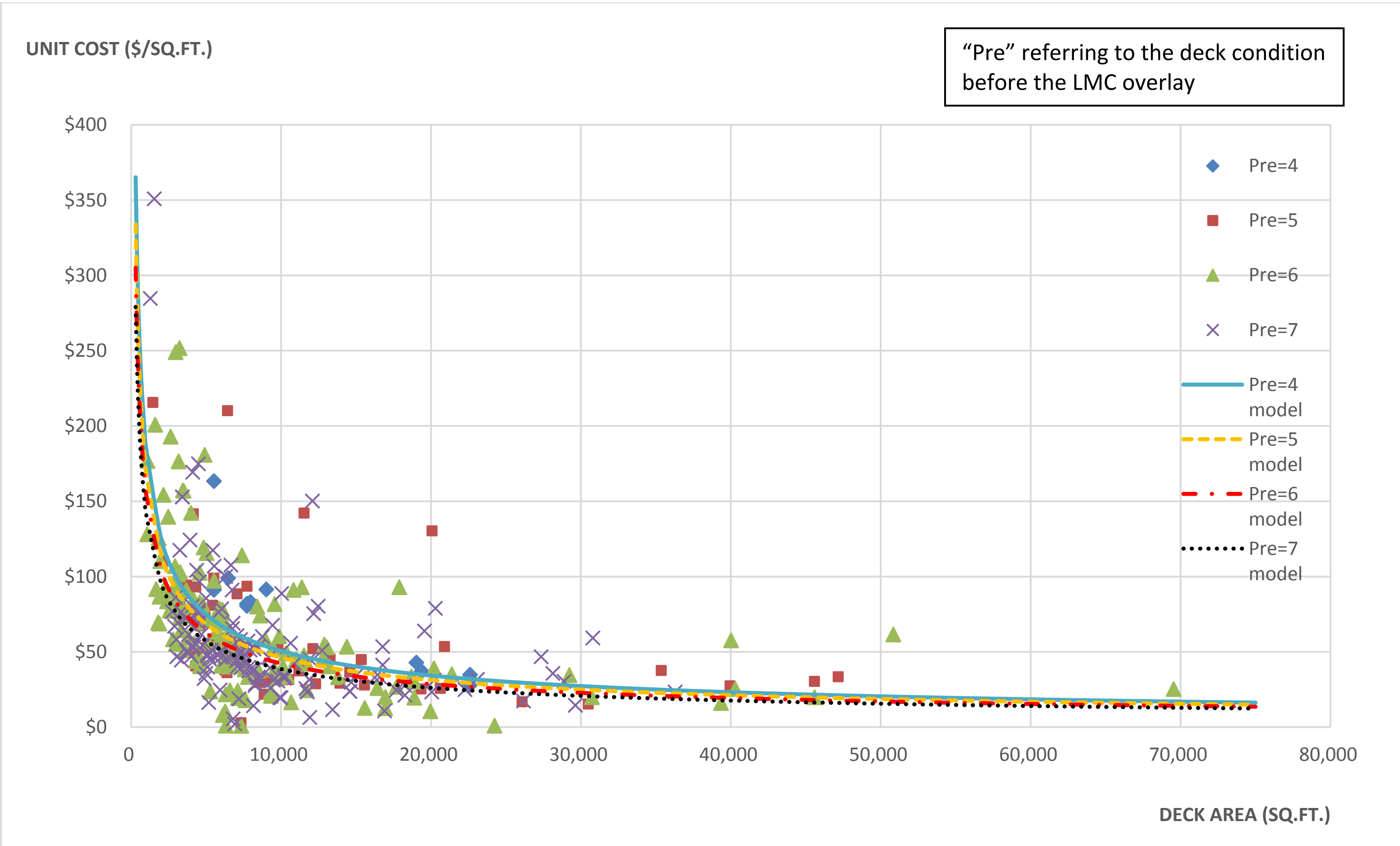


Figure 3.7 LMC Overlay Unit Costs: Observed Data Points and Models

3.5.1.2 Polymeric Overlay Unit Cost Model

Because the number of INDOT polymeric overlay contracts was limited, it was difficult to build a reliable cost model from the limited data. Therefore, in this dissertation, a cost formula provided by INDOT was adopted. The formula is as follows:

$$CPO = [(DeckArea \times 16.8) + 35,000] \times 1.05 \tag{3.26}$$

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 by dividing both sides of the formula by DeckArea (i.e., Unit Cost = (16.8+35,000/DeckArea)×1.05). This unit cost formula indicates the economies of scale in terms of the deck area. Figure 3.8 illustrates the effect. The unit cost of a polymeric overlay can be seen to decrease as the deck area increased.

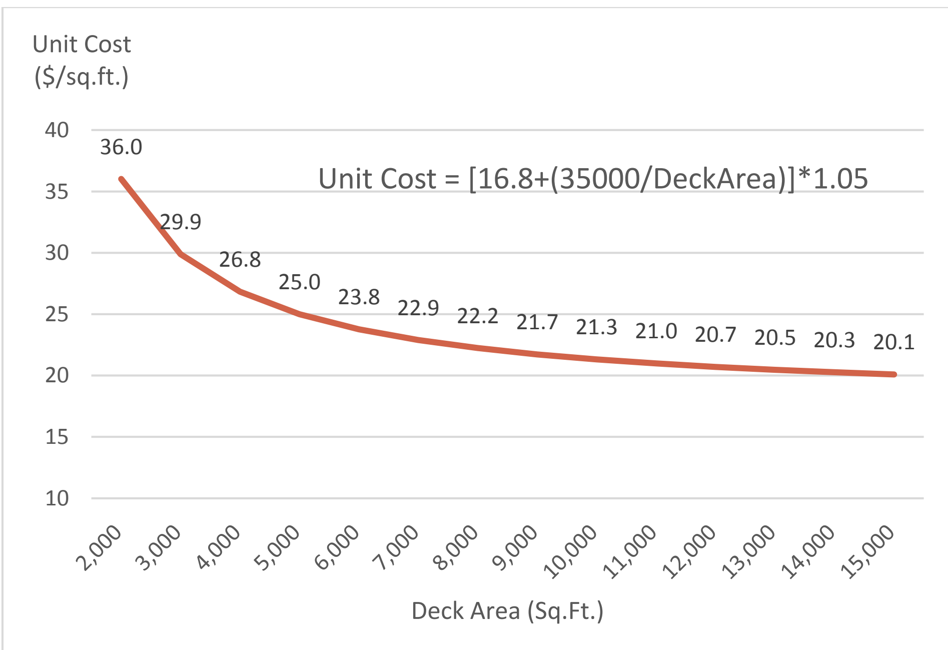


Figure 3.8 Unit Cost Model for Polymeric Overlay

3.5.1.3 Deck Replacement, Deck Patching, and Other Maintenance Costs

For deck replacement, the unit cost was found to be statistically not 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, which reflects the economies of scale, although the overall model fit (adjusted R-squared) was not high. The model estimation results are presented in Table 3.6. The average unit cost of partial-depth patching based on the contract data in Site Manager is $\$30.41/ft^2$ in 2010 constant dollars, with standard deviation $\$18.20/ft^2$.

Table 3.6 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			

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: $\$39.33/ft^2$ in 2010 constant dollars, with standard deviation $\$17.50/ft^2$.

For other maintenance and repair costs, the data in the IBMS manual (Sinha et al., 2009) was used as a reference. Table 3.7 presents the costs in 2007 constant dollars for the Interstates and other highways. Bridge hand cleaning and flushing is carried out annually in Indiana. However, the treatment types of “bridge repair” and “other bridge maintenance treatments” are ambiguous. It was assumed in the analysis that they are also carried out annually.

Table 3.7 Unit Costs for Other Bridge Maintenance and Repairs ($/Treatment Unit)

Treatment Type	**Treatment 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

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:

$$Index_i \times (1 + r)^{j-i} = Index_j \qquad (3.27)$$

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 this dissertation used a discount rate of 4%, which is the rate typically used by INDOT (Jiang et al., 2013).

3.5.2 User Costs

The user costs considered in this dissertation were the travel time delay due to work zones of bridge deck rehabilitation (overlays) and deck replacement and the incremental VOC during normal operations caused by the increasing wearing surface roughness.

3.5.2.1 Travel Time Costs due to Work Zone Delay

In this dissertation, it is assumed that the lane-closure policy is used for deck rehabilitation work on NHS highway bridges. Given that NHS highway bridges typically have more lanes and are more important links, they typically are not entirely closed to traffic. The detour policy was assumed for deck rehabilitation work on non-NHS bridges. For bridge deck replacement work, it was assumed that the 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:

$$TTC = \sum_{i=1}^{k} TTC_i = \sum_{i=1}^{k} [VTT_i \times (\frac{L}{S_{iC}} - \frac{L}{S_{iN}}) \times ADT_i \times D_R] \quad (3.28)$$

where TTC_i represents 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 treatment *R*.

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

$$TTC = \sum_{i=1}^{k} TTC_i = \sum_{i=1}^{k} [VTT_i \times (\frac{DL}{S_{iD}} - \frac{L}{S_{iN}}) \times ADT_i \times D_R] \quad (3.29)$$

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 treatment *R*.

In this dissertation, due to limited availability of data, the vehicles were grouped only as autos and trucks. Regarding the value of travel time, there was significant variability found among past studies in the literature. This dissertation adopted the travel time values from Sinha and Labi (2007): approximately $26/hr and $35/hr for autos and trucks, respectively, in 2005 dollars. Detour length (DL), structure length (L), and ADT_i (i = auto, truck) were taken from the NBI database. S_{iC} and S_{iD} were both assumed to be 35 mph. S_{iN} was assumed to be 55 mph for NHS and 45 mph for non-NHS. D_R took the average value from Table 3.1; for example, the work zone duration for LMC overlay using the detour policy was four to eight weeks, thus six weeks (42 days) was used for this dissertation.

3.5.2.2 Vehicle Operating Costs (VOC) due to Surface Roughness

The VOC due to increased surface roughness during normal traffic operations were often 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), rough pavement surfaces provide additional resistance to vehicle movement and increased vibration. These effects can lead to greater fuel consumption and accelerated wear and tear on vehicle parts. Another indirect impact of poor surface condition is that vehicles may experience higher fuel consumption if they are forced to drive at lower speeds. Therefore, M&R treatments, such as overlays, that improve deck surface condition can lead to VOC reductions.

In this dissertation, the VOCs included in the user costs were the incremental VOCs, which are 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),

$$m = 0.001 \times \left(\frac{IRI-80}{10}\right)^2 + 0.018 \times \left(\frac{IRI-80}{10}\right) + 0.9991 \qquad (3.30)$$

where *IRI* is the international roughness index of the road surface (bridge deck surface, in this dissertation) and *m* is the calculated VOC adjustment multiplier. The relationship between the incremental VOCs and the IRI is presented in Figure 3.9. 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 are calculated as $Base\_VOC \times (m - 1.0)$.

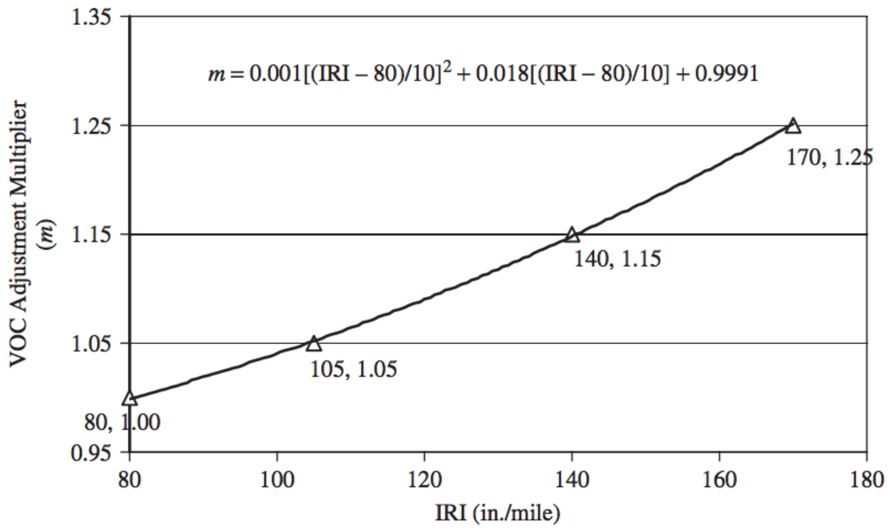


Figure 3.9 VOC Adjustment Factors for Surface Roughness (Barnes and Langworthy, 2003)

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

Two forms of IRI performance models were investigated. The first is the exponential form developed by Irfan et al. (2009) and Khurshid et al. (2008):

$$IRI = e^{(\beta_0 + \beta_1 \cdot AATT \cdot t + \beta_2 \cdot ANDX \cdot t)} \tag{3.31}$$

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):

$$IRI = -232.26 + 4.863 \times Treatment\_Age + 1.368 \times Precipitation + 117.84 \times Log(Pretreatment\_IRI\ ) \quad (3.32)$$

where *Treatment Age* is the time since the pavement treatment (years), *Precipitation* is inches/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 in this dissertation. For the base VOC, this dissertation 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,

$$CPI_i \times (1 + r)^{j-i} = CPI_j \quad (3.33)$$

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 was 2.35%, and it was assumed to remain the same for the analysis period in this dissertation.

The annual growth of traffic was also considered. Increases in the number of road users lead to increases in user costs. The average annual traffic growth factor for Indiana was calculated as 0.72%.

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

3.6 Chapter Summary

In this chapter, the methodology framework for the deterministic situation was established. An optimization framework in terms of life-cycle cost analysis was proposed. The overall concept of the optimization framework was further illustrated using figures. Deterministic statistical models were developed, including bridge deck and wearing surface deterioration models, performance jump models, and deck treatment cost models. 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. Two types of user costs were taken into account, including travel time costs due to work zone delays and the incremental VOC during normal operations due to the increased roughness of the bridge deck surface. The developed framework is demonstrated using data collected from Indiana in Chapter 4 as well as the results for the optimal triggers.

CHAPTER 4. RESULTS AND ANALYSIS FOR THE DETERMINISTIC SITUATION

This chapter uses data from the state of Indiana as a case study to demonstrate the framework for the deterministic situation established in Chapter 3. The framework is applicable to other states or agencies as long as the data sets are adequately available. This chapter also discusses the analysis and implications of the results.

4.1 Introduction

The results are presented in terms of three climate region categories (cold region – northern Indiana, moderate region – central Indiana, and warm region – southern Indiana), two highway functional class categories (NHS and non-NHS), and two overlay implementation strategies (LMC overlays only, and polymeric overlay followed by LMC overlays). Therefore, the results contain a total of 3×2×2=12 combinations of categories.

The climate regions were analyzed separately because climate conditions, such as temperature, precipitation, and freeze index, can impact the deterioration rate of bridge decks. 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. As far as INDOT's overlay strategies, polymeric overlays have been used more frequently in the last 10 years in Indiana. A polymeric overlay is typically implemented on a deck in relatively good condition or even on a new deck as a preventive maintenance treatment. LMC overlays are typically used on older decks as a corrective treatment. Therefore, this dissertation considered two alternative overlay strategies: (1) only LMC overlays were implemented one or more times during the life cycle of the deck; and 2) polymeric overlays were placed at an early stage of the life cycle, and LMC overlays then were used as deck rehabilitation treatments once or more during the rest of the life cycle.

4.2 Data Collection

4.2.1 Basic Bridge Deck Characteristics

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

With regard to functional class, in this dissertation, bridges with NBI Item 5B codes of 1-Interstate highway, 2-U.S. highway, and 3-State highways are categorized as part of the National Highway System (NHS); other functional classes are categorized as non-NHS. Bridge structure length and deck width are coded in meters in the NBI database. These data were used for calculating the costs of deck treatments, work zone delay costs, and VOC. Detour length was used for calculating user costs.

"Type of wearing surface" was used to identify the deterioration rates of different bridge wearing surfaces. By noting a change in the wearing surface type for every bridge during the analysis period (1992-2015), some bridge treatments, such as deck overlay, were detected if it was 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 currently there are not have many entries in INDOT's NBI for 5-epoxy overlay (a polymer overlay or thin deck overlay), INDOT has been programming and implementing it more aggressively in recent years.

4.2.2 Traffic Data

Traffic data, including average daily traffic (ADT) and percent trucks, were also collected from the NBI database. Truck traffic volume affects the deterioration rates of bridge components, and ADT is used to calculate the user costs, including work zone delay costs and 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 (-23%). The negative traffic growth during this period could have been largely due to the economic 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, (0.72%) was used in the analysis for all functional classes, which was assumed to remain constant during the analysis period.

4.2.3 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 documented. 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 et al., 2015).

4.2.4 Project Type and Agency Cost Data

Bridge contract data, including the specific work type of M&R treatments, contract costs, and letting finish dates, were obtained from INDOT’s SPMS and Site Manager databases. 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 treatment 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 treatments, 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 also used, 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 as 1.15% and was applied to the entire analysis period.

4.2.5 Work Zone Duration and User Cost Data

Work zone duration data were 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 historical contracts and expert opinions. The details are presented in Table 4.1, including the maintenance of traffic (MOT) type and their corresponding closure durations. The values in Table 4.1 are solely for time when traffic is affected and not the total contract time.

Table 4.1 Work Zone Duration Estimates by Bridge Deck Project Type (Source: INDOT, 2016)

<table>
<tr><th>Work Type</th><th>MOT Type</th><th>Closures</th><th>Comments</th></tr>
<tr><td rowspan="3">Deck patching</td><td>Flagger</td><td>Restrictions during daytime hours for 2-3 days</td><td>Needs rapid set patch, which drives up the cost of the project</td></tr>
<tr><td>Lane closure (4 or more lanes)</td><td>3 days per lane</td><td></td></tr>
<tr><td>Detour</td><td>3 days total</td><td></td></tr>
<tr><td rowspan="3">Joint repair (BS or silicon seals)</td><td>Flagger</td><td>Restrictions during daytime hours for 2-3 days</td><td>If patching required, rapid set materials needed</td></tr>
<tr><td>Lane closure (4 or more lanes)</td><td>3 days per lane</td><td></td></tr>
<tr><td>Detour</td><td>3 days total</td><td></td></tr>
<tr><td rowspan="3">Joint repair (SS or modular joints)</td><td>Flagger</td><td>NOT typically an option</td><td rowspan="3">Partial deck reconstruction typically required</td></tr>
<tr><td>Lane closure (4 or more lanes)</td><td>5-7 days per lane</td></tr>
<tr><td>Detour</td><td>5-7 days total</td></tr>
</table>

Table 4.1 continued

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	Two 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

The value of the travel time of users and the VOC 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) data from 1999 to 2014 were 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 as 2.35% and was used in this dissertation to estimate the annual increase in user costs during the analysis period.

4.2.6 Summary of Basic Bridge Deck Statistics and Climate Data for Indiana

The basic statistics for bridge decks in the three Indiana climate regions are summarized in Table 4.2, including average daily traffic (ADT) on the bridges, percent trucks on the bridges, detour length, structure length, and deck width. The data in Table 4.2 were used in the deterioration models and in calculating user costs.

Table 4.2 Statistics for Bridge Decks in Different Indiana Regions (Source: NBI 2014)

Cold Region (Northern Indiana)				
Functional Class		Interstate	Non-Int-NHS	Non-NHS
ADT	Mean	23,848	10,201	7,556
	Max	117,408	70,283	111,751
	Min	106	102	407
Truck%	Mean	14	12	9
	Max	40	52	45
	Min	5	3	1
Detour Length (km)	Mean	3	5	7
	Max	25	28	52
	Min	2	1	2
Structure Length (m)	Mean	61	50	42
	Max	357	306	334
	Min	18	9	7
Deck Width (m)	Mean	18	14	13
	Max	69	34	43
	Min	9	10	8
Moderate Region (Central Indiana)				
Functional Class		Interstate	Non-Int-NHS	Non-NHS
ADT	Mean	34,653	8,889	5,247
	Max	170,840	45,880	40,113
	Min	2,493	367	467
Truck%	Mean	19	9	10
	Max	75	45	33
	Min	4	3	1
Detour Length (km)	Mean	3	7	8
	Max	24	66	44
	Min	0	2	1
Structure Length (m)	Mean	67	47	39
	Max	834	446	404
	Min	13	7	7
Deck Width (m)	Mean	17	14	11
	Max	64	38	30
	Min	10	9	7

Table 4.2 continued

Warm Region (Southern Indiana)				
Functional Class		Interstate	Non-Int-NHS	Non-NHS
ADT	Mean	18,167	9,119	5,979
	Max	101,668	42,963	56,438
	Min	1,612	1,084	102
Truck%	Mean	14	10	10
	Max	36	28	28
	Min	3	5	2
Detour Length (km)	Mean	4	6	10
	Max	28	27	144
	Min	1	2	1
Structure Length (m)	Mean	72	61	46
	Max	997	501	885
	Min	14	9	7
Deck Width (m)	Mean	15	14	12
	Max	63	41	35
	Min	7	8	7

The climate regions for Indiana defined in this dissertation are based on the existing Indiana highway regions. The climate conditions, such as annual average temperature, annual precipitation, and freeze index in each region are similar and different from those in other regions. The basic climate statistics for the three climate regions in Indiana are presented in Table 4.3. The data were collected from National Oceanic and Atmospheric Administration (NOAA). It should be mentioned that the analysis and results in this chapter may also be applicable to bridge decks in other states or regions that have similar characteristics to those in the corresponding Indiana regions.

Table 4.3 Climate Statistics for Different Indiana Regions (Source: NOAA)

Climate Region	**Avg. Annual Temperature (F)**	**Avg. Annual Precipitation (in)**	**Avg. Annual Freeze Index**
Cold Region (Northern IN)	49.64	38.24	527
Moderate Region (Central IN)	51.04	40.18	390
Warm Region (Southern IN)	54.26	45.39	112

4.3 Life-Cycle Cost Analysis Results

Based on the models developed in Sections 3.2 through 3.5, the optimization framework discussed in Section 3.1 was applied to obtain the optimal performance thresholds.

In terms of the upper and lower bounds defined in constraints 3.14 and 3.15, based on the historical data and the expert opinion of INDOT engineers, LMC overlays were chosen to be applied when the wearing surface condition was 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 was 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 an LMC overlay is a rehabilitation treatment and is not used on a new deck. WS = 4 also is not considered because when the wearing surface condition drops to 4, the deck condition typically drops 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 this dissertation, 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 was used to investigate the life-cycle cost results for every candidate trigger threshold. This method also helped 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 climate region and functional class category are presented, due to space limitations. The results for other regions and functional classes can be found in Appendix A of this dissertation. Table 4.4 and Figure 4.1 present the results for the bridges on NHS highways in the moderate region. The life-cycle costs were calculated in terms of EUAC for comparisons under different analysis periods (service life). The EUACs were normalized by the 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 served as a base case for the purposes of comparison and assumed that no major deck rehabilitation treatments (LMC overlays) were applied, except for minor repairs and maintenance. Triggers at “5”, “6”, or “7” meant that the LMC overlays were implemented when the surface condition of the deck reached 5, 6, or 7. LMC overlays are allowed to be used multiple times during the service life of the deck; and in this dissertation, a 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 one or two applications of LMC overlays are implemented before the deck is replaced; for concrete bridges, two to three LMC overlays are implemented. The detailed life-cycle strategies are illustrated by Figure 4.4, Figure 4.5, and Figure 4.6 in the next section of this chapter.

Table 4.4 Life-Cycle Agency and User EUAC Results for Moderate Region, 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

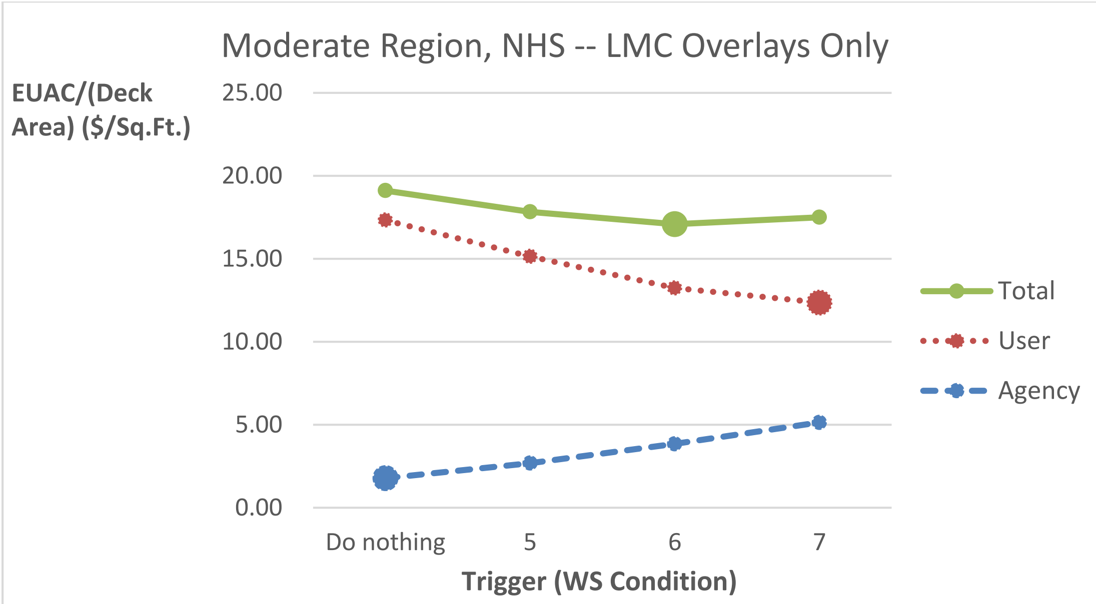


Figure 4.1 Life-Cycle Agency and User EUAC Results for Moderate Region, NHS, LMC Overlays Only (AC:UC=1:1)

Based on the results in Table 4.4, under the Do Nothing case, the deck was supposed to have a service life of 35 years (i.e., when deck condition reached 4). If the LMC overlay was triggered at condition 5 and triggered once, the deck service life was extended by eight years and reached 43 years. Similarly, if the LMC overlay was triggered at condition 6 (or 7) two (or three) times, deck service life was extended by 47 (or 53) years.

With respect to the EUAC results, when only the agency cost was considered, Do Nothing led to the lowest EUAC, which indicates that the extended service life due to overlay treatments did not compensate the additional costs of the overlays. However, if Do Nothing was not considered as a realistic case, then Trigger 5 led to the lowest EUAC among candidate Triggers 5, 6, and 7 because, although Triggers 6 and 7 led to a 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 were triggered more frequently (e.g., trigger at condition 7), there were more work zone delays leading to more travel time costs.

However, the average surface condition was better than that with less frequent overlays, which led to lower VOCs during normal operations. The results in Table 4.4 and Figure 4.1 show that Trigger 7 led to the lowest user cost EUAC. The total EUAC when the agency and user costs were combined with equal weight (1:1) was lowest when Trigger 6 was used. This result indicates a trade-off between the agency costs and the user benefits.

Table 4.5, Figure 4.2, and Figure 4.3 present the results for the scenario in which both polymeric and LMC overlays were implemented. It was assumed that the polymeric overlay was used before LMC overlays and used on a better wearing surface condition than for LMC overlays, based on historical data. It was also assumed that the polymeric overlay was implemented only once during the life cycle, while LMC overlays were implemented multiple times. Do Nothing again served as a base case for the purposes of comparison. It was assumed that no major deck rehabilitation treatments (polymeric or LMC overlays) had been applied, except for minor repairs and maintenance. Trigger "PaLb" indicates that the polymeric overlay was implemented at a wearing surface condition rating of "a" (a = 8, 7, 6), and the LMC overlay was implemented at a 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.

Table 4.5 Life-Cycle Agency and User EUAC Results for Moderate Region, 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**

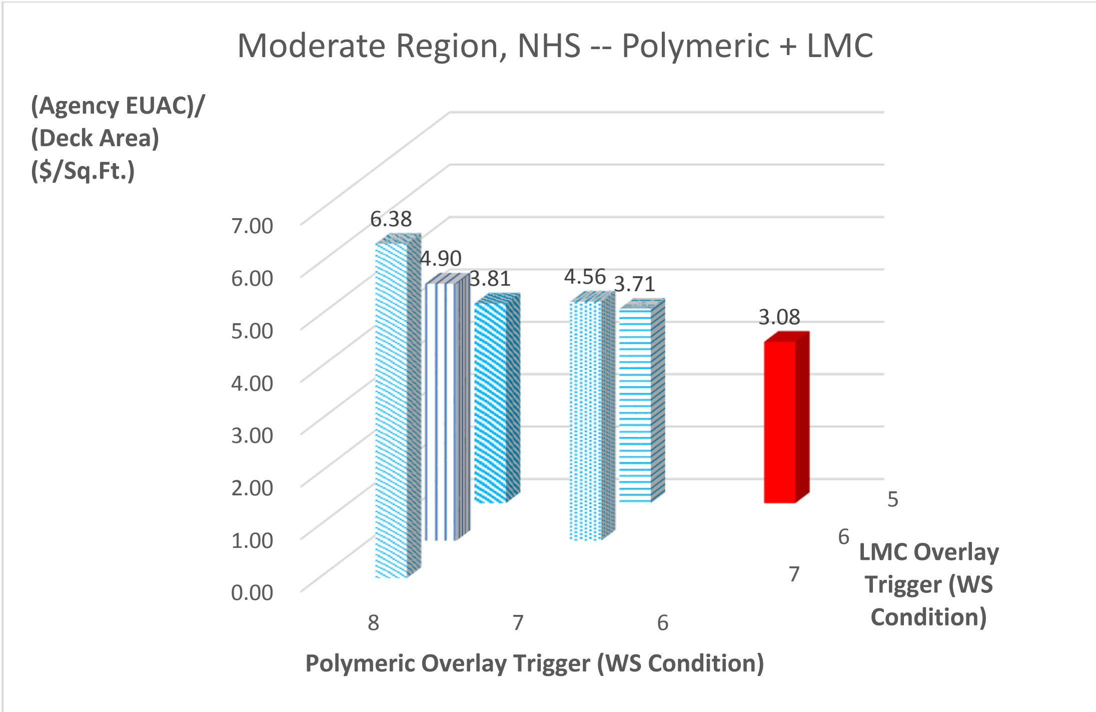


Figure 4.2 Life-Cycle Agency EUAC Results for Moderate Region, NHS, Polymeric and LMC Overlays

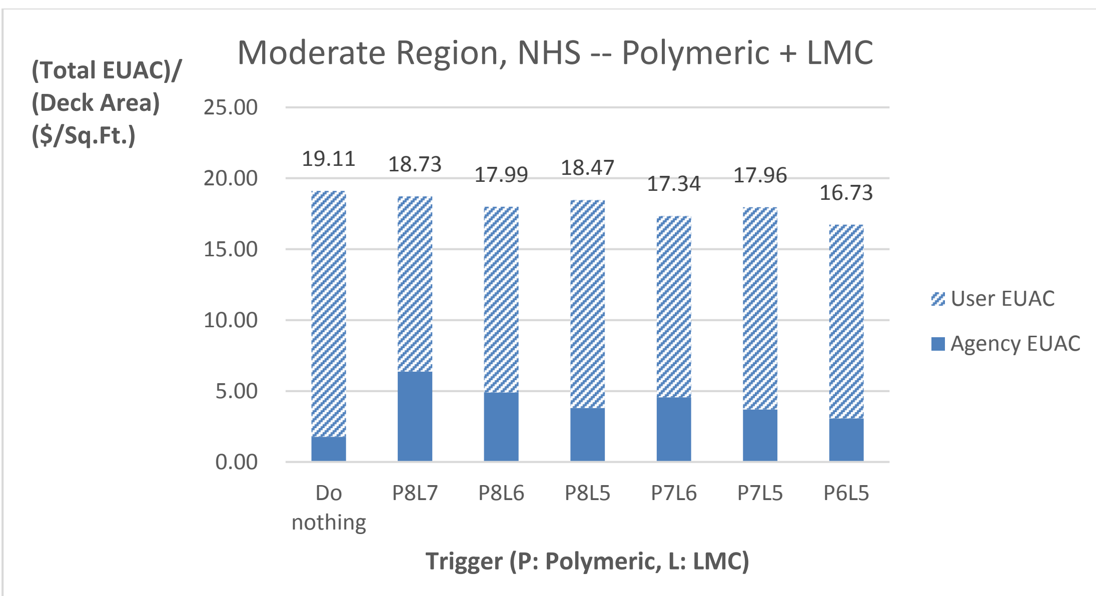


Figure 4.3 Life-Cycle Total EUAC Results for Moderate Region, NHS, Polymeric and LMC Overlays (AC:UC=1:1)

Based on the results in Table 4.5, 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, when only the agency cost was considered, Do Nothing again led to the lowest EUAC. If Do Nothing was not considered as a real case, then Trigger “P6L5” had the lowest EUAC because it led to the longest service life and had fewer frequent overlay treatments.

The user cost did not show a clear trend because user cost is a combination of travel time cost due to work zone delays and VOC due to surface roughness. The Do Nothing case had the highest user EUAC, which 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 had a lower condition, indicating again that the user benefits gained from (or the user costs were 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 the agency and user costs were combined using weight 1:1. This trigger result was the same as when only the agency cost was considered. Agency costs had more influence than user costs in this scenario, in which both polymeric and LMC overlays were implemented.

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

The life-cycle analysis results for other categories (i.e., moderate region non-NHS, cold region NHS and non-NHS, and warm region NHS and non-NHS), are presented in Appendix A of this dissertation. The results across various climate region categories were consistent. However, the results between NHS and non-NHS were different, probably because of the assumption that the detour policy was used for non-NHS bridges, which caused much higher user costs when there were more frequent overlay treatments.

4.4 Proposed Bridge Deck Life-Cycle M&R Strategies

Results presented in the previous section indicated that:

a) For NHS bridges, 1) if only LMC overlays were 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; 2) if both polymeric and LMC overlays were used, Trigger P6L5 (Polymeric at WS=6 and LMC at WS=5) led to the least EUAC, regardless of whether user costs were included.

b) For non-NHS bridges, 1) if only LMC overlays were used, Trigger WS = 5 led to the least EUACs, regardless of whether user costs were included; 2) if both polymeric and LMC overlays were 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, the results for moderate region, NHS are presented in this section due to space limitations. Results for the other climate regions and functional class categories can be found in Appendix B and Appendix C of this dissertation, respectively.

Figure 4.4 illustrates the proposed condition-based deck M&R strategy for moderate region, NHS bridges, when only LMC overlays were used, given that both the agency and user costs were considered. The blue solid curves refer to the changes in the 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 resulted in 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 deck life cycle ended 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 not considered cost-effective to trigger a third overlay. In addition, in practice, overlays cannot be applied indefinitely. Typically, one to two 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 optimal when only the agency costs were considered. The result was intuitive because the less frequently the overlays are triggered, the less costly it would be for the agency.

Figure 4.6 presents the life-cycle profile of the recommended 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 the deck condition reached 4, at which threshold deck replacement was triggered.

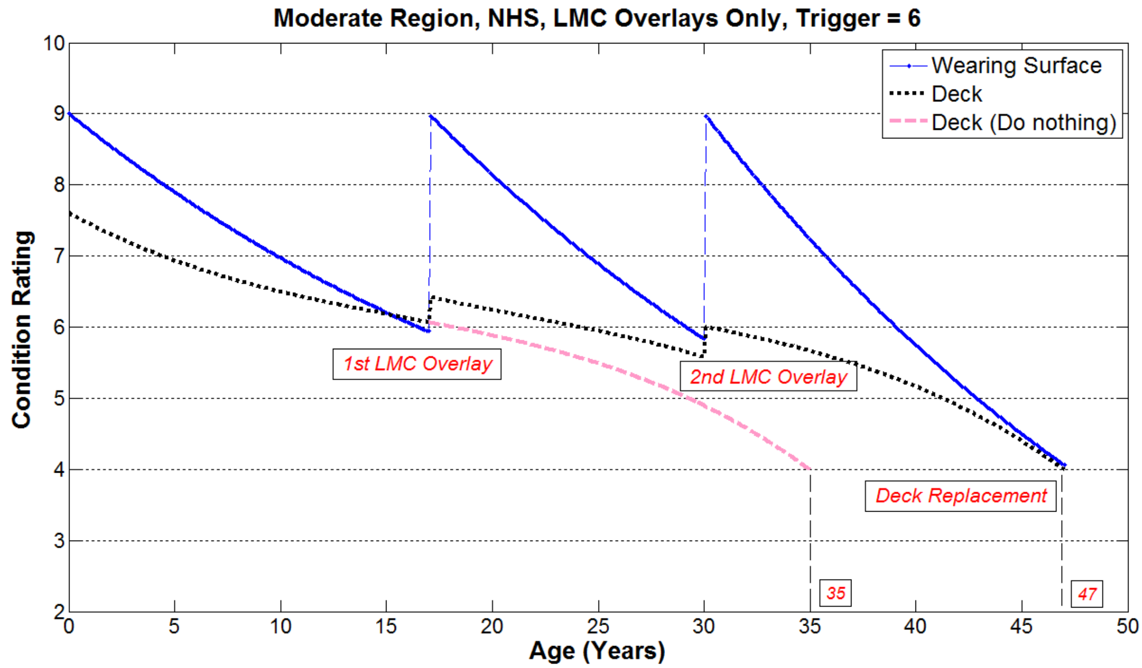


Figure 4.4 Proposed Condition-Based Bridge Deck M&R Strategy for Moderate Region, NHS, LMC Overlays Only (Agency and User Costs 1:1 Combined)

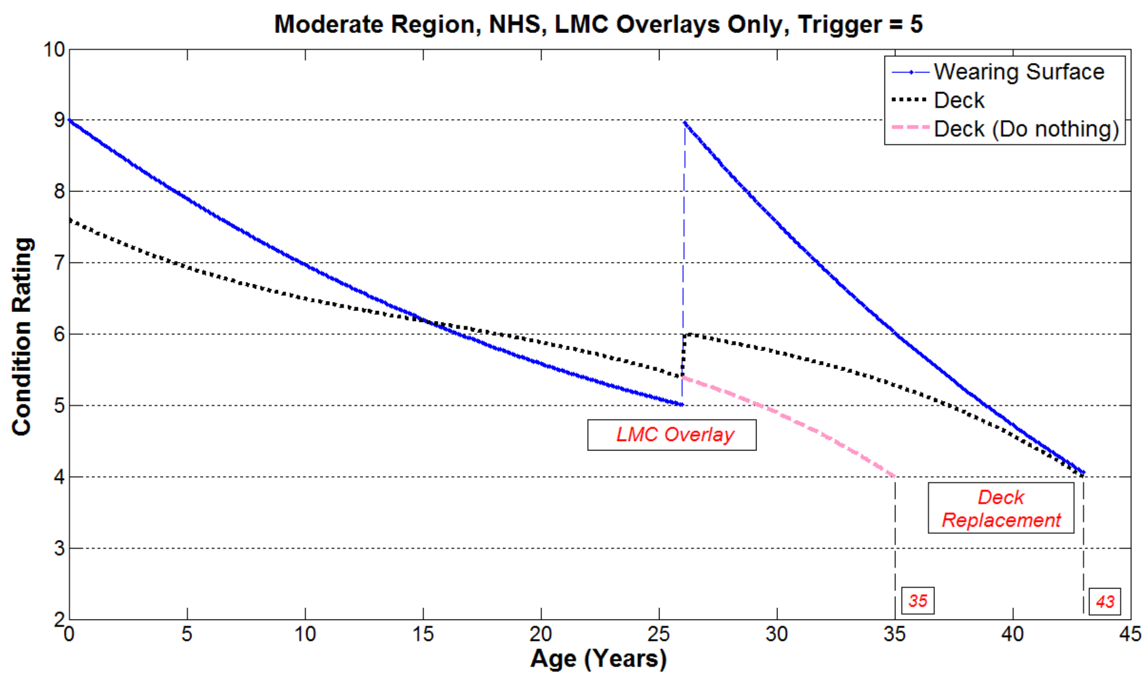


Figure 4.5 Proposed Condition-Based Bridge Deck M&R Strategy for Moderate Region, NHS, LMC Overlays Only (Agency Costs Only)

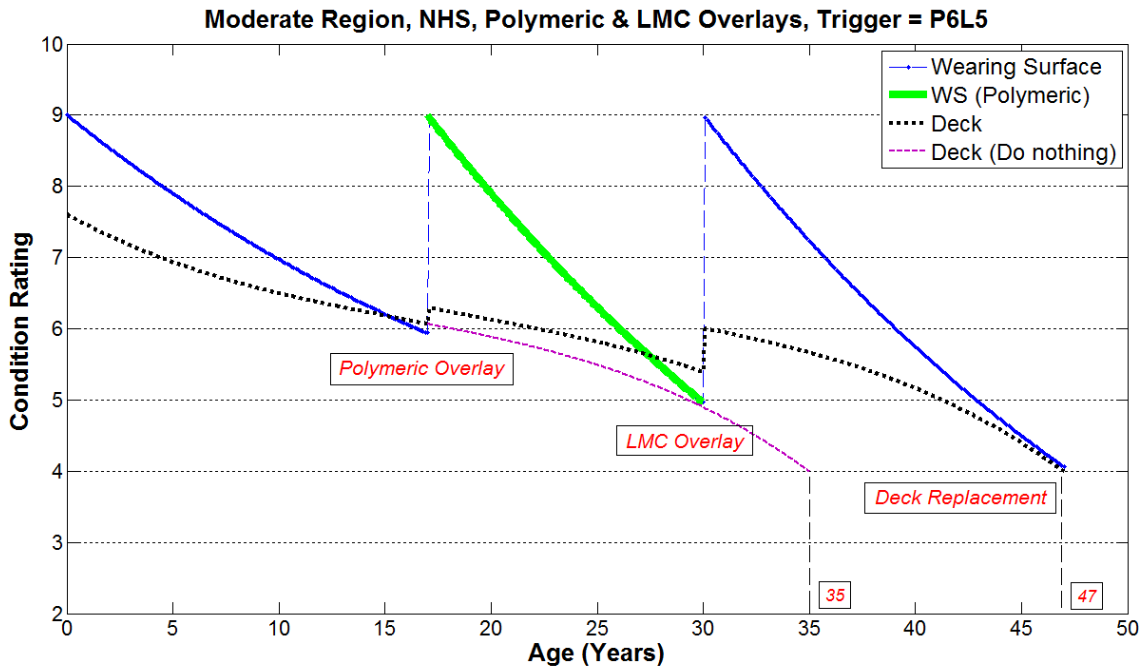


Figure 4.6 Proposed Condition-Based Bridge Deck M&R Strategy for Moderate Region, NHS, Polymeric and LMC Overlays

Figure 4.7 and Figure 4.8 present two examples of other candidate strategies that were found to be less cost-effective. For the strategy in Figure 4.7, LMC overlays were triggered at WS = 7 and were triggered three times during the life cycle. Furthermore, although the strategy could extend the service life to 53 years, it would cost more. Furthermore, its life-cycle cost turned out to be higher than the others. Figure 4.8 shows the strategy of P8L6 for the scenario if both polymeric and LMC overlays were implemented. Polymeric overlay was triggered at WS=8 and LMC was triggered at WS=6 twice. This strategy was also found to be the least cost-effective strategy.

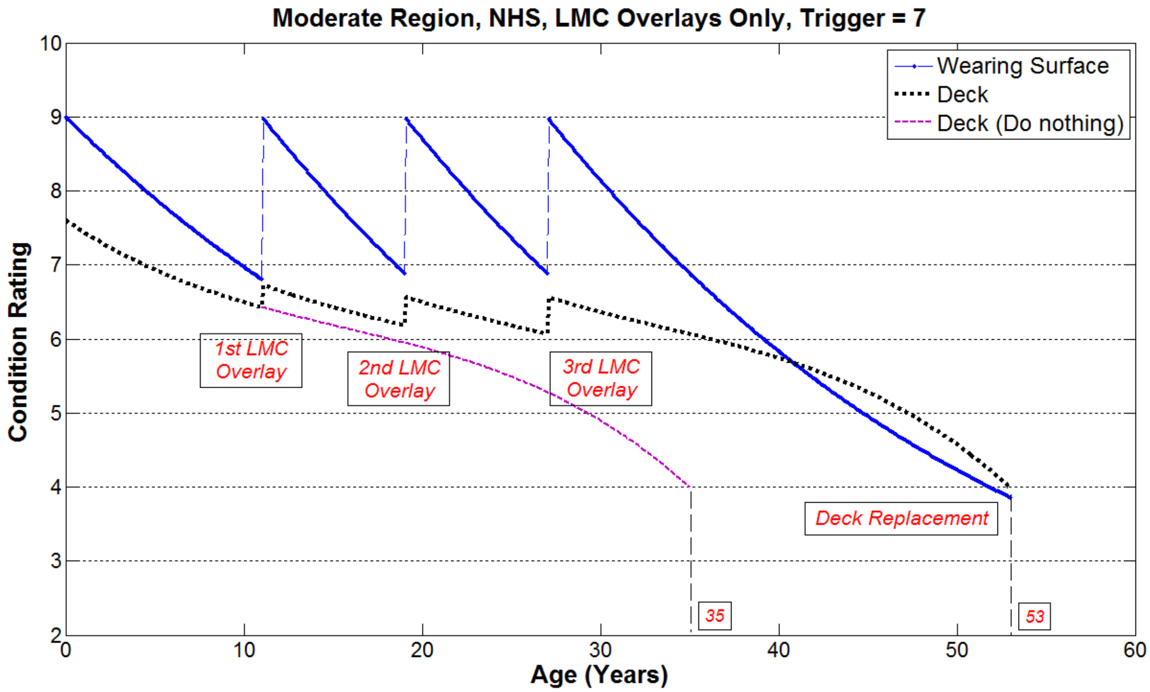


Figure 4.7 Example Profile of Other Candidate Deck M&R Strategies for Moderate Region, NHS, LMC Overlays Only (Trigger WS=7)

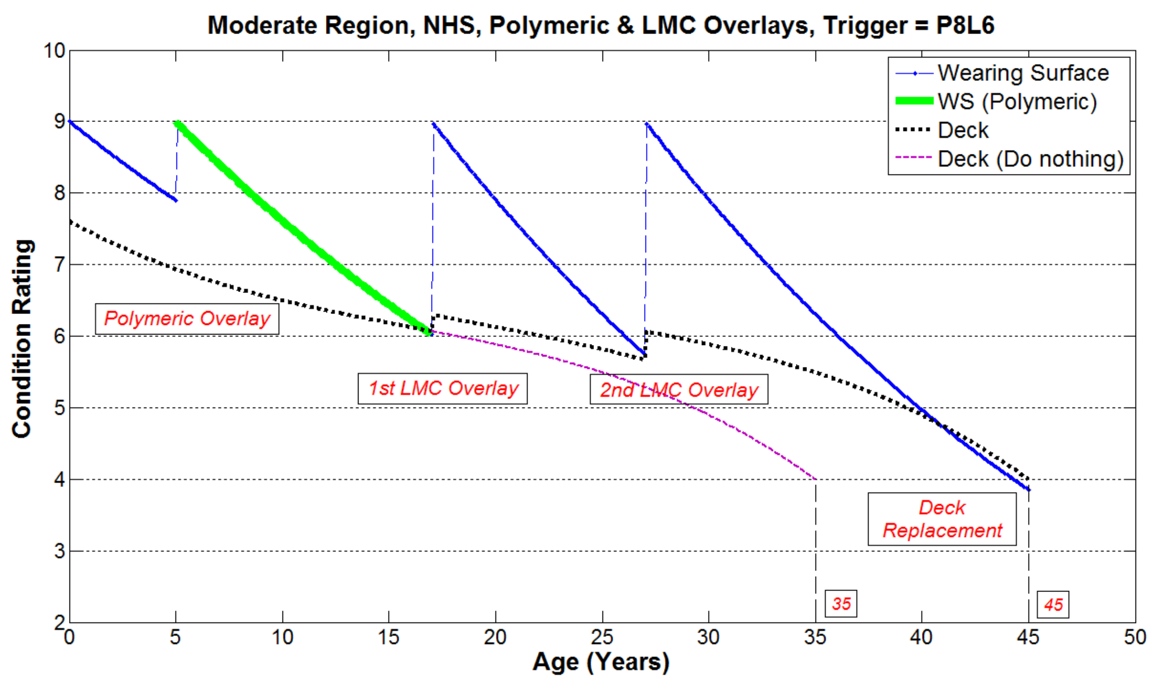


Figure 4.8 Example Profile of Other Candidate Deck M&R Strategies for Moderate Region, NHS, Polymeric and LMC Overlays (Trigger = P8L6)

4.5 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, changes in the parameter values could change the EUAC results, and thus could possibly affect the optimal 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), and discount rate (which affects EUAC), as well as 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). These factors were the relative weight between the agency cost and user cost dollars and the traffic volume.

4.5.1 Sensitivity to Weights between Agency and User Cost

The first tested factor was the relative 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? This dissertation does not establish a fixed weight, but provides the results under different assumed weights. As a result, highway agencies can have the flexibility to choose the weights based on their needs.

Table 4.6 and Figure 4.9 present the sensitivity analysis results in terms of weights between agency costs and user costs, for bridges in cold region NHS highways, using LMC overlays only. It was found that when the weights between the agency and user costs equaled 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 yielded the least life-cycle cost (EUAC). The overall trend was that when agency costs played a more significant role, the trigger shifted to less frequent overlay treatments. This is intuitive because an agency would prefer fewer frequent M&R treatments to reduce expenditures. The diamond points in Figure 4.9 indicated the triggers with the lowest life-cycle cost (EUAC) for each scenario.

Table 4.6 Life-Cycle Cost Sensitivity to Weights between Agency and User Costs, Cold Region, NHS, LMC Overlays Only

	Weight (AC:UC)	**Trigger**			
		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

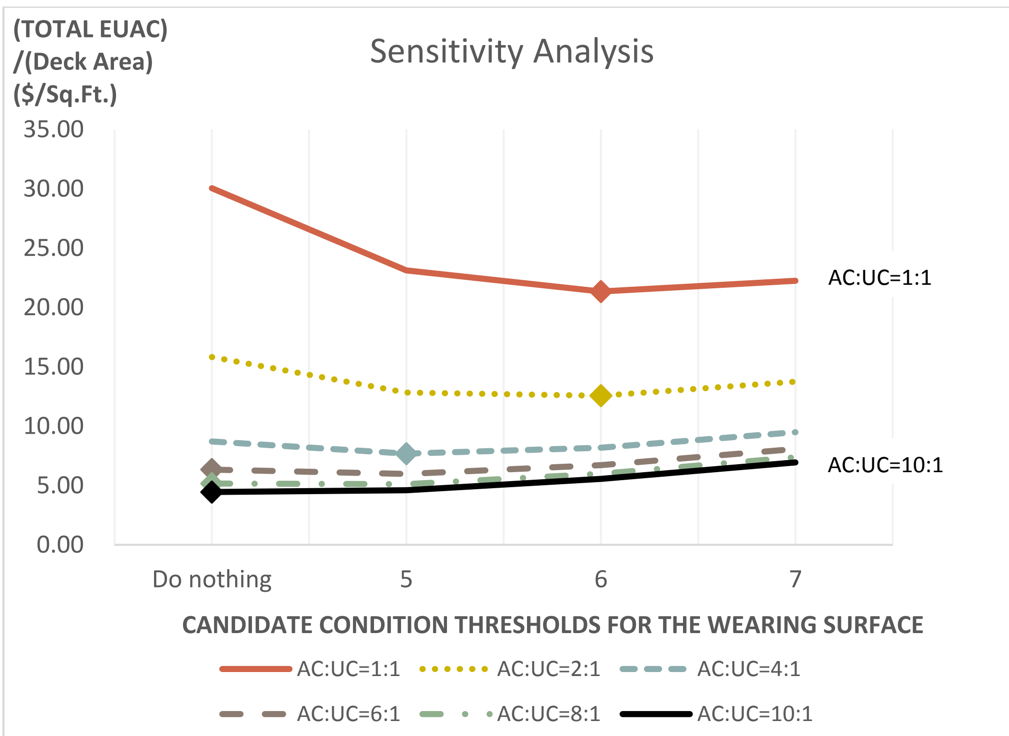


Figure 4.9 Life-Cycle Cost Sensitivity to Weights between Agency and User Costs, Cold Region, NHS, LMC Overlays Only

Table 4.7 presents the sensitivity analysis results in terms of the weights between agency costs and user costs, for bridges in cold region NHS highways, using both polymeric and LMC overlays. Trigger P6L5 had the least EUAC for weights of 1:1, 2:1, and 4:1. Do Nothing had the least EUAC when the agency costs began 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 M&R treatments. For example, P8L5 did not necessarily indicate more frequent treatments than P7L6, or vice versa. However, an observed trend was that, when the weight of the agency costs increased, the results shifted to the trigger that had a lower agency EUAC. In this case specifically, Trigger P6L5 had the lowest agency EUAC, except for Do Nothing, and 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 further strengthen the advantage of P6L5, until AC became really dominant (AC:UC=10:1) and Do Nothing took over the position.

Table 4.7 Life-Cycle Cost Sensitivity to Weights between Agency and User Costs, Cold Region, NHS, Polymeric and LMC Overlays

	Weight (AC:UC)	**Trigger**						
		Do Nothing	**P8L7**	**P8L6**	**P8L5**	**P7L6**	**P7L5**	**P6L5**
(Total EUAC) / (Deck Area) ($/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

4.5.2 Sensitivity to Traffic Volume

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

Table 4.8 and Figure 4.10 present the sensitivity analysis results in terms of the traffic volume (ADT) for bridges on cold region NHS highways, using LMC overlays only. In fact, the increase in ADT had a similar effect to that of increasing the weight of the user costs because the user costs largely depend on the number of road users. Therefore, when the ADT increased, the trigger with the least EUAC shifted to the ones with more frequent overlays. The diamond points in Figure 4.10 indicate the triggers with the lowest EUAC for each scenario. Table 4.9 presents the sensitivity analysis results in terms of traffic volume (ADT) for bridges on cold region NHS highways, using both polymeric and LMC overlays. It was found that when ADT reached 20,000, which means that user costs became more dominant, P8L7 led to the lowest total EUAC because the frequent overlays would provide users with a smoother wearing surface and thus lower VOCs. The sensitivity analysis results for other climate regions and functional class categories can be found in Appendix D of this dissertation.

Table 4.8 Life-Cycle Cost Sensitivity to Traffic Volume,
Cold Region, NHS, LMC Overlays Only (AC:UC=1:1)

	Traffic (ADT)	**Trigger**			
		Do Nothing	**WS = 5**	**WS = 6**	**WS = 7**
(Total EUAC) / (Deck Area) ($\$/ft^2$)	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

Table 4.9 Life-Cycle Cost Sensitivity to Traffic Volume,
Cold Region, NHS, Polymeric and LMC Overlays (AC:UC=1:1)

	Traffic (ADT)	**Trigger**						
		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

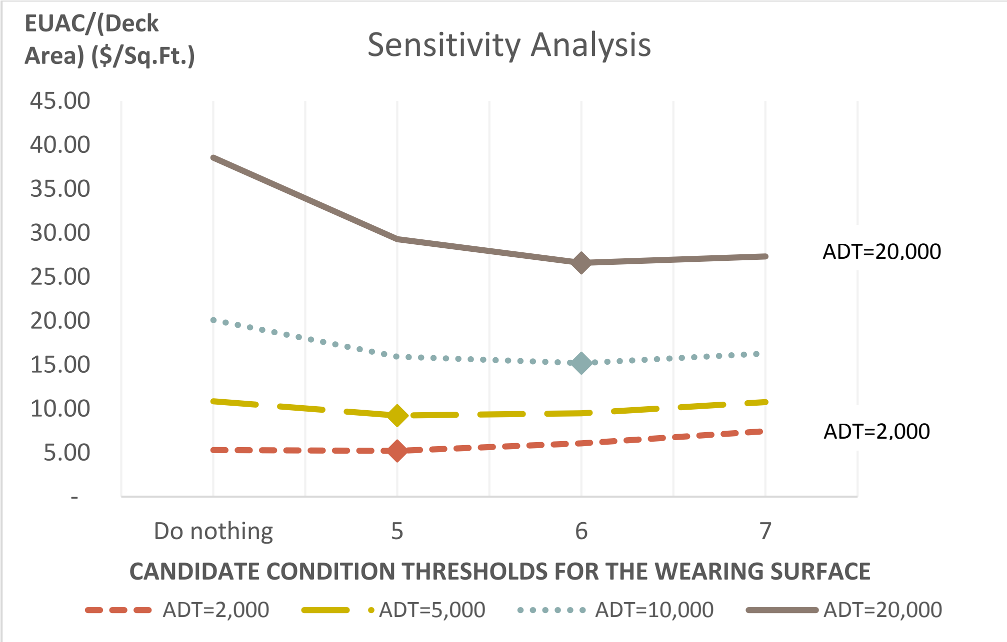


Figure 4.10 Life-Cycle Cost Sensitivity to Traffic Volume,
Cold Region, NHS, LMC Overlays Only (AC:UC=1:1)

4.6 Discussion of Results

Based on the results of the sensitivity of the weights between the agency and user costs, accurate "critical" weights were calculated. The critical weight indicates the ratio that the optimal trigger changes if the weight is greater than or less than this ratio. Specifically, it was found that, for NHS bridges in the moderate climate region, 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 (i.e., AC:UC ≥ 1.64). Likewise, the optimal LMC trigger was WS = 6 if each dollar agency cost was weighted at least 0.68 times but less than 1.64 times of each dollar of user cost (i.e., 0.68 ≤ AC:UC < 1.64); and the optimal LMC trigger was WS = 7 if each dollar agency cost was weighted less than 0.68 times of each dollar of user cost (i.e., 0 ≤ AC:UC < 0.68). Similarly, for NHS bridges in the cold climate region, the optimal LMC trigger was WS = 5 if each dollar of agency cost was weighted at least 2.13 times as much as each dollar of user cost (i.e., AC:UC ≥ 2.13); the optimal LMC trigger was WS = 6 if each dollar agency cost was weighted at least 0.05 times but less than 2.13 times of each dollar of user cost (i.e., 0.05 ≤ AC:UC < 2.13); and the optimal LMC trigger was WS = 7 if each dollar of agency cost was weighted less than 0.05 times of each dollar of user cost (i.e., 0 ≤ AC:UC < 0.05). For NHS bridges in the warm climate region, the optimal LMC trigger was WS = 5 if each dollar of agency cost was weighted at least 2.59 times as much as each dollar of user cost (i.e., AC:UC ≥ 2.59); the optimal LMC trigger was WS = 6 if each dollar of agency cost was weighted at least 0.98 times but less than 2.59 times of each dollar of user cost (i.e., 0.98 ≤ AC:UC < 2.59); and the optimal LMC trigger was WS = 7 if each dollar agency cost was weighted less than 0.98 times of each dollar of user cost (i.e., 0 ≤ AC:UC < 0.98). In addition, it was found that for non-NHS highway bridges, Trigger = 5 always led to the lowest total EUAC, given AC:UC ≥ 1. If both polymeric overlays and LMC overlays were considered, it was found that the polymeric overlay triggered at WS = 6 and the LMC overlay triggered at WS = 5 yielded the lowest total EUAC, given AC:UC ≥ 1.

The above results for the LMC overlay are summarized in Figure 4.11. The horizontal axis represents the relative weight between the agency and user costs (AC:UC). The four bars, from top to bottom, represent the results for NHS-cold region, NHS-moderate region, NHS-warm region, and non-NHS bridges. The general trend within the NHS categories was that the more weight that was assigned to the agency cost, the less frequent LMC overlays (characterized by lower trigger values) were preferred. This is intuitive because less frequent LMC overlays would lead to lower life-cycle agency costs. The optimal trigger remained the same (WS=5) for non-NHS bridges regardless of the weight because of the assumptions made in this dissertation. It was assumed that for NHS bridges, the lane-closure MoT plan was used during the overlay while for non-NHS bridges, the detour MoT plan was assumed. Owing to the typical long detour distance for non-NHS bridges, the user costs due to work zones for the non-NHS bridges were much higher. Therefore, for non-NHS bridges, more frequent LMC overlays yielded both higher agency costs as well as higher user costs. Consequently, Trigger WS=5, which included the least overlay applications always yielded the lowest total life-cycle cost for non-NHS bridges.

However, in practice, because a public agency typically would not assign a higher weight to the user cost than to the agency cost, AC:UC is typically greater than or equal to 1. In this case, Trigger = WS 7 would not be recommended as an appropriate trigger, except for special situations where the user cost may be allocated at a higher weight. The vertical line is AC:UC=1. Figure 4.11 indicates that when AC:UC≥ 1, only Trigger = WS 6 and Trigger = WS 5 were the candidate optimal triggers.

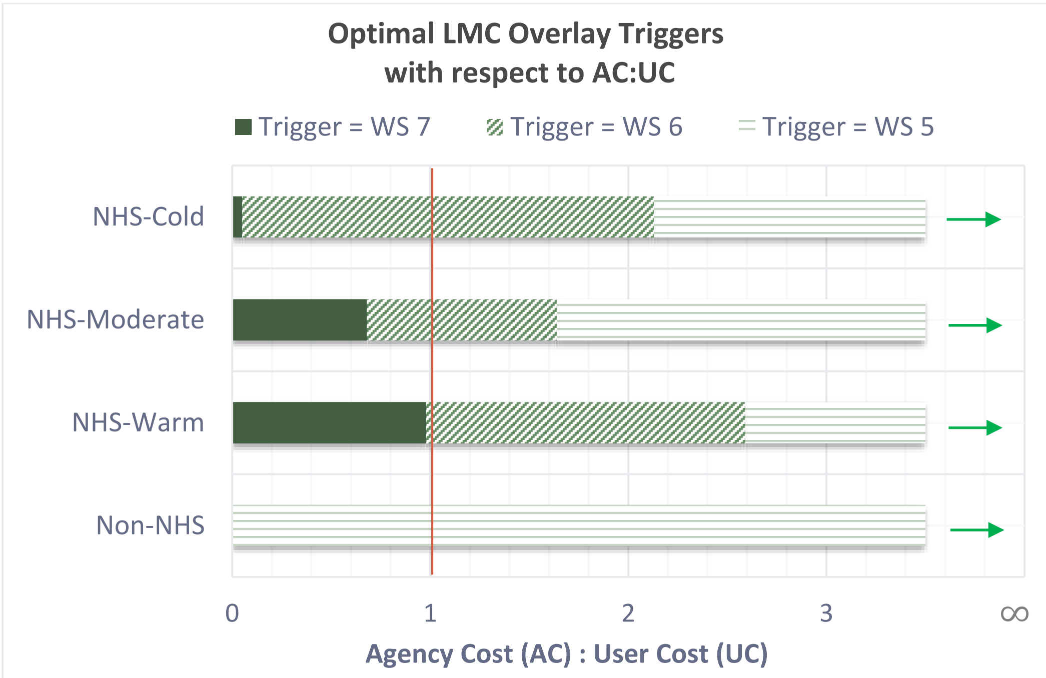


Figure 4.11 Change of the Optimal LMC Overlay Trigger with the Relative Weight between Agency and User Cost

4.7 Chapter Summary

In this chapter, the life-cycle cost analysis under the deterministic situation was conducted. The framework was demonstrated using data from state-owned bridges in Indiana. Separate analyses were conducted with respect to different climate regions (cold, moderate, and warm) and different highway functional classes (NHS and non-NHS). Sensitivity analysis was conducted to investigate the impacts of the change in the relative weight between the agency and user cost dollars and the change in traffic volume on the life-cycle costs. It was found that different weighting and traffic had an impact on the optimal trigger that led to the lowest EUAC for some scenarios. In addition, the life-cycle condition-based deck M&R strategies for various scenarios were proposed and presented. The life-cycle cost analysis under the stochastic situation is discussed in Chapter 5.

CHAPTER 5. METHODOLOGY FOR THE STOCHASTIC SITUATION

Chapter 3 of this dissertation discussed the analysis framework under deterministic situations. However, in the real world, due to the inherent variability in natural processes, all the input factors for deck M&R treatments decision-making are characterized with significant uncertainties and, subsequently, the decision-making outputs. For instance, deck deterioration is inherently a stochastic process that can be influenced by various unobserved factors; the amount of traffic traveling across the bridge changes at every moment and long-term traffic increases or decreases can never be predicted with certainty; weather conditions that affect the deck deterioration process is another significant source of uncertainty; and cost overruns frequently occur in any transportation project's constructions and operations. Therefore, given all these risks and uncertainties, the following questions are appropriate. 1) *Will the optimal performance thresholds developed under the deterministic situation still remain the optimal choice? 2) To what extent is one performance threshold statistically significantly different from another?* The following two chapters address these questions through incorporating risks and uncertainties into the framework, including development of probabilistic deck deterioration models and investigation of uncertainties in terms of costs, traffic, and other factors.

In Chapter 3, statistical regression techniques were used to develop deterministic bridge deterioration models. However, deterministic models are associated with some critical inherent limitations. First, the deterioration process of the infrastructure is a stochastic process in nature that is affected by a variety of factors, some of which are generally unobservable or not captured by available data (Jiang and Sinha, 1989b; Mauch and Madanat, 2001). Second, because the bridge condition rating is typically expressed as an integer scale from 0 - 9 as defined in the National Bridge Inventory (NBI), the response variable is actually count data, which cannot be modeled appropriately using linear regression, for which the predicted result is continuous. Third, it was found that deterministic models provide reasonable results only within the bounds of the available data, and their predictions beyond those bounds could be misleading (Cavalline et al., 2015).

5.1 Probabilistic Bridge Deck Deterioration Modeling

5.1.1 Introduction

Among the stochastic models, as indicated in Section 2.3.2 of this dissertation, the Markov-chain model is the most commonly used tool to describe the probabilistic transition process of bridge deterioration (Jiang et al., 1987; Cesare et al., 1992; Madanat and Wan Ibrahim, 1995; Thompson and Johnson, 2005; Li et al., 2014). However, the Markov-chain model is not always suitable for all situations because of its following limitations (Madanat et al., 1995; Morcous 2006). 1) The Markov process assumes state independence (i.e., future bridge condition depends only on the present condition and not on the past condition). To account for the possible violation of this assumption, an ad hoc segmentation of age is usually performed. However, the segmentation can be subjective and the possible state dependence still is not directly captured. 2) The Markov model does not explicitly capture the effect of explanatory variables. Separate Markovian transition probabilities have to be developed for different groups of explanatory variables. 3) The underlying unobserved continuous deterioration process of the infrastructure facility is not reflected in the Markov model. 4) The Markov model assumes a constant inspection period (i.e., bridge inspections are performed at predetermined and fixed time intervals).

Research studies have attempted to overcome the limitations of the Markov-chain model. Among them, duration modeling, also often referred to as survival analysis, has been found to be an appropriate approach to modeling stochastic infrastructure deterioration processes. The duration model has the following advantages: 1) it can explicitly capture the state dependence through the hazard functions (Washington et al., 2011; Cavalline et al., 2015); 2) the impact of right-censored duration observations can be easily accounted for by the duration model (Greene 1997; Hosmer and Lemeshow, 1999); and 3) it can capture the relationship between the observed discrete-state deterioration performance measures and the unobserved underlying deterioration process (Mishalani and Madanat, 2002). Agrawal et al. (2009), using historical NYSDOT bridge inspection data since 1981, found that the Weibull-based duration models were more reliable for calculating the deterioration rates for bridge elements than the Markov-chain models. In fact, it has been observed that the Markovian state transition probabilities can be determined from the probability density function of the state duration, and vice versa (Mauch and Madanat, 2001; Mishalani and Madanat, 2002). Therefore, given its advantages, the duration model was used in this dissertation to capture the stochastic deterioration process of bridge decks.

5.1.2 Duration Model Specification

Detailed explanations of the concepts regarding the duration model and the model specifications can be found in various previous literature resources, such as Kalbfleisch and Prentice (1980), Kiefer (1988), Fleming and Harrington (1991), Mannering (1993), Hensher and Mannering (1994), and Washington et al. (2011). This section only presents the fundamental concepts and basic relationships between different functions.

The survival function is defined as the probability that the duration of the event, *T*, a random variable, is greater than or equal to some specified time, *t*:

$$S(t) = P(T \geq t) \tag{5.1}$$

The cumulative distribution function is defined as the probability that the duration of the event, *T*, a random variable, is less than some specified time, *t*:

$$F(t) = P(T < t) = 1 - S(t) \tag{5.2}$$

Define the conditional probability that the event will end between time *t* and *t*+*dt*, given that the event has not ended up to time *t*, as:

$$C(t,dt) = P(t \le T < t+dt \,|\, T \ge t) = \frac{P(t \le T < t+dt)}{P(T \ge t)}$$

$$P(t \le T < t+dt) = F(t+dt) - F(t),$$

thus, $C(t,dt) = \dfrac{F(t+dt) - F(t)}{S(t)}$ (5.3)

If *dt* is a very short interval, then:

$$h(t) = \lim_{dt \to 0} \frac{C(t,dt)}{dt} = \lim_{dt \to 0} \frac{F(t+dt) - F(t)}{dt \cdot S(t)} = \frac{1}{S(t)} \cdot \lim_{dt \to 0} \frac{F(t+dt) - F(t)}{dt} = \frac{f(t)}{S(t)}$$

where,

$$f(t) = \frac{dF(t)}{dt} \tag{5.4}$$

is the density function corresponding to the cumulative distribution function;

$$h(t) = \frac{f(t)}{S(t)} \tag{5.5}$$

is defined as the hazard rate function (or hazard function), indicating the instantaneous rate, or risk, at which the duration of the event will end.

The integrated hazard function is expressed as:

$$H(t) = \int_0^t h(t)dt \tag{5.6}$$

In fact, the survival function, the cumulative distribution function, the hazard rate function, and the integrated hazard function defined in Eqs. 5.1, 5.2, 5.4, and 5.5, respectively, can be derived from each other if any of one of them is available. Some of their relationships are as follows:

$$\frac{d}{dt}H(t) = h(t) = \frac{f(t)}{S(t)} = \frac{f(t)}{1-F(t)} = \frac{1}{1-F(t)}\frac{dF(t)}{dt} = -\frac{d}{dt}\ln[1-F(t)] \tag{5.7}$$

$\therefore H(t) = -\ln[1 - F(t)] = -\ln S(t)$, $S(t) = e^{-H(t)}$

(5.8)

$$\therefore f(t) = -\frac{d}{dt}S(t) = -\frac{d}{dt}e^{-H(t)} = -e^{-H(t)}\frac{d}{dt}[-H(t)] = h(t) \cdot e^{-H(t)} \quad (5.9)$$

An illustration of the relationship between these hazard-based functions is presented in Figure 5.1. Among them, of particular interest is the shape of the hazard rate function *h*(*t*). Specifically, the first derivative of *h*(*t*) with respect to *t* has significant implications. It captures that effect of state dependence, which, in the Markov-chain model, is assumed to be independent from the duration length. Figure 5.2 illustrates four possible shapes of the hazard rate function *h*(*t*). In the figure, $h_1(t)$, whose hazard is monotonically decreasing with respect to duration, implies that the longer the duration of the event, the less likely the event is going to end; while $h_3(t)$ implies the opposite. The hazard of $h_2(t)$ is changing with the duration, increasing first and then decreasing. The hazard function $h_4(t)$ indicates the state independence (i.e., the hazard rate does not vary with the duration of the event).

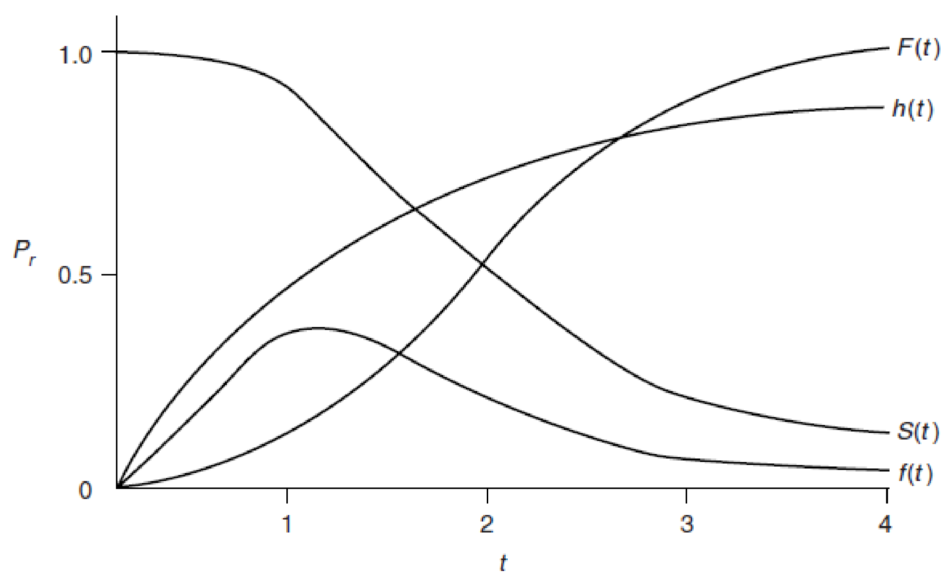


Figure 5.1 Illustration of the Relationships Between the Hazard-Based Functions (Source: Washington et al., 2011)

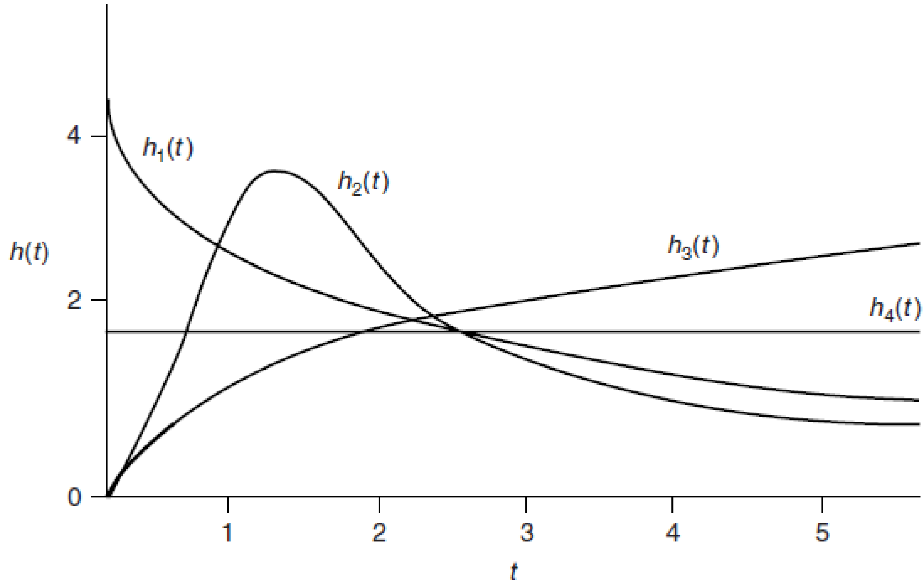


Figure 5.2 Illustration of Four Possible Hazard Rate Function Shapes (Source: Washington et al., 2011)

In addition to their capability of investigating state dependence, duration models are also able to account for the effects of covariates (i.e., explanatory variables). One of the most commonly-used approaches is the proportional hazard approach, which assumes that the hazard rate function with covariates is the product of a baseline hazard function denoted as $h_0(t)$, and the influence of the covariates on the hazard function that typically takes the functional form of $e^{\boldsymbol{\beta}\mathbf{X}}$, where $\mathbf{X}$ is the covariate vector, and $\boldsymbol{\beta}$ is the vector of estimable parameters. Then the hazard function incorporating the effect of covariates can be expressed as:

$$h(t \mid \mathbf{X}) = h_0(t) \cdot e^{\boldsymbol{\beta}\mathbf{X}} \tag{5.10}$$

5.1.3 Comparison of Nonparametric, Semiparametric, and Fully-Parametric Models

The duration models can be categorized as nonparametric models, semiparametric models, and fully parametric models, depending on the assumptions in terms of the distribution of the duration time and the functional form of the influence of the covariates on the hazard function.

As indicated in Washington et al. (2011), choosing one of these three model types can be difficult. Generally, nonparametric or semiparametric models are the preferred choices when the underlying distribution is unknown, while parametric models are more appropriate when the underlying distribution is known or theoretically justified (Lee, 1992).

For the nonparametric approach, the product-limit (PL) method developed by Kaplan and Meier (1958) is the most widely used. The Kaplan-Meier method provides useful estimates of survival probabilities and a graphical presentation of the survival distribution. One limitation of the Kaplan-Meier method is that if more than half of the observations are censored and the largest observation is censored, the PL estimate is undefined beyond the largest observation and the median survival time cannot be estimated (Washington et al., 2011).

For the semiparametric approach, the Cox proportional hazards model developed by Cox (1972) has been widely applied. This model defines the probability of an observation i exiting a duration at time t_i, give that at least one observation exits at time t_i, to be

$$(e^{\boldsymbol{\beta}\mathbf{X}_i})/(\sum_{j\in R_i} e^{\boldsymbol{\beta}\mathbf{X}_j}) \tag{5.11}$$

where R_i denotes the set of observations, and j denotes the observations with durations greater than or equal to t_i. Two limitations of the semiparametric method are: a) the state dependence is difficult to be captured accurately, and b) the efficiency of parameter estimation may suffer when censoring exists.

The fully parametric models assume specific and well-behaved statistical distribution for the hazard rate function. Some of the commonly-used distributions include gamma, exponential, Weibull, log-logistic, and Gompertz.

In this dissertation, considering that some previous studies (e.g. Mishalani and Madanat, 2002; Agrawal et al., 2009) applied fully-parametric models (e.g., Weibull) on bridge deterioration modeling and achieved reasonable results, there is at least some information regarding the distribution of the hazard function. Also, the state dependence is of interest in this dissertation and needs to be accurately tracked. Therefore, this dissertation selected the fully-parametric models as the duration model approach. Different functional forms of the fully parametric models are discussed and tested in the following sections.

5.1.4 Specification, Goodness of Fit, and Heterogeneity of Fully Parametric Models

This section investigates three popular distributions for the fully parametric models: exponential, Weibull, and log-logistic. Table 5.1 presents the density functions, the hazard functions, and the trend of the hazard function in terms of the parameter for exponential, Weibull, and log-logistic distributions, respectively. In the table, $\lambda = e^{-\boldsymbol{\beta}\mathbf{X}}$ and P are the parameters to be estimated from the models.

Table 5.1 Density Function and Hazard Functions for Exponential, Weibull, and Log-logistic Based Duration Models

	Density Function	Hazard Function	Notes
Exponential	$f(t) = \lambda e^{(-\lambda t)}$	$h(t) = \lambda$	Hazard is constant (i.e.. state independence)
Weibull	$f(t) = \lambda P(\lambda t)^{P-1} e^{-(\lambda t)^P}$	$h(t) = (\lambda P)(\lambda t)^{P-1}$	If P>1, hazard is increasing; if P<1, hazard is decreasing; if P=1, hazard is constant (reduces to Exponential)
Log-logistic	$f(t) = \lambda e^{(-\lambda t)}$	$h(t) = \frac{(\lambda P)(\lambda t)^{P-1}}{1+(\lambda t)^P}$	If P≤1, hazard is decreasing; if P>1, hazard increases for t $\in \left(0, \frac{(P-1)^{\frac{1}{P}}}{\lambda}\right)$, and decreases for t $\in \left(\frac{(P-1)^{\frac{1}{P}}}{\lambda}, \infty\right)$

The selection between the exponential and Weibull models is relatively straightforward because the exponential is simply a special case of the Weibull (when P=1). To test if the difference between the exponential and Weibull is significant, a significance test with respect to the Weibull parameter P can be conducted. The t statistic for testing whether P is significantly different from 1 is:

$$t = \frac{\beta_P - 1}{S(\beta_P)} \quad (5.12)$$

where β_P is the parameter estimate of P, and $S(\beta_P)$ is the standard deviation of the parameter estimate.

To compare the goodness-of-fit between the exponential and Weibull models, a likelihood ratio test can be conducted through the log likelihoods at convergence. The X^2 test statistic is:

$$X^2 = -2[LL(\boldsymbol{\beta}_e) - LL(\boldsymbol{\beta}_w)] \quad (5.13)$$

where $LL(\boldsymbol{\beta}_e)$ is the log likelihood at convergence for the exponential distribution, and $LL(\boldsymbol{\beta}_w)$ is the log likelihood at convergence for the Weibull distribution. This X^2 statistic is χ^2 distributed with 1 degree of freedom. Then, a confidence level can be obtained indicating the confidence level that the Weibull model leads to a better fit compared to the exponential model.

The selection between the Weibull and log-logistic models is more difficult than that between Weibull and exponential. Nam and Mannering (2000) suggested a likelihood ratio statistic:

$$X^2 = -2[LL(0) - LL(\boldsymbol{\beta}_c)] \quad (5.14)$$

where $LL(0)$ is the initial log likelihood with all parameters equal to zero, and $LL(\boldsymbol{\beta}_c)$ is the log likelihood at convergence. This X^2 statistic is χ^2 distributed with the degrees of freedom equal to the number of estimated parameters included in the model. The best-fit distribution can be determined by selecting the distribution that provides the highest level of significance for this statistic.

The proportional hazard model assumes that the survival function is homogeneous across observations. However, if some unobserved factors which have not been included in the covariates affect the durations, a major specification error can arise that can lead to erroneous inferences on the shape of the hazard function and inconsistent parameter estimates (Gourieroux et al., 1984; Heckman and Singer, 1984). To deal with the issue of unobserved heterogeneity, a heterogeneity term designed to capture unobserved effects across the population can be introduced. Taking the Weibull distribution with gamma heterogeneity as an example, the modified hazard function becomes:

$$h(t) = \frac{(\lambda P)(\lambda t)^{P-1}}{1+\theta(\lambda t)^{P}} \tag{5.15}$$

To test the heterogeneity, the likelihood ratio statistic is:

$$\mathrm{X}^2 = -2[LL(\boldsymbol{\beta}_w) - LL(\boldsymbol{\beta}_{wh})] \tag{5.16}$$

where $LL(\boldsymbol{\beta}_w)$ is the log likelihood at convergence for the Weibull distribution, and $LL(\boldsymbol{\beta}_{wh})$ is the log likelihood at convergence for the Weibull distribution with gamma heterogeneity. This X^2 statistic is χ^2 distributed with 1 degree of freedom. Then, a confidence level can be obtained indicating the confidence level that heterogeneity is present in the underlying Weibull model (assuming the Weibull specification is correct). Besides, the test of whether θ is significantly different from zero also provides implication of whether the Weibull model and the Weibull model with gamma heterogeneity is significantly different.

5.1.5 Duration Models for the Impact of Overlays on Bridge Deck Deterioration

5.1.5.1 Selection of Dependent and Explanatory Variables

The dependent variable of the duration model should be the duration of an event. In the case of this dissertation, the events are the sojourn of bridge decks in certain condition ratings. Thus, the dependent variable is the duration lengths (in years) of a bridge deck staying in a given NBI condition rating, such as 7, before it drops to a lower condition rating such as 6. Ideally, such durations should exclude the effects of M&R treatments. Given the data accessibility, the duration data for the current analysis excludes the effects of major repair and rehabilitation treatments but may not exclude the effects of minor repairs and routine maintenance.

The available NBI data range is from Year 1992 to Year 2015. Therefore, the duration of a condition state is likely to be right-censored, either because of the end of the inspection period (Year 2015) or because of a major treatment, such as deck rehabilitation and deck replacement, which terminates the current condition state. The duration of a condition state is also likely to be left-censored in terms of those condition states that began before Year 1992. Because the hazard-based model cannot readily handle the left-censored data issue because of the greater complexity added to the likelihood function, the left-censored observations were excluded from the analysis in this dissertation. In the model estimation process, an indicator variable signifying the existence of right censoring was added to the left-hand side of the model along with the dependent variable. The data sources used for the duration models are the same as those mentioned in Section 4.2 of this dissertation. Table 5.2 lists the candidate variables considered for the duration models.

Table 5.2 List of Variables for the Duration Models

Variable	**Description**
Duration	Time in years that the deck maintains in the current condition rating
Status	If the duration is uncensored, Status=1; if right censored, Status=0
Age	Age (in years) of the deck when entering the current condition rating
INT	If the bridge is located on an Interstate highway, INT=1; otherwise, INT=0
NNHS	If the bridge is located on a non-NHS highway, NNHS=1; otherwise, NNHS=0
North	If the bridge is located in the cold region of Indiana (i.e., northern Indiana, North=1; otherwise, North=0)
South	If the bridge is located in the warm region of Indiana (i.e., southern Indiana, South=1; otherwise, South=0)
ADT	Average daily traffic on the bridge
Truck	Percentage of truck traffic on the bridge (in percentage, e.g. if 5%, Truck=5)
Water	If the bridge is located above a waterway, Water=1; otherwise, Water=0
Concrete	If the material type of the bridge is concrete, Concrete=1; otherwise, Concrete=0
WS	If the type of wearing surface is monolithic concrete (no additional wearing surface placed on the bare deck), WS=1; otherwise, WS=0
LMC	If the type of wearing surface is latex-modified concrete, LMC=1; otherwise, LMC=0
ASP	If the type of wearing surface is asphalt, Asp=1; otherwise, Asp=0

The dummy variable for non-Interstate NHS was not included because of the correlation issue. Its effect is captured by INT=0 and NNHS=0 at the same time. Similarly, the dummy variable for the moderate region (central Indiana) was not included either, and its effect is captured by North=0 and South=0 at the same time. The climate variables, such as temperature and number of freeze-thaw cycles, were not included primarily for two reasons: a) the climate impact can be basically captured by the region variables (North and South), and inclusion of other climate variables may cause the issue of correlation; and b) the climate within the state of Indiana is not significantly different, and inclusion of accurate values of the climate variables, such as temperature or freeze-thaw cycles may exaggerate their impact on the duration lengths of certain deck condition ratings.

5.1.5.2 Model Estimation

The statistical analysis was completed using the statistical software package NLOGIT 4.0 developed by Econometric Software, Inc. Separate models were developed for durations in condition state 8, condition state 7, condition state 6, and condition state 5, for wearing surface types of monolithic concrete, LMC, and asphalt, respectively. The durations of condition state 9 were added to the durations of condition state 8 because based on INDOT's typical practice, condition ratings 9 and 8 are not clearly distinguishable clearly and may even record an 8 instead of a 9 for a new bridge deck. Thus, condition ratings 9 and 8 were regarded as the same state in the current analysis. The durations of condition state 4 were not considered because there were few observations with a condition rating of 4 and most of them were right-censored. Hazard-based duration models require a reasonably large percentage of uncensored observations. INDOT typically replaces a deck before its condition drops to 4 or only a few years after it drops to 4.

It should be mentioned that models for the polymeric overlays were not developed in this chapter because the number of observations is too small to build reliable duration models. The analysis with respect to polymeric overlays was carried out only for the deterministic situations in Chapter 3 and Chapter 4, using the simple models provided by

INDOT and limited available information regarding polymeric overlays from the databases. Instead, a new wearing surface type, asphalt, was investigated in this chapter. It could come with a deck overlay treatment -- an asphalt wearing surface is placed on the deck after a deck rehabilitation or repair. But it was used more often on a new bridge deck -- to match the flexible pavements on both sides of the bridge approaches. An asphalt wearing surface on a concrete deck is similar to an AC-over-PCC composite pavement. The duration models in this chapter investigated the protection effects of the asphalt wearing surface to the deck.

Four functional forms of distributions for the fully-parametric hazard functions were estimated and tested for each condition state and wearing surface type combination. Due to space limitations, the test statistics and selection procedures are presented for only one model. For the other models, only the distribution that resulted in the best goodness-of-fit was selected and presented because the test statistics and selection procedures were similar.

The estimation results are presented in the tables and figures in the following sections. The parameters for the hazard rate functions and the survival functions for each condition state and wearing surface type combination were estimated and the corresponding functions were plotted. The durations for a certain wearing surface type across different condition states were compared as well as the durations for a certain condition state across the wearing surface types. The following sections present the model estimation results and interpretations for some of the selected models only. The remaining model estimation results can be found in Appendix F of this dissertation.

5.1.5.3 Demonstration of Selection between Different Distribution Functional Forms

Table 5.3, Table 5.4, and Table 5.5 present the estimation results for the durations in condition 9 and 8 for wearing surface type of monolithic concrete, using Weibull distribution, Weibull distribution with gamma heterogeneity, and log-logistic distribution, respectively, for the hazard functions. For the purpose of concise denotation, durations in condition 9 and 8 for wearing surface type of monolithic concrete is denoted as D8WS.

Table 5.3 Parameter Estimates of the Duration Model with Hazard Function of Weibull Distribution for D8WS

Variable	**Estimated Parameter**	**t-Statistic**	**p-Value**
Constant	2.436	56.39	0.0000
NNHS	0.113	3.39	0.0007
North	-0.141	-4.71	0.0000
South	0.0487	1.60	0.1091
ADT	-0.468e-05	-2.74	0.0061
Truck	-0.0150	-5.26	0.0000
Concrete	0.0893	2.90	0.0037
P	3.076	29.68	
λ	0.0877	72.50	
No. of observations	697		
Log likelihood at convergence	-292.15		

Table 5.4 Parameter Estimates of the Duration Model with Hazard Function of Weibull Distribution with Gamma Heterogeneity for D8WS

Variable	**Estimated Parameter**	**t-Statistic**	**p-Value**
Constant	2.299	38.54	0.0000
NNHS	0.125	3.50	0.0005
North	-0.121	-3.34	0.0008
South	0.0976	2.76	0.0057
ADT	-0.380e-05	-1.98	0.0479
Truck	-0.0140	-4.79	0.0000
Concrete	0.105	3.05	0.0023
P	3.732	13.84	
λ	0.0944	44.54	
θ	0.340	2.68	
No. of observations	697		
Log likelihood at convergence	-283.84		

Table 5.5 Parameter Estimates of the Duration Model with Hazard Function of Log-logistic Distribution for D8WS

Variable	**Estimated Parameter**	**t-Statistic**	**p-Value**
Constant	2.178	39.14	0.0000
NNHS	0.137	3.81	0.0001
North	-0.110	-2.84	0.0045
South	0.124	3.39	0.0007
ADT	-0.294e-05	-1.43	0.1523
Truck	-0.0125	-4.49	0.0000
Concrete	0.0956	2.68	0.0073
P	4.744	25.16	
λ	0.103	71.28	
No. of observations	697		
Log likelihood at convergence	-295.57		

For the comparison between the Weibull and exponential models, the test statistic for whether the distribution parameter *P* of the Weibull model is significantly different from 1 is as given in Eq. 5.12:

$$t = \frac{\beta_P - 1}{S(\beta_P)} = \frac{3.076 - 1}{0.1036} = 20.04$$

This *t*-statistic shows that P is significantly different from 1 and the Weibull model is preferred over the exponential model. Furthermore, a likelihood ratio test can be conducted using the log likelihoods at convergence for the two models. The test statistic is as given in Eq. 5.13:

$$\mathrm{X}^2 = -2[LL(\boldsymbol{\beta}_e) - LL(\boldsymbol{\beta}_w)] = -2 \times [-741.03 - (-292.15)] = 897.76$$

With one degree of freedom, the confidence level is over 99.99%, indicating that the Weibull model provides a better fit than the exponential model.

For the comparison between the Weibull and Weibull with gamma heterogeneity models, as given in Eq. 5.16, the test statistic is:

$$\mathrm{X}^2 = -2[LL(\boldsymbol{\beta}_w) - LL(\boldsymbol{\beta}_{wh})] = -2 \times [-292.15 - (-283.84)] = 16.62$$

With one degree of freedom, this statistic at a confidence level of 99.99%, indicated that heterogeneity was present in the underlying Weibull survival process. In addition, the *t*-statistic of the estimated parameter θ was 2.68, which also signified that the Weibull model with heterogeneity was significantly different from the Weibull model.

For the comparison between the Weibull and log-logistic models and the Weibull with heterogeneity and log-logistic models, the likelihood ratio statistic as provided in Eq. 5.14 was used. The Weibull with heterogeneity models provided the highest level of significance.

Therefore, through comparison, the final distribution functional form for the hazard function for D8WS was selected to be the Weibull distribution with gamma heterogeneity, as presented in Table 5.4. The model comparison and selection process was similar in terms of other condition state and wearing surface type combinations.

5.1.5.4 Model Estimation Results and Interpretations

Twelve separate models were estimated for D8WS, D7WS, D6WS, D5WS, D8LMC, D7LMC, D6LMC, D5LMC, D8ASP, D7ASP, D6ASP, and D5ASP. As defined in Section 5.1.5.3, the notation D*x* refers to the duration that the deck stays in condition rating *x*; WS, LMC, and ASP refer to the types of wearing surface: monolithic concrete, latex-modified concrete, and asphalt, respectively. Considering space limitations, the estimation results and interpretations of the parameters for only one typical model for D8WS is presented and discussed in this section. The results for the remaining models can be found in Appendix F of this dissertation.

Table 5.6 presents the model estimation results for D8WS. It should be mentioned that NLOGIT actually estimates the parameter vector $-\boldsymbol{\beta}$ instead of just $\boldsymbol{\beta}$ so that the effect of the covariates on the hazard is $e^{-\boldsymbol{\beta}\mathbf{X}}$, which means that the negative parameter in NLOGIT increased the hazard and thus decreased the duration, and thus produced the effect on duration instead of on the hazard.

Table 5.6 Model Estimation Results for D8WS (Weibull with Gamma Heterogeneity)

Variable	**Estimated Parameter**	**t-Statistic**	**p-Value**
Constant	2.299	38.54	0.0000
NNHS	0.125	3.50	0.0005
North	-0.121	-3.34	0.0008
South	0.0976	2.76	0.0057
ADT	-0.380e-05	-1.98	0.0479
Truck	-0.0140	-4.79	0.0000
Concrete	0.105	3.05	0.0023
P	3.732	13.84	
λ	0.0944	44.54	
θ	0.340	2.68	
No. of observations	697		
Log likelihood at convergence	-283.84		

The signs of the estimated parameters in Table 5.6 are mostly intuitive. In this model, for non-NHS bridges the duration that the deck stayed in condition 9 and 8 tended to be longer, most likely because the low traffic volume and small amount of truck traffic on non-NHS highways contributed to the bridge deck remaining in a good condition state for a longer time. The indicator variables for Interstate bridges and non-Interstate-NHS bridges were not found to be statistically significant in this model. Thus, the individual effects of Interstate and non-Interstate NHS were not clear in this model, although their combined effect was to decrease the duration.

Bridges located in the cold region were found to have shorter durations in deck condition 9 and 8, whereas bridges in the warm region were found to have longer durations in those condition states. This result is intuitive because bridges in the cold region tend to suffer from more severe winter climate conditions. For example, more frequent freeze-thaw cycles would accelerate the cracking of the concrete deck and the use of deicing chemicals in winter would cause faster corrosion to the reinforced steel bars in the concrete decks. In contrast, bridges in the warm region tend to experience milder climate conditions. Because the indicator variables for both the cold and warm regions were statistically significant in this model, the effect of the moderate region was easily inferred in that the coefficient for the moderate region can be regarded as 0 (when both North=0 and South=0), and its effect on the duration lies between the effect of the cold region and the effect of the warm region.

The ADT and the proportion of truck traffic going through the bridges were found to have negative impacts on the durations of the deck condition. Higher ADTs and higher truck percentages would cause shorter durations in condition 9 and 8. These findings matched the expectation that heavier traffic would accelerate the deterioration of bridge decks.

The results also indicated that if the material type of the main bridge structure was concrete (including both reinforced concrete and prestressed concrete), the duration that the deck stayed in condition 9 and 8 was longer, as opposed to when the main structure material was steel. The exact reason behind this is not quite clear. One possible reason could be that decks on concrete bridges suffer from less vibration because steel bridges tend to have greater displacements in their spans compared with concrete bridges. Moreover, concrete bridges tend to have a longer service life than steel bridges because concrete bridges are less vulnerable to chemical damage and do not suffer from fatigue to the extent that steel bridges do. Thus, the longer service life of the main structure of the concrete bridge may be helping extend its deck's service life.

Several other variables were found not to be statistically significant in this particular model but were found statistically significant in other models, as presented in Appendix F. It was generally found that the higher the age when the deck entered condition states 7, 6, or 5, the shorter the duration that condition state would last. Also, in most cases, bridges on the Interstate highways had shorter durations in a condition state, possibly due to the high volume of traffic and larger proportion of heavy vehicles. Lastly, it was found that if the service under the bridge was a waterway, the duration that deck stayed in a condition state was shorter. This is perhaps because the higher humidity of the waterway environment would cause faster deterioration of the steel reinforcement in the decks.

The signs of the variable parameters in the twelve estimated models were mostly consistent. However, it is interesting to note that for a few cases, the signs of the parameters were contrary to expectations. For example, the sign of the Interstate indicator was positive in the model for D5LMC, and the sign of Age was positive in D5ASP, which possibly were caused by the underlying unobserved heterogeneity in the observations. The random parameter technique is an appropriate tool to account for the unobserved heterogeneity issue. It is likely that for some variables, such as the Interstate indicator and the Age variable, their corresponding parameters could be found to be statistically significant random parameters. For example, although there is greater traffic volume and a higher percentage of heavy vehicle traffic on the Interstates, the design standards for the Interstate bridges are also higher, which is likely to maintain the bridge in a condition state for a longer duration. For the positive sign of the Age variable, an interpretation could be that the higher a deck's age when it enters a condition may indicate a natural slower deterioration process for that bridge, either due to milder surrounding environments or its high design and construction standards. However, the random parameter models were not adopted in this dissertation, not due to the technical difficulty, but because of the difficulty in the interpretations and applications of the results in the subsequent optimization analysis. Therefore, given that the parameter signs were intuitive and consistent for most models, this dissertation chose the traditional duration models without taking into account random parameters.

Figure 5.3 and Figure 5.4 graphically illustrate the estimated survival function and hazard function for the duration model for D8WS (i.e., duration in deck condition 9 and 8 with monolithic concrete wearing surface). As discussed above, the best model fit for D8WS was the Weibull distribution with gamma heterogeneity. The graphical illustrations of the survival functions and hazard functions of the models for other cases are presented in the Appendix F of this dissertation.

The survival function is always monotonically decreasing in terms of all distribution functional forms. For the hazard fucntions, different distributions would result in different shapes. The hazard function for the Weibull model is monotically decreasing or increasing (or constant for the exponential model, a special case of Weibull model when P=1). For the Weibull model with gamma heterogeneity, its hazard function has an inflection point, which can be calculated as:

given $h_{WH}(t) = \frac{(\lambda P)(\lambda t)^{P-1}}{1+\theta(\lambda t)^P}$

then $h'_{WH}(t) = \frac{(\lambda P)(P-1)t(\lambda t)^{P-2}[1+\theta(\lambda t)^P] - \theta P^2(\lambda t)^{2P-1}}{[1+\theta(\lambda t)^P]^2}$

for $h'_{WH}(t) = 0$

then the inflection point is $t_{WH} = \left(\frac{P-1}{\theta}\right)^{\frac{1}{P}} / \lambda$ (5.17)

Similarly, for the log-logistic model,

given $h_{LL}(t) = \frac{(\lambda P)(\lambda t)^{P-1}}{1+(\lambda t)^P}$

then $h'_{LL}(t) = \frac{(\lambda P)(P-1)t(\lambda t)^{P-2}[1+(\lambda t)^P] - P^2(\lambda t)^{2P-1}}{[1+(\lambda t)^P]^2}$

for $h'_{LL}(t) = 0$

then the inflection point is $t_{LL} = \frac{(P-1)^{\frac{1}{P}}}{\lambda}$ (5.18)

For the case of D8WS, the estimated $P = 3.732, \lambda = 0.0944, \theta = 0.340$. Thus, the inflection point $t_{WH} = \left(\frac{3.732-1}{0.340}\right)^{\frac{1}{3.732}} / 0.0944 = 18.5$, as marked in Figure 5.4.

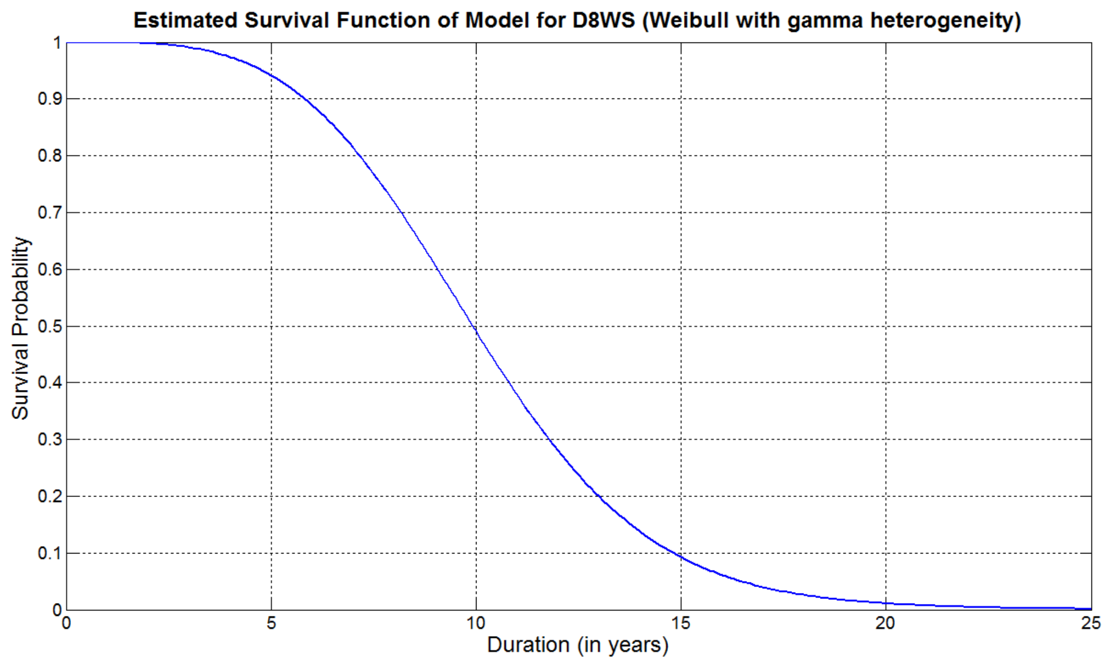


Figure 5.3 Estimated Survival Function of Model for D8WS (Weibull Distribution with Gamma Heterogeneity)

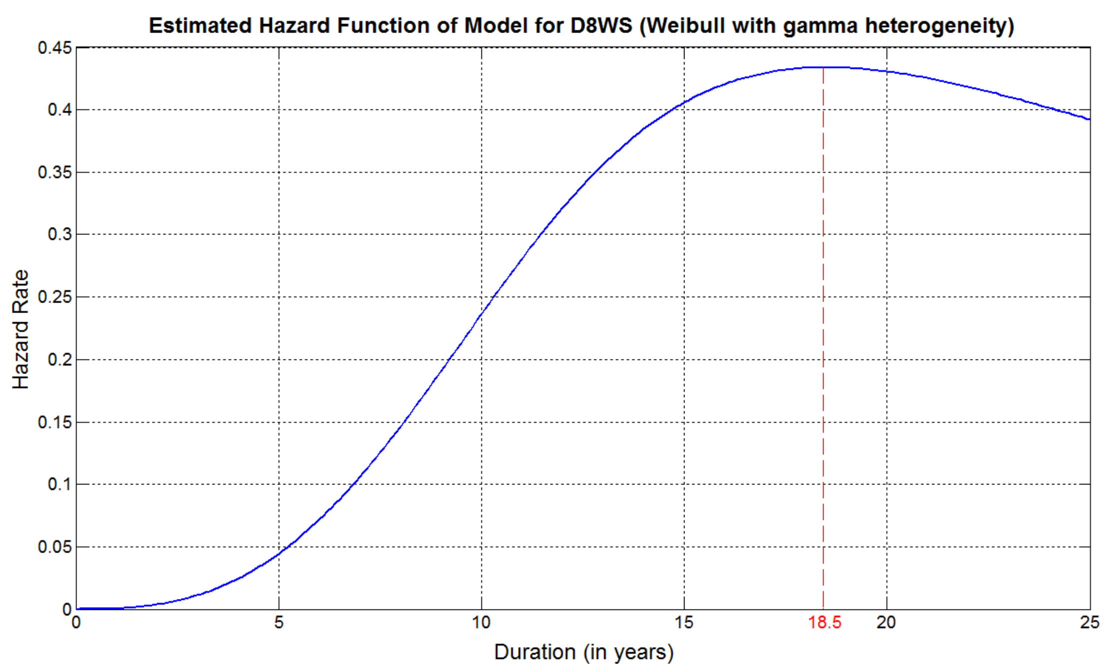


Figure 5.4 Estimated Hazard Function of Model for D8WS (Weibull Distribution with Gamma Heterogeneity)

As indicated in Figure 5.3, there was approximately 95% probability that condition 8 would survive for five years, approximately 50% probability for 10 years, and approximately only 10% probability for 15 years. It can be inferred that, on average, a new deck of monolithic concrete surface (no additional wearing surface) can stay in the condition rating 9 and 8 for approximately 10 years. The hazard rate function in Figure 5.4 indicates that the hazard continued to increase for most of the duration, except for a short period after approximately 18.5 years, although the survival probability was extremely low.

The duration models also were capable of capturing the effects of the stratifications (different levels) of the explanatory variables. Again, taking the model for D8WS as an example, Figure 5.5, Figure 5.6, and Figure 5.7 illustrate the impacts of the Indiana climate regions, the levels of average daily traffic on the bridge, and the levels of truck traffic percentages on the survival probabilities for the duration in deck condition 9 and 8.

From Figure 5.5, it can be seen that the climate regions had significant impacts on the duration survival probabilities. For example, for the southern regions, there was about 65% likelihood that condition 9 and 8 would continue for 10 years, whereas for the central and northern regions, the likelihood dropped to approximately 50% and 40%, respectively. Based on Figure 5.6, it appears that the impact of traffic volume was not as significant as the climate region. ADT = 2000, 20000, 50000, and 80000 were carried out as examples, and it was found that the survival probabilities decreased as the levels of ADT increased. Figure 5.7 indicated the impact of truck traffic on the duration. Truck traffic proportion = 5%, 10%, 15%, and 20% were selected as examples. The survival probabilities for particular durations were as much as 30%. It should be noted that the inferences made in this paragraph are based on one particular model only (D8WS). The inferences may change in terms of other model results.

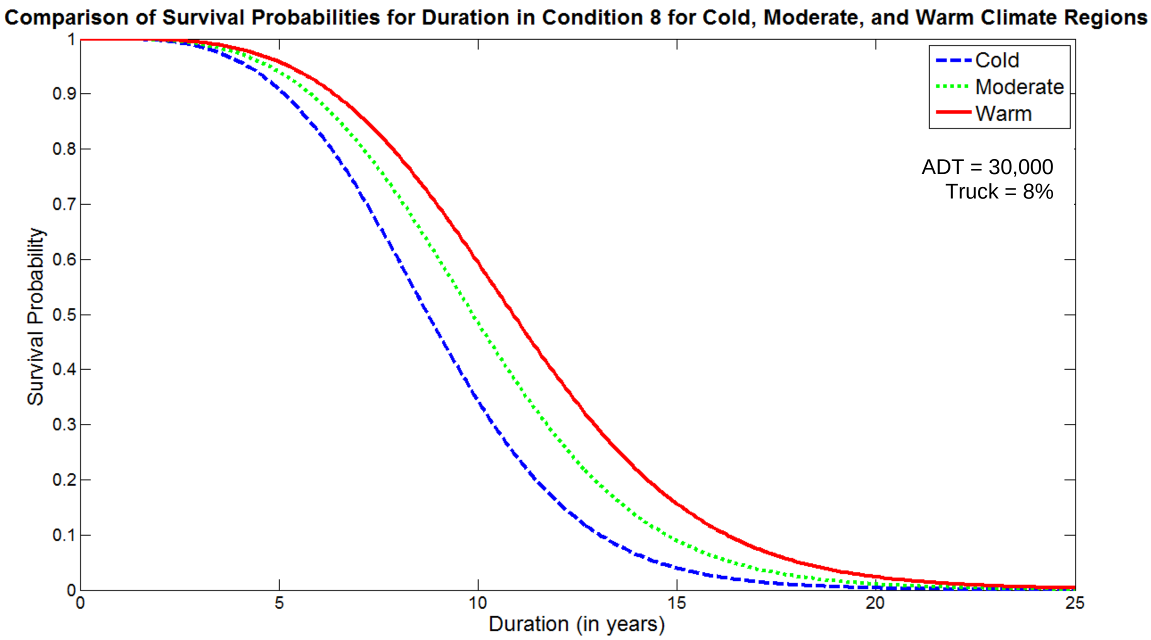


Figure 5.5 Comparison of Survival Probabilities for Duration in Deck Condition 8 for Cold, Moderate, and Warm Climate Regions

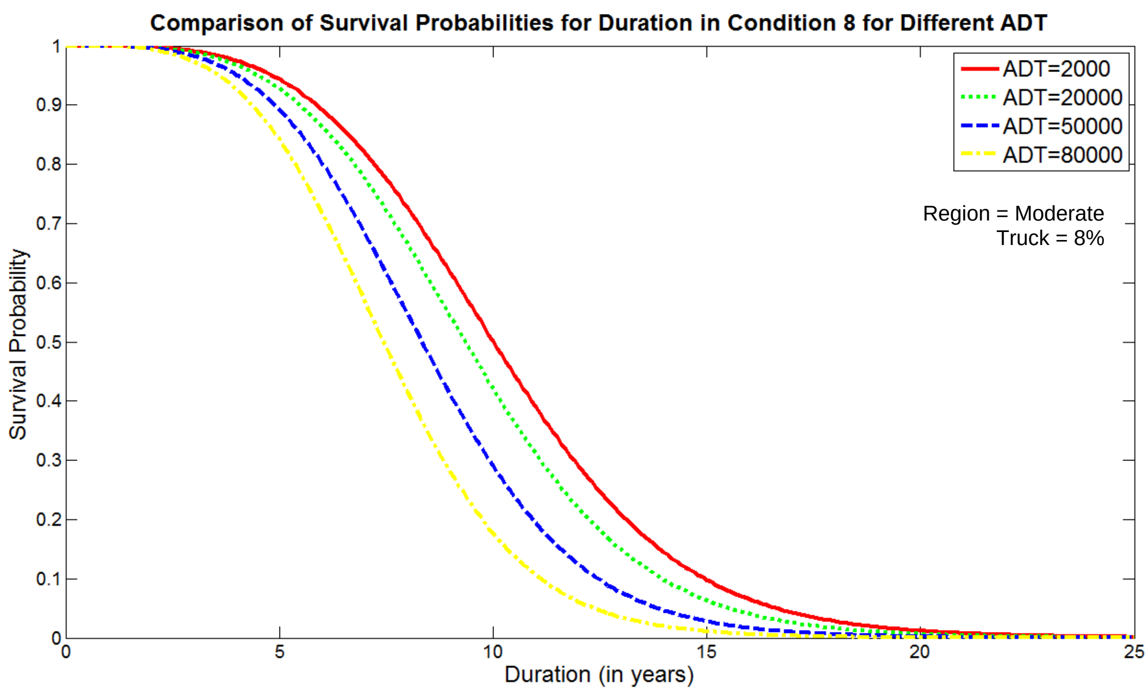


Figure 5.6 Comparison of Survival Probabilities for Duration in Deck Condition 8 for Different Levels of Average Daily Traffic

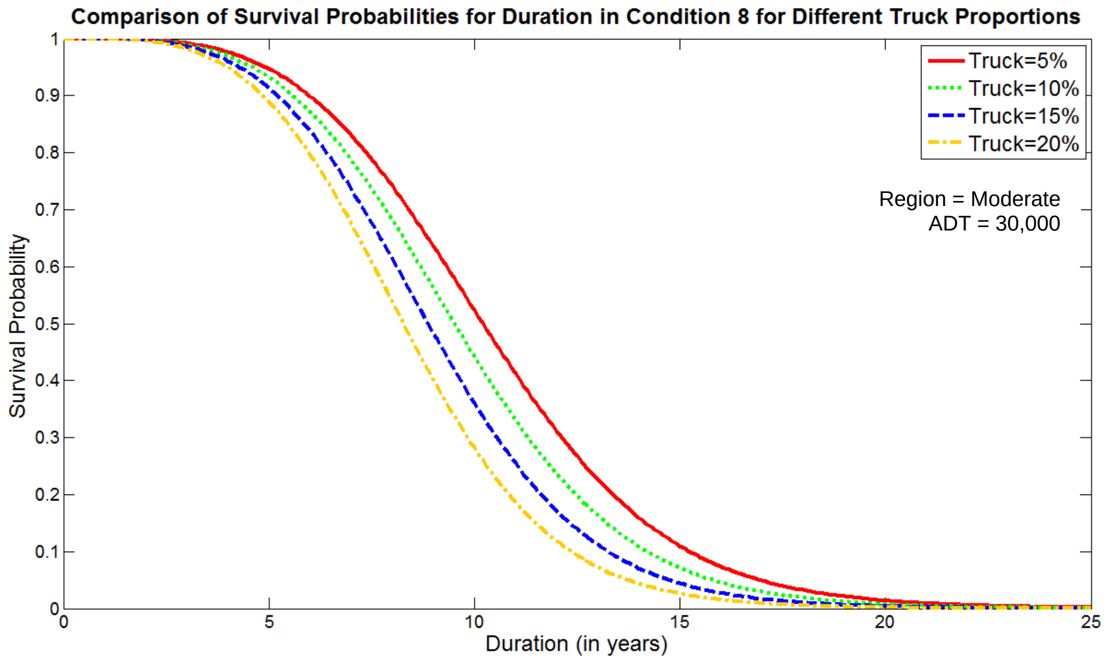


Figure 5.7 Comparison of Survival Probabilities for Duration in Deck Condition 8 for Different Levels of Truck Traffic Percentages

Because different duration models were developed for three types of wearing surface, the impacts of different wearing surface types on the durations were investigated. Monolithic concrete (WS) is concurrently placed with the structural deck, and it actually refers to the surface of a newly constructed or a replaced deck, without additional layers of wearing surfaces. The other two wearing surface types are latex-modified concrete (LMC) and asphalt (ASP). Figure 5.8, Figure 5.9, Figure 5.10, and Figure 5.11 graphically present the survival functions for the durations in deck conditions 8, 7, 6, and 5, respectively, under different wearing surface types. Different hazard distribution functional forms were used (Weibull, Weibull with gamma heterogeneity, and log-logistic). Therefore, the shapes of the survival functions in these figures vary significantly.

It should be noted that the LMC is not placed on a new deck but rather is commonly used as an overlay. Therefore, the durations under LMC were regarded as the post-treatment durations rather than comparing them with the monolithic concrete in the same context. With regard to asphalt, it is placed to match the flexible pavements on bridge approaches. It can be placed on a new deck or used as an overlay. Sometimes the asphalt is replaced by other wearing surface types, such as LMC, after a deck overlay.

From Figure 5.8, it can be seen that for the first ten years, the survival probabilities for the monolithic concrete and the asphalt were similar, whereas after ten years, the asphalt was more likely to maintain the deck in condition 8 for a longer time. This may indicate a protection effect of the asphalt wearing surface to the deck. For the LMC, the overall duration was much shorter when compared to the other two wearing surfaces. As mentioned above, the duration of LMC should be regarded as a post-overlay effect. Also, the observations of decks with LMC under condition 9 and 8 were rare because decks typically would not need an overlay when they are still in a good condition. Therefore, the implication for the LMC curve could be that, if an LMC overlay is implemented at a deck condition of 8 (or at 7 and improves to 8), the duration of condition 8 after the LMC overlay was on average approximately 6 years (based on the LMC curve).

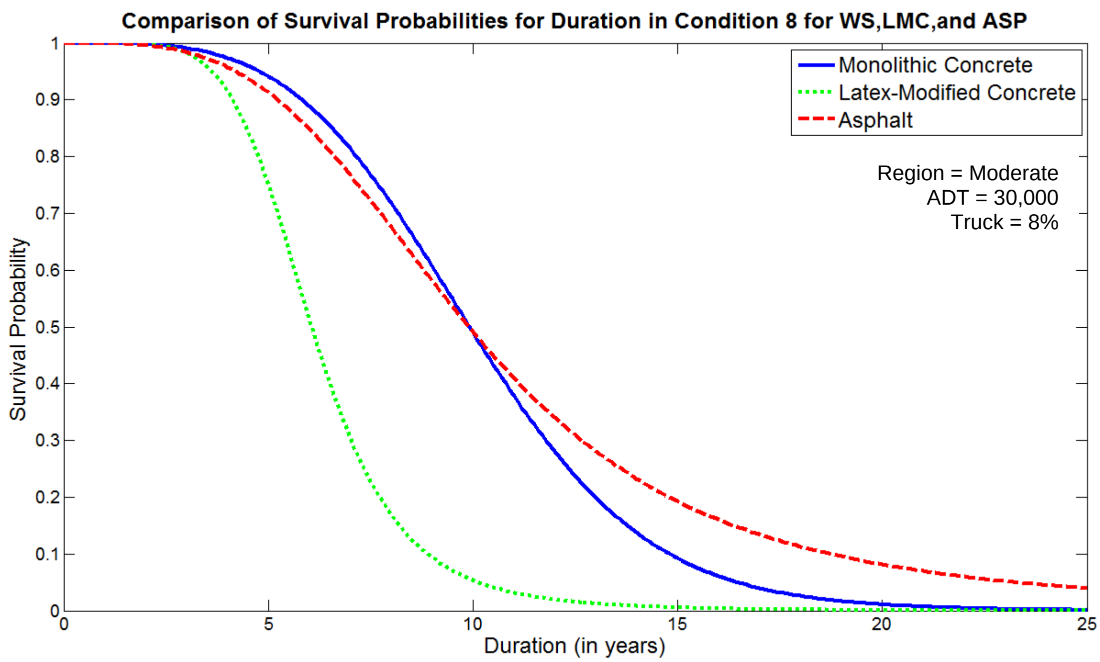


Figure 5.8 Comparison of Survival Probabilities for Duration in Deck Condition 8 for Different Wearing Surface Types

Figure 5.9 shows that within approximately the first nine years, the survival probabilities of the LMC and the asphalt were both higher than that of the monolithic concrete. After the first ten years, the survival probability of the LMC became lower than the monolithic concrete, whereas that of the asphalt still remained higher than the monolithic concrete. This may indicate an effective protection function of the LMC for the first nine or ten years in condition 7, and a protection effect of the asphalt wearing surface throughout the duration in condition 7. Figure 5.10 illustrates three extremely close survival functions, indicating that the monolithic concrete, LMC, and asphalt wearing surfaces had similar effects with regard to condition 6. Figure 5.11 indicates information similar to Figure 5.8. However, it should be noted that because the decks were mostly replaced at condition 4 or 5, the observations for durations in condition 5 had a large proportion of censored data, which was likely a result of less accurate model estimations and shorter average durations in condition 5 compared to other condition states.

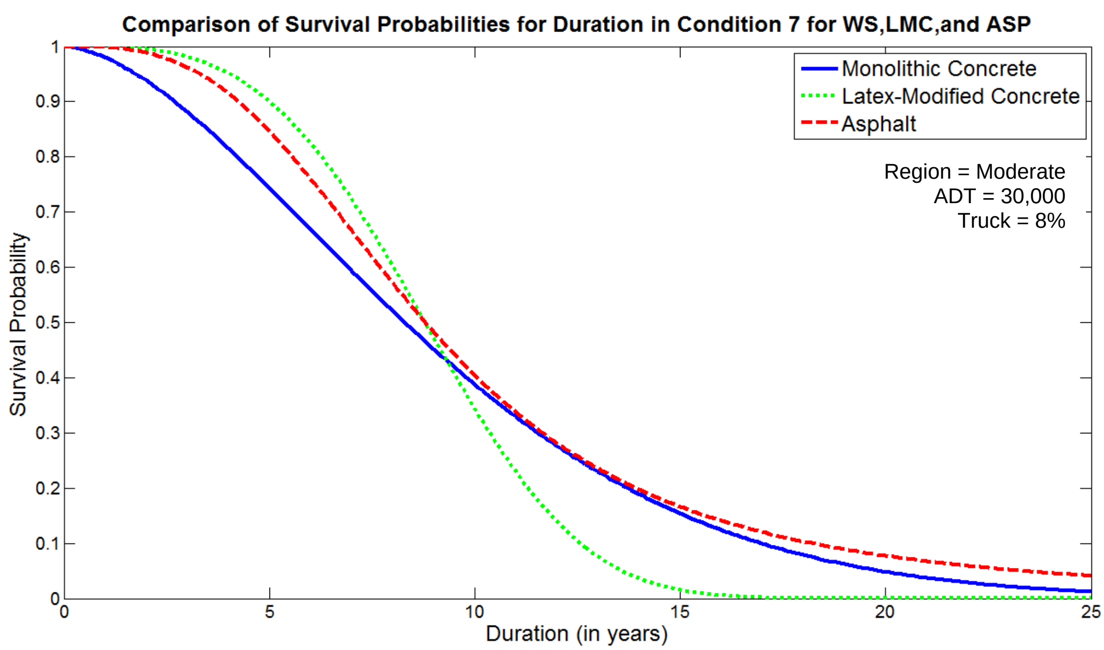


Figure 5.9 Comparison of Survival Probabilities for Duration in Deck Condition 7 for Different Wearing Surface Types

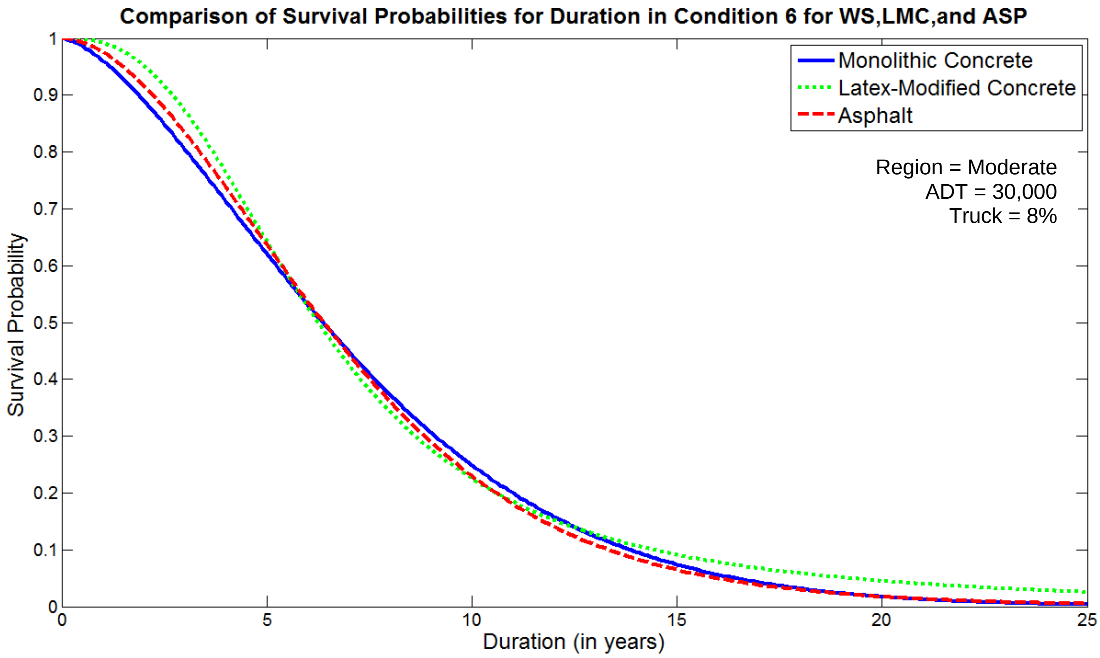


Figure 5.10 Comparison of Survival Probabilities for Duration in Deck Condition 6 for Different Wearing Surface Types

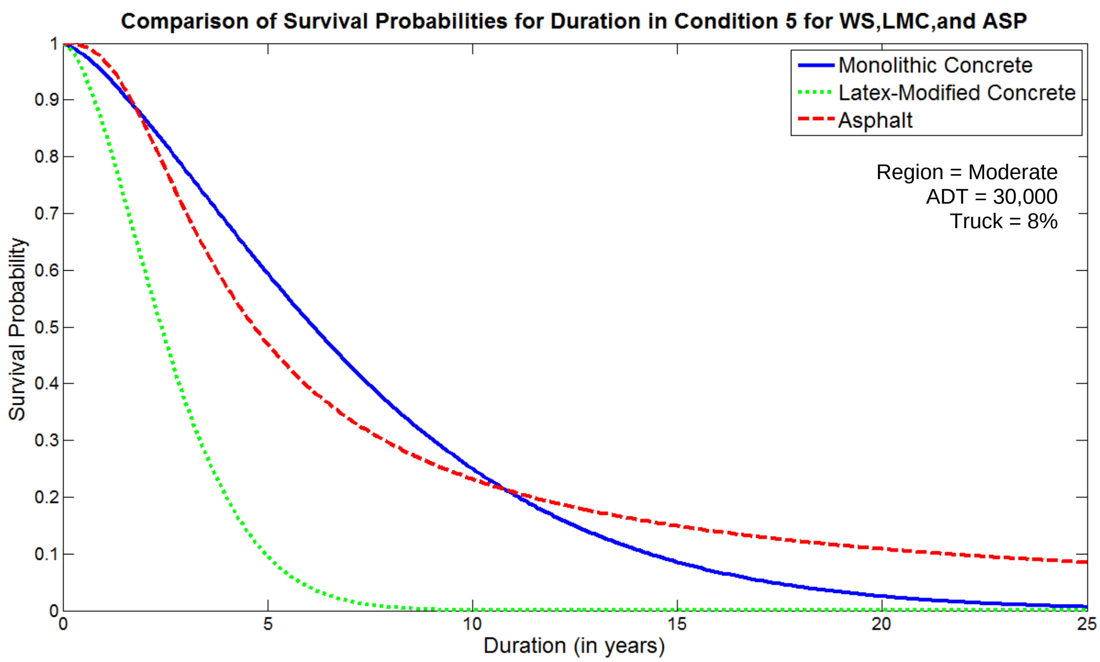


Figure 5.11 Comparison of Survival Probabilities for Duration in Deck Condition 5 for Different Wearing Surface Types

Table 5.7 summarizes the accurate values of the estimated durations corresponding to different survival probabilities (95%, 75%, 50%, and 25%), based on the estimated survival functions. As already indicated by the previous figures, the asphalt wearing surface may have had some positive impacts on extending the duration in deck conditions, although the magnitude of these impacts did not seem to be statistically significant. Also, the durations in certain conditions after LMC overlays were found to be typically shorter than those before the overlays (under monolithic concrete). This intuitively makes sense because the overlay would only replace the surface of the deck, but the bottom side of the deck would continue to deteriorate from the condition before the overlay.

Table 5.7 Summary of Survival Probabilities of Durations for Various Models

Model	**Survival Probabilities with respect to Duration (Years)**			
	95%	**75%**	**50%**	**25%**
D8WS	4.79	7.69	9.91	12.34
D7WS	1.76	4.92	8.31	12.55
D6WS	1.18	3.61	6.37	9.97
D5WS	0.97	3.29	6.13	10.02
D8LMC	3.61	4.99	6.05	7.33
D7LMC	4.04	6.76	8.79	10.80
D6LMC	2.04	4.11	6.25	9.50
D5LMC	0.50	1.41	2.40	3.65
D8ASP	4.22	7.21	9.91	13.64
D7ASP	3.32	6.12	8.80	12.67
D6ASP	1.51	3.89	6.41	9.68
D5ASP	1.24	2.69	4.67	9.33

5.2 Uncertainties of Costs, Traffic, and Others

Section 5.1 discussed the uncertainties in terms of deck deterioration. The stochastic deterioration process would result in uncertain durations of different condition states that lead to uncertain time for deck overlays and deck replacement, and hence the uncertain life-cycle agency costs and user costs. Although such a stochastic deterioration process is a significant factor that influences the life-cycle costs, there are various other sources of uncertainties, such as uncertain project unit costs, uncertain project duration, and uncertain traffic volume and traffic growth. The following subsections discuss the specifics of these uncertainties and their impacts.

5.2.1 Uncertainties of Agency and User Costs

5.2.1.1 Uncertainties of Agency Costs

Generally, the uncertainties of agency costs come from the uncertain material costs, labor costs, and project durations. The unit prices of construction materials vary with time, which can either increase or decrease, depending on the overall economic environment. The prices of materials may also vary with locations. Similarly, the unit cost of labor can also vary with time and location. Labor costs typically keep increasing as the economy grows. Different cities, counties, and states may have different standards for labor costs. Project durations can be affected by weather condition, techniques of the contractors, and other unforeseen factors, such as work site accidents, which can extend the planned contract durations.

Specifically, in this dissertation, the LMC deck overlay costs varied a lot across different contracts, based on the databases used for this study mentioned in Section 3.1. Figure 5.12 presents a histogram showing the variation of the unit cost (total contract cost divided by deck area) of LMC overlays, based on the contract cost data in the SPMS database. As was mentioned in Section 3.5.1.1, the sample mean of the LMC overlay unit cost was calculated to be \$62.81/ft^2 in 2010 constant dollars, and the sample standard deviation was \$44.47/ft^2, which is quite large, given the sample mean.

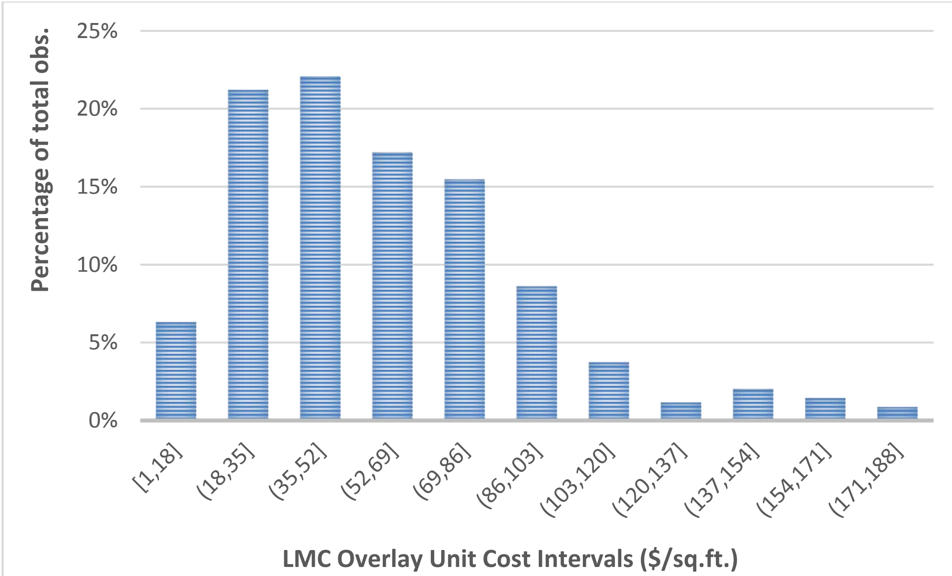


Figure 5.12 Histogram of LMC Overlay Unit Cost ($/Sq.Ft.)

The variation of the unit LMC overlay cost could be the result of various factors:

a) Project scale: the LMC overlay contract typically involves some other work types associated with the overlay, such as hydro-demolition 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. Different overlay projects may have different amounts of associated work, and the cost of this work may not be related to the deck area. Besides, the project scale will also result in the effect of scale economies, which is common in highway construction projects (Fricker et al., 2016). For deck overlays, larger deck areas and hence larger overlays would typically have lower unit contract costs. The impact of project scale was basically captured by the model defined in Eq. 3.25 and Table 3.5.

b) Project duration -- different maintenance of traffic (MoT) schemes can affect the project duration. For example, for bridges with low traffic volume, the bridge can be fully closed without significantly disturbing the traffic. Under the full closure MoT, the overlay can be completed within a relatively shorter time because the workers do not need to consider the traffic. On the other hand, for bridges with higher traffic volumes, partial lane closure schemes may be adopted, and such MoTs would typically result in a longer project duration, which would result in higher labor and equipment costs. In addition, different amounts of associated work as mentioned in a) also can affect project duration.

c) Pre-treatment deck condition: as indicated in a), the LMC overlay typically requires preparation work such as patching and demolition. If the surface condition before the LMC overlay is poor, more preparation work will be needed and thus a greater cost is incurred. The impact of the pre-treatment condition was also captured by the model defined in Eq. 3.5 and Table 3.5.

d) Other factors: the variations in material and labor coss with respect to time and location would surely influence the unit cost of the overlay. However, because such variations could not be obtained from the available databases, the impact of these factors were not explicitly captured in this dissertation.

Table 5.8 supplements the 95% confidence intervals of the estimated parameters, on the basis of Table 3.5. The lower 95% and upper 95% limits would indicate the ranges of the marginal effects of the respective explanatory variables.

Table 5.8 Confidence Intervals of the Estimated Parameters of the Model for LMC Overlay Unit Cost

Variable	**Coefficient**	**Std. Err.**	**Lower 95%**	**Upper 95%**
Intercept	9.4748	0.5138	8.4643	10.4853
PreDeck	-0.0897	0.0417	-0.172	-0.00767
Ln (DeckArea)	-0.5634	0.0484	-0.659	-0.468

For deck replacement, the unit cost also can vary significantly. Similar to LMC overlays, scale economies can play an important role. Deck replacement contracts can also involve other associated work. The MoT scheme may not be a factor in the variation because deck replacements typically require a full closure of the bridge. Pre-treatment condition may not have significant impacts because full deck replacement would replace the whole deck regardless of its condition before the replacement. Figure 5.13 presents a histogram showing the variation of the unit cost (total contract cost divided by deck area) of the deck replacement, based on the SPMS database. As was mentioned in Section 3.5.1.3, the sample mean of the deck replacement unit cost was calculated to be $76.22/ft^2 in 2010 constant dollars, and the standard deviation was $50.10/ft^2.

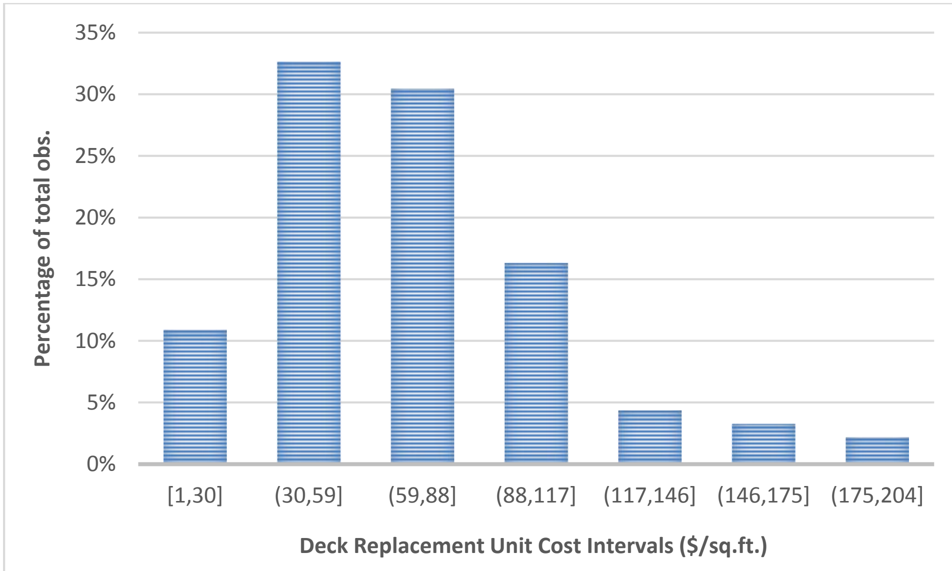


Figure 5.13 Histogram of Deck Replacement Unit Cost ($/Sq.Ft.)

The costs for minor deck repairs and routine maintenance, despite their relative magnitude, are also likely to have uncertainties and variations. Because some repair treatments are conducted only when needed rather than regularly or periodically, the time when they are incurred and the cost amount could have randomness. For example, when some unexpected damages occur, some repair work such as rail repairs, deck patching, or joint repairs, may need to be implemented. In addition, like other M&R treatments, the unit price of materials and labor could vary with time and location. Figure 5.14 and Figure 5.15 present two histograms showing the variation of the unit cost for partial-depth and full-depth deck patching, respectively. The cost information was extracted from the Site Manager database. As was mentioned in Section 3.5.1.3, based on limited available observations, the sample mean of the partial-depth deck patching unit cost was calculated to be $30.41/ft^2 in 2010 constant dollars, and the standard deviation was

\$18.20/ft^2. For the full-depth deck patching, the sample mean was \$39.33/ft^2 in 2010 constant dollars, and the standard deviation was \$17.50/ft^2.

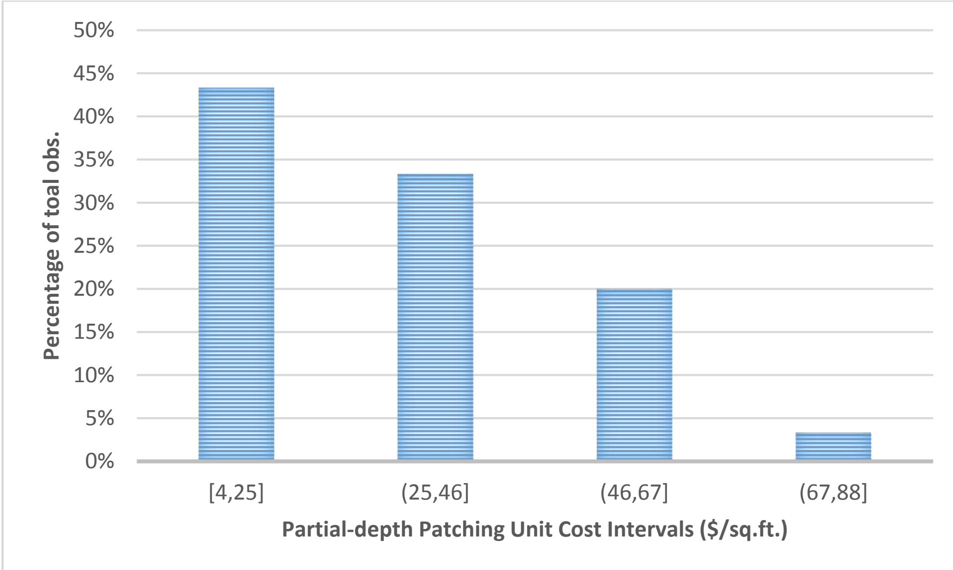


Figure 5.14 Histogram of Partial-Depth Deck Patching Unit Cost (\$/Sq.Ft.)

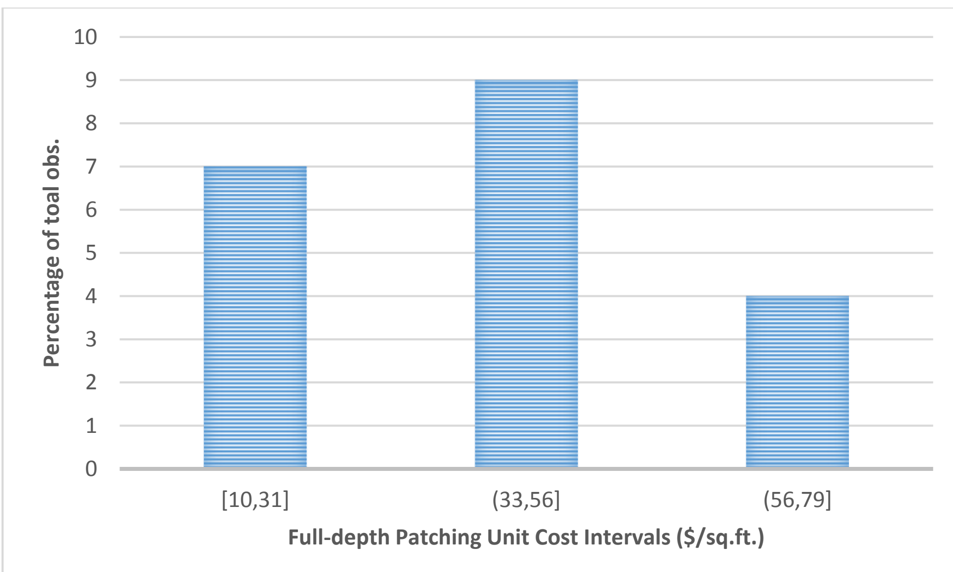


Figure 5.15 Histogram of Full-Depth Deck Patching Unit Cost (\$/Sq.Ft.)

5.2.1.2 Uncertainties of User Costs

The uncertainties associated with user costs can be greater than the uncertainties associated with agency costs. The largest source of uncertainty, plausibly, is the "unit user cost," such as the value of travel time of each road user and the operating cost of each vehicle. Unlike the agency costs, which are the actual expenses spent on materials, equipment, and labor, the user costs are essentially intangible. Therefore, there are several assumptions that need to be made in the estimation of user costs.

Specifically, in terms of the travel time costs due to work zone delay, the factors that may cause uncertainties include:

a) Work zone duration: as discussed in the previous section for agency costs, the durations can be affected by weather condition, scheme for the maintenance of traffic (MoT), additional associated work, etc. Longer work zone durations would affect a larger number of road users and hence incur more travel time costs.

b) Value of travel time: as indicated in Sinha and Labi (2007), the values of travel time of different road users can be significantly different, depending on a number of factors, such as trip purpose, vehicle class, traveler income, and trip status (on-the-clock and off-the-clock). Because it is impossible to acquire the characteristics of each traveler, assumptions and estimations had to be made for the analysis. Even the value of the travel time itself is an estimated amount, and not a directly observed amount.

c) Traffic volume, vehicle class, and vehicle occupancy: the number and class distribution of vehicles that cross a bridge. These attributes change with time and therefore cannot be predicted accurately. Also, the number of passengers in each vehicle is unknown. These uncertainties associated with vehicular traffic lead to uncertainties in the estimated total travel time costs.

d) Detour length and travel speed: for the detour MoT scheme, vehicles may choose different detour routes and may have different travel speeds. Thus, their additional travel time caused by the work zone is not known with absolute certainty.

e) Work zone accidents: although safety cost was not considered a part of the user cost in the current analysis, the possible accidents that occur at work zones can cause lane blockages, and thus significant increases, in travel time delay costs.

Similar to the travel time cost, the VOC due to surface roughness is uncertain due to variabilities in the "unit user cost" (i.e., VOC of each user) and the number of users. Sinha and Labi (2007) indicated that the VOC could be influenced by a number of factors, such as vehicle type, fuel type, and travel speed. As mentioned previously, because it is difficult to obtain the characteristics of each vehicle on the road, assumptions need to be made to estimate the VOC. Also, the surface roughness of the deck depends on the deterioration of the deck and wearing surface, which is a stochastic process. Therefore, the uncertain surface roughness development can bring about additional uncertainties to the VOC.

5.2.2 Uncertainties of Traffic

Traffic volume is a significant factor that directly impacts user costs. Traffic can also indirectly affect agency costs because larger traffic volumes, particularly heavy traffic, generally accelerates the deck deterioration. Hence, more repair and rehabilitation work may be needed, deck service life is shortened, and the life-cycle agency cost is increased. For this reason, the inherent uncertainties in traffic volume, vehicle class distribution, and traffic growth eventually translate into uncertainties in both agency costs and user costs.

Figure 5.16 and Figure 5.17 present the traffic (AADT) growth information for the state of Indiana from year 2005 through year 2015. The data were collected from the INDOT website for traffic statistics (INDOT, 2015). In Figure 5.16, the AADT in 2005 was used as a base and its index was set to 1.00. The traffic index for other years (e.g., year *t*) was simply the ratio of the AADT in year *t* to the AADT in year 2005. In Figure 5.17, the vertical axis refers to the annual AADT growth rate. The year on the horizontal axis actually refers to that year compared with the previous year. For example, the negative growth in year 2008 indicated a decrease in traffic in 2008 compared with that in 2007. From these two figures, it can be seen that the traffic in Indiana has gradually recovered to its original level before 2007 since a significant decrease in traffic volume due to the well-known economic crisis that seriously hit the U.S. in 2008. During the most recent two years, 2014 and 2015, particularly, all the highway functional classes experienced positive traffic growth rates. Overall, the traffic on the urban interstates was least impacted by the economic crisis and basically maintained a positive growth thereafter.

These two figures provide convincing proof that not only is the absolute traffic growth rate unpredictable but also the overall traffic growth trend may be interrupted by some unforeseen economic recessions or business cycles. Therefore, within the life cycle of a bridge, which could be as long as a hundred years, significant uncertainties exist in terms of the traffic volume it carries over its life cycle.

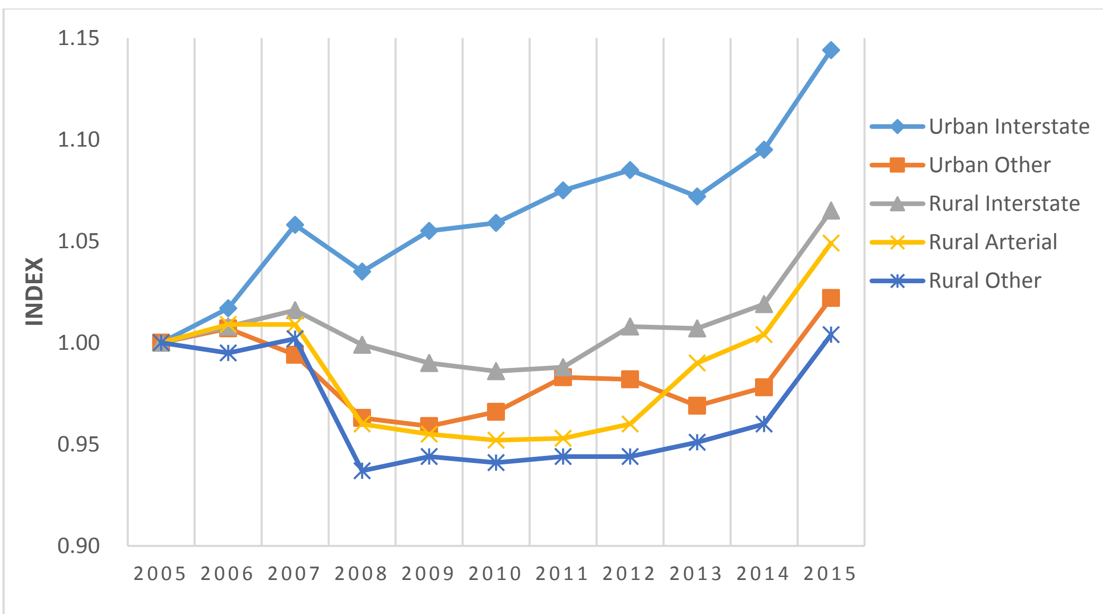


Figure 5.16 Indiana Annual Traffic Index (Year 2005 as 1.00)
(Data Source: INDOT, 2015)

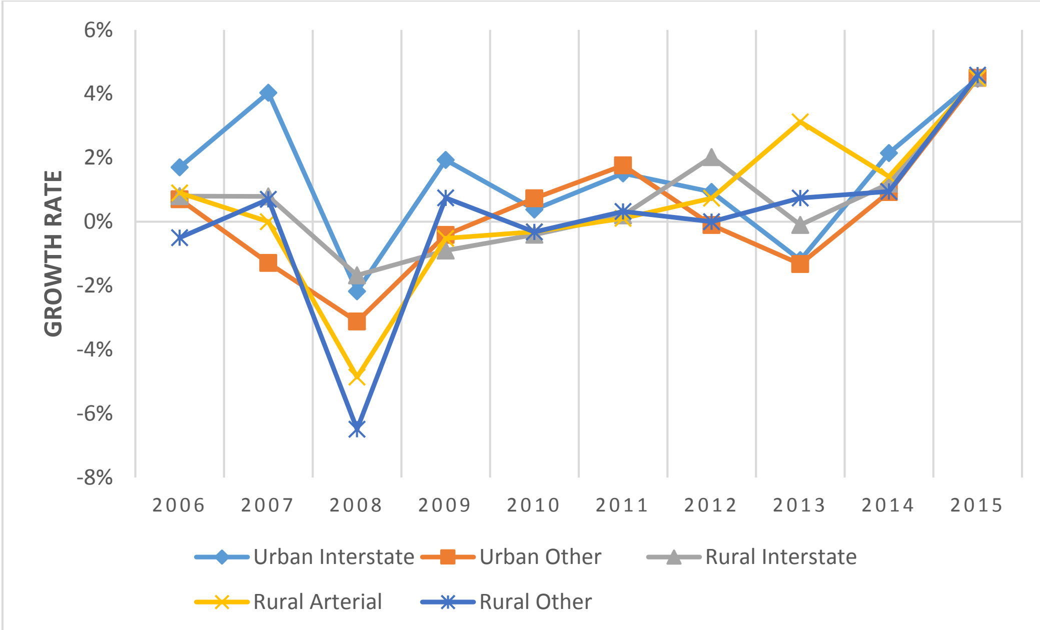


Figure 5.17 Indiana Annual Traffic Growth Rate (Data Source: INDOT, 2015)

5.2.3 Uncertainties of Inflation Rate and Discount Rate

Because the service life of a deck can be a long period of perhaps thirty or forty years (INDOT, 2013), in its life-cycle cost analysis, the impact of inflation of construction costs and user costs are taken into account. As mentioned in Chapter 3, in this dissertation, the inflation of agency costs was considered using the FHWA National Highway Construction Cost Index (NHCCI) (FHWA, 2015), and the inflation of user costs was assumed to be reflected by the change in the CPI (Bureau of Labor Statistics, 2016).

Figure 5.18 presents the quarterly NHCCI from March 2003 through March 2016. The chained-type index set the construction cost in March 2003 as 1.0. It can be seen that the index increased rapidly before 2007, followed by a moderate drop in 2007, and then a decreased markedly in 2008 and 2009 due to the financial crisis. Interestingly, the construction cost index has remained relatively stable at a low level since the crisis until present day.

Figure 5.19 presents the annual change in the CPI for the most recent twenty years (1996-2015). Year *t* on the horizontal axis refers to year *t* compared with year *t-1*. It can be seen that the change was mainly between 1.5% and 3.5%, except for years 2008, 2009 (financial crisis), and 2015 (reason unknown).

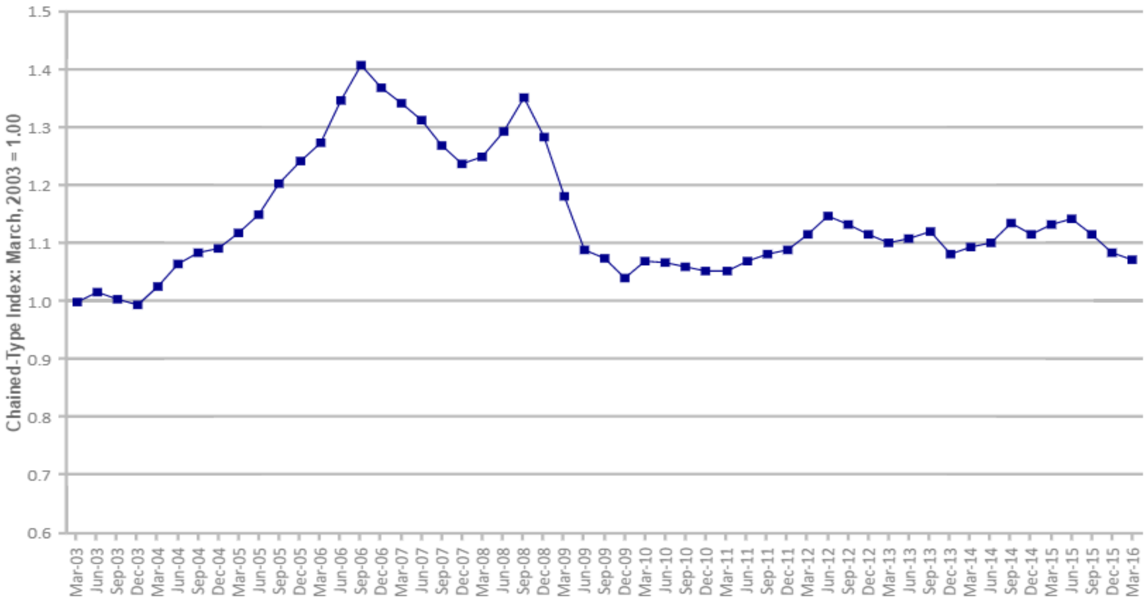


Figure 5.18 FHWA Quarterly National Highway Construction Cost Index (NHCCI) (2003-2016) (Data Source: FHWA, 2015)

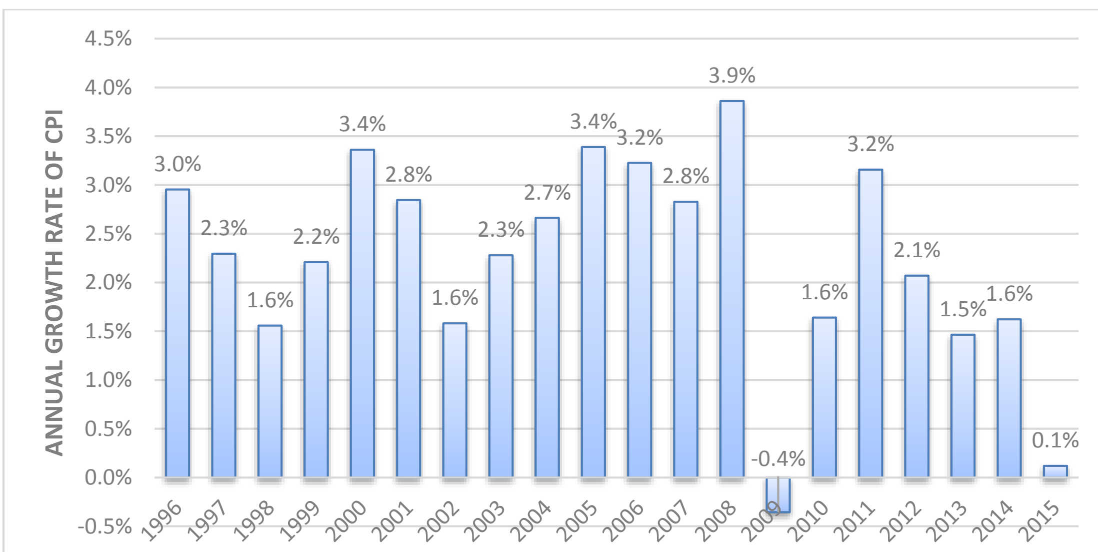


Figure 5.19 Annual Growth Rate of Consume Price Index (CPI) (1996-2015) (Data Source: Bureau of Labor Statistics, 2016)

The above two figures indicate that, similar to traffic growth, the annual inflation rates of the agency and user costs represented by NHCCI and CPI, respectively, have significant variations and therefore are not fully predictable.

In addition to inflation rates, another important input in life-cycle cost analysis is the discount rate. While the inflation rate is used to determine the actual or absolute cost values at year *t*, the discount rate is used to discount future cash flows into the present value. A reasonable discount rate combines the effect of the time value of money and the systematic (or market) risk of a project (Infrastructure Australia, 2008b). Cash today does not have risk, whereas cash flow in the future does. The discount rate needs to compensate for the risks of waiting to receive the cash flow in the future. Uncertainties exist in the future because the discount rate can be adjusted at any time when the market risks change.

5.3 Optimization of Deck Strategies based on Life-Cycle Cost under the Stochastic Situation

Section 3.6 discussed the optimization framework under the deterministic situation. With risks and uncertainties incorporated, the basic elements and flows of the optimization framework remained unchanged for the stochastic situation in this section, for which the objective was to minimize the expected value (*E*) of the weighted sum of agency and user costs over life cycle, where both costs contained uncertain components. Also, the deck service life was characterized by uncertainty because the duration at each condition state was probabilistic. The decision variable was the trigger condition for the LMC deck overlay. Polymeric overlays were not considered because the available data were inadequate to develop stochastic duration models for them. The selection of the LMC overlay trigger affected the life-cycle deck deterioration trend and the frequency of implementing the LMC overlay and thus affected the service life of the deck and the agency and user costs incurred during the life cycle. The constraints included the upper and lower bounds of the LMC trigger and the maximum number of overlays during the deck service life. These constraints were made on the basis of historical practices in Indiana and expert opinion from engineers in the field.

The formulation of the optimization problem under the stochastic situations was as follows:

Objective function:

$$\min_{T_l} \ \mathrm{E}\left\{\sum_{t=1}^{\mathbf{L}}\left[[\mathbf{AC}(t,\xi)+w\mathbf{UC}(t,\xi)]\cdot\frac{1}{(1+\mathbf{r})^{t}}\right]\cdot\left[\frac{\mathbf{r}\cdot(1+\mathbf{r})^{\mathbf{L}}}{(1+\mathbf{r})^{\mathbf{L}}-1}\right]\right\} \tag{5.19}$$

where E(·) refers to expected value of the expression in the parentheses; T_l is decision variable, which is the trigger condition for the LMC overlay; $\mathbf{AC}(t,\boldsymbol{\xi})$ and $\mathbf{UC}(t,\boldsymbol{\xi})$ are the agency costs and user costs incurred in year t, where both costs are random variables; $\boldsymbol{\xi}$ herein denotes general random factors associated with the variables $\mathbf{AC}$ and $\mathbf{UC}$, and the $\boldsymbol{\xi}$ in $\mathbf{AC}(t,\boldsymbol{\xi})$ and $\mathbf{UC}(t,\boldsymbol{\xi})$ do not necessarily represent the same random factors; w is the weight for user costs, indicating the value placed by the agency of each dollar of agency cost versus each dollar of user cost; $\mathbf{L}$ represents the service life of the deck, and it is a random variable determined by both the inherent stochastic deterioration process and the deck M&R strategy; and $\mathbf{r}$ is the discount rate, which could change with the uncertain market risk.

In Eq. 5.19,

$$\mathbf{AC}(t,\xi)=I_{lt}\mathbf{C_l}(\xi)+I_{mt}\mathbf{C_m}(\xi)+I_{rt}\mathbf{C_r}(\xi) \tag{5.20}$$

$$\mathbf{UC}(t,\xi)=\mathbf{VOC}(t,\xi)+I_{wt}\mathbf{TTC_w}(\xi) \tag{5.21}$$

$$\mathbf{L}=f_{\mathrm{L}}\left(\sum_{\tau\in\boldsymbol{\Omega}}\mathbf{D}_{\tau},T_l\right) \tag{5.22}$$

where $\mathbf{C}_{\boldsymbol{l}}(\boldsymbol{\xi})$, $\mathbf{C}_{\boldsymbol{m}}(\boldsymbol{\xi})$, and $\mathbf{C}_{\boldsymbol{r}}(\boldsymbol{\xi})$ are the costs for LMC deck overlays (l), minor deck repairs and maintenance (m), and deck replacement (r), respectively, with their corresponding associated random factors $\boldsymbol{\xi}$, again, $\boldsymbol{\xi}$ herein is a general term denoting random factors and many have different elements for different variables; $I_{xt}\in\{0,1\},\ x=m,l,r,\forall t\in(0,\mathbf{L})$, (i.e., I_{xt} is the indicator of whether treatment x is implemented in year t); $\mathbf{VOC}(t,\boldsymbol{\xi})$ is the total VOC in year t, with uncertainties; $\mathbf{TTC}_{\boldsymbol{w}}(\boldsymbol{\xi})$ is the travel time costs due to work zone delays, with uncertainties; I_{wt} is the indicator of whether there are work zone delays in year t; and **L**, the random variable denoting deck service life, is a function of the sum of $\mathbf{D}_{\tau}$, the random duration (in years) of condition state τ, for all $\tau \in \mathbf{\Omega} = \{9,8,7,6,5\}$, and of T_l, the trigger condition for the LMC overlay.

Specifically, in Eq. 5.20,

$$\mathbf{C_l}(\xi) = \mathbf{u_l}(T_l, q_l, \xi) \cdot q_l \tag{5.23}$$

$$\mathbf{C_m}(\xi) = \mathbf{u_m}(q_m, \xi) \cdot q_m \tag{5.24}$$

$$\mathbf{C_r}(\xi) = \mathbf{u_r}(q_r, \xi) \cdot q_r \tag{5.25}$$

where $\mathbf{C}_{l}(\boldsymbol{\xi})$ is equal to the product of the unit cost of LMC overlay $\mathbf{u_l}$ (as a function of T_l, q_l, and other random factors mentioned in Section 5.2.1) and the quantity of LMC overlay q_l (e.g., in areas); $\mathbf{C}_{m}(\boldsymbol{\xi})$ is equal to the product of the unit cost of minor repairs and maintenance $\mathbf{u_m}$ (as a function of q_m and random factors) and the quantity of minor repairs and maintenance q_m (in various units); and $\mathbf{C}_{r}(\boldsymbol{\xi})$ is equal to the product of the unit cost of deck replacement $\mathbf{u_r}$ (as a function of q_r and random factors) and the quantity of deck replacement q_r (e.g., in areas).

Specifically, in Eq. 5.21,

$$\mathbf{VOC}(t, \xi) = f_{\mathbf{V}}(\mathbf{T_t}, \mathbf{DC_t}, \xi) \tag{5.26}$$

$$\mathbf{DC}_t = f_{\mathbf{D}}(\mathbf{D}_{\tau \in \mathbf{\Omega}}) \tag{5.27}$$

$$\mathbf{TTC_w}(\xi) = f_{\mathbf{T}}(\mathbf{ADT_w}, \mathbf{DL_w}, \mathbf{MoT_w}, \xi) \tag{5.28}$$

where $\mathbf{VOC}(t, \boldsymbol{\xi})$, the incremental VOCs due to surface roughness in year t, is a function of total traffic volume in year t (random variable $\mathbf{T_t}$), the deck condition at year t (random variable $\mathbf{DC_t}$), and other uncertainties $\boldsymbol{\xi}$; $\mathbf{DC_t}$ depends on the random duration $\mathbf{D}_{\tau}$ of each condition state $\tau \in \mathbf{\Omega} = \{9,8,7,6,5\}$; $\mathbf{TTC}_{w}(\boldsymbol{\xi})$, the travel time cost due to work zone delay, is a function of the ADT affected by the work zone (random variable $\mathbf{ADT_w}$), the detour length for the work zone (random variable $\mathbf{DL_w}$), and the type of traffic maintenance at the work zone (random variable $\mathbf{MoT_w}$) that affects the work zone durations, and other uncertain factors $\boldsymbol{\xi}$.

Constraints:

$$T_{ll} \le T_l \le T_{lu} \quad (5.29)$$

$$I_{lt} = 1 \text{ if } \mathbf{DC_t} = T_l \quad (5.30)$$

$$I_{rt} = 1 \text{ if } \mathbf{DC_t} = T_r \quad (5.31)$$

$$I_{mt} + I_{lt} + I_{rt} = 1, \ \forall t, \ \ for \ \ I_{mt}, I_{lt}, I_{rt} \in \{0,1\} \quad (5.32)$$

$$I_{wt} = 1 \text{ if } I_{lt} + I_{rt} = 1, \ \forall t \quad (5.33)$$

where in constraint Eq. 5.29, T_{ll} and T_{lu} are the empirical lower bound and upper bound for the trigger of LMC overlay, based on historical data and expert opinions; constraints Eq. 5.30 and Eq. 5.31 mean that costs for the LMC overlay (*l*) and deck replacement (*r*) are incurred only when these treatments are triggered; constraint Eq. 5.32 means that for any given year *t*, only one type of treatment among *m*, *l*, and *r* is implemented; constraint Eq. 5.33 means that cost for work zone delay is incurred only when *l* or *r* is implemented.

5.4 Chapter Summary

In this chapter, hazard-based duration models were developed to estimate the probabilistic duration for each deck condition state in which the deck stays. The fully-parametric models were selected as the model form because of a) the experience in past literature and b) the capability of accurately calculating the distribution of the life-cycle costs. Various functional forms for the hazard distribution were attempted, including exponential distribution, Weibull distribution, Weibull distribution with gamma heterogeneity, and log-logistic distribution. The estimation results indicated that the state-dependence existed in terms of all condition states. Separate duration models were also developed for three different types of wearing surface: monolithic concrete, latex-modified concrete (LMC), and asphalt, to investigate the post-treatment effect of the LMC overlay and the potential protection effect of the asphalt wearing surface.

The underlying uncertainties in terms of agency costs, user costs, traffic, and inflation rates were discussed in the second section of this chapter. Costs can be influenced by a number of factors with uncertainties, such as the unit cost of materials and labor, weather, economies of scale, traffic volume, and unexpected accidents. The distributions of unit cost for some deck M&R treatments were found based on the available databases. The optimization framework under the stochastic situation was developed. The objective function was to minimize the expected value of the life-cycle weighted sum of the agency costs and user costs. Each element in the formulations was redefined by including random factors. However, the framework only showed abstract and generic formulations. More specifics regarding the solution process and its results will be discussed in Chapter 6.

CHAPTER 6. RESULTS AND ANALYSIS FOR THE STOCHASTIC SITUATION

6.1 Probability of a Condition State Ending at a Particular Year

In Section 5.1, separate duration models were developed for each different deck condition state. These models address the probability that in a given year *t*, a bridge deck ends its sojourn in a given condition state. For example, the probability that condition 7 ends in the t^{th} year of its life, by:

$$P(t-1<T_7 \le t)=F_7(t)-F_7(t-1)=[1-S_7(t)]-[1-S_7(t-1)]=S_7(t-1)-S_7(t) \qquad (6.1)$$

where T_7 is the survival duration of condition 7, F_7 is the cumulative distribution function for condition 7, and S_7 is the survival function for condition 7.

However, in this dissertation, it is of more interest to know, from the perspective of the entire deck service life, at which year a particular condition state is likely to end (e.g., condition 7) and the subsequent condition state is entered (e.g., condition 6). This issue is important for determining the probability distribution of the costs that are incurred in which year. For example, suppose a LMC deck overlay is triggered when the deck condition drops to 6. Then, if condition 7 ends in year 10 (year 0 = beginning of deck service life), with probability $F_7(10)-F_7(9)$, the LMC overlay should be implemented at the end of year 10 (or the beginning of year 11); or, if condition 7 ends in year 15, with probability $F_7(15)-F_7(14)$, then the LMC overlay should be implemented at the end of year 15 (or the beginning of year 16). Obviously, different implementation years for the LMC would lead to different discounted agency costs and different amounts of user costs as well. Therefore, the probability distribution of the incurred costs is directly related to the probability of the duration of each condition state.

This problem can become more complicated because the duration of interest is a cumulative duration (i.e., the sum of the durations of all preceding condition states).

As a simple example, consider that if it is sought to know the probability that a deck leaves condition 7 (that is, it enters condition 6) at the end of year 5 (or the beginning of year 6), there could be five scenarios: 8-8-8-8-8-7-6 (referring to the condition at the beginning of year0-year1-year2-year3-year4-year5-year6), 8-8-8-8-7-7-6, 8-8-8-7-7-7-6, 8-8-7-7-7-7-6, and 8-7-7-7-7-7-6. Note that, as mentioned in Chapter 5, conditions 9 and 8 both refer to the new condition state and were given the same regard in this dissertation, and 8 therefore was used as the starting condition state. Apparently, each of these five scenarios has a probability and the probability of interest would be the sum of these five probabilities. Specifically, the probability of 8-8-8-8-8-7-6 is $[F_8(4) - F_8(3)] \times [F_7(1) - F_7(0)]$. The overall probability that a deck ends its sojourn in condition 7 at the end of year 5 can be calculated as:

$$\begin{aligned} P_7(5) &= [F_8(4) - F_8(3)] \times [F_7(1) - F_7(0)] + [F_8(3) - F_8(2)] \times [F_7(2) - F_7(1)] + [F_8(2) \\ &\quad - F_8(1)] \times [F_7(3) - F_7(2)] + [F_8(1) - F_8(0)] \times [F_7(4) - F_7(3)] \\ &= \sum_{i=1}^{5-1} \{[F_8(i) - F_8(i-1)] \cdot [F_7(5-i) - F_7(4-i)]\} \end{aligned} \tag{6.2}$$

where F_8 is the cumulative distribution function for the sojourn duration in condition 8 and F_7 is the cumulative distribution function for the sojourn duration in condition 7.

More generally, the overall probability that the deck ends its sojourn in condition state 7 at the end of year *t* (year 0 = beginning of deck service life) is:

$$P_7(t) = \sum_{i=1}^{t-1} \{[F_8(i) - F_8(i-1)] \cdot [F_7(t-i) - F_7(t-1-i)]\} \tag{6.3}$$

By definition, the duration variable *t* in the duration model can be $+\infty$. In reality, however, it is impossible for a deck condition state to last indefinitely. Therefore, based on the estimated model results, an upper bound for each condition state duration was selected. The selection criterion was that the survival probability of these upper bounds is less than approximately 2%. For the monolithic concrete, the upper bounds for the durations in condition states 8, 7, 6, and 5 were selected to be 20, 20, 20, and 20 years, respectively; for the LMC wearing surface type, the upper bounds for the durations in condition states 8, 7, 6, and 5 were selected to be 12, 15, 20, and 8 years, respectively. Under these assumptions, the longest possible deck service life (without LMC overlay) would be 20+20+20+20=80 years. However, obviously its probability would be extremely low (i.e., less than $0.02^4 = 1.6\times10^{-7}$).

With the assumptions for the upper bounds of durations, Eq. 6.3 was modified to be a piecewise function, as follows:

$$P_7(t) = \begin{cases} \sum_{i=1}^{t-1} \{[F_8(i) - F_8(i-1)]\cdot[F_7(t-i) - F_7(t-1-i)]\}, & for\ t \in (1,20] \\ \sum_{i=t-20}^{20} \{[F_8(i) - F_8(i-1)]\cdot[F_7(t-i) - F_7(t-1-i)]\}, & for\ t \in (20,40] \end{cases} \quad (6.4)$$

For calculating the probability that the deck ends other condition states (8, 6 and 5) at the end of year t (year 0 = beginning of deck service life), the underlying logic is similar to that for condition state 7, although the algorithms can become increasingly complicated. Eq. 6.5 presents the functions for determining the probability that the deck ends its sojourn in condition state 6 at the end of year t:

$$P_6(t) = \begin{cases} \sum_{i=1}^{t-2} \sum_{j=1}^{t-1-i} \{[F_8(i) - F_8(i-1)]\cdot[F_7(j) - F_7(j-1)]\cdot[F_6(t-i-j) - F_6(t-1-i-j)]\} \\ for\ t \in (1,21] \\ \sum_{i=1}^{20} \sum_{j=\max(1,t-20-i)}^{\min(t-1-i,20)} \{[F_8(i) - F_8(i-1)]\cdot[F_7(j) - F_7(j-1)]\cdot[F_6(t-i-j) - F_6(t-1-i-j)]\} \\ for\ t \in (21,41] \\ \sum_{i=t-40}^{20} \sum_{j=t-20-i}^{20} \{[F_8(i) - F_8(i-1)]\cdot[F_7(j) - F_7(j-1)]\cdot[F_6(t-i-j) - F_6(t-1-i-j)]\} \\ for\ t \in (41,60] \end{cases} \quad (6.5)$$

The probability that the deck ends its sojourn in condition state 8 at the end of year t is straightforward, because there is no previous cumulated duration. It is actually just the difference between $F_8(t)$ and $F_8(t-1)$:

$$P_8(t) = P(t-1 < T_8 \le t) = F_8(t) - F_8(t-1) \quad (6.6)$$

The calculation of probability for condition state 5 was determined by adding one more sum index k, following the same logic.

The algorithms for calculating $P_8(t)$, $P_7(t)$, $P_6(t)$, and $P_5(t)$ were programmed in the MATLAB software and the results for their density distributions were plotted as shown in Figure 6.1, Figure 6.2, Figure 6.3, and Figure 6.4, respectively. The sojourn duration probability for condition state 4 was not included because condition 4 is regarded as the trigger for deck replacement, as explained in Chapter 6. Besides, as mentioned earlier in this section, conditions 9 and 8 were regarded as the same in this dissertation. Therefore, $P_8(t)$ actually accounts for the durations for both condition 9 and condition 8.

From the figures, the years in which conditions 8, 7, 6, and 5 were most likely to end were year 10, year 18, year 26, and year 33, respectively, with probabilities of 0.12, 0.062, 0.049, and 0.042, respectively. It can be seen that even the largest probability was still quite low because the possible duration ranges can be rather lengthy (e.g., 80 years for condition 5). Given the presumption that condition 4 triggers deck replacement, the year at which condition 5 ends actually signifies the end of service life of the deck.

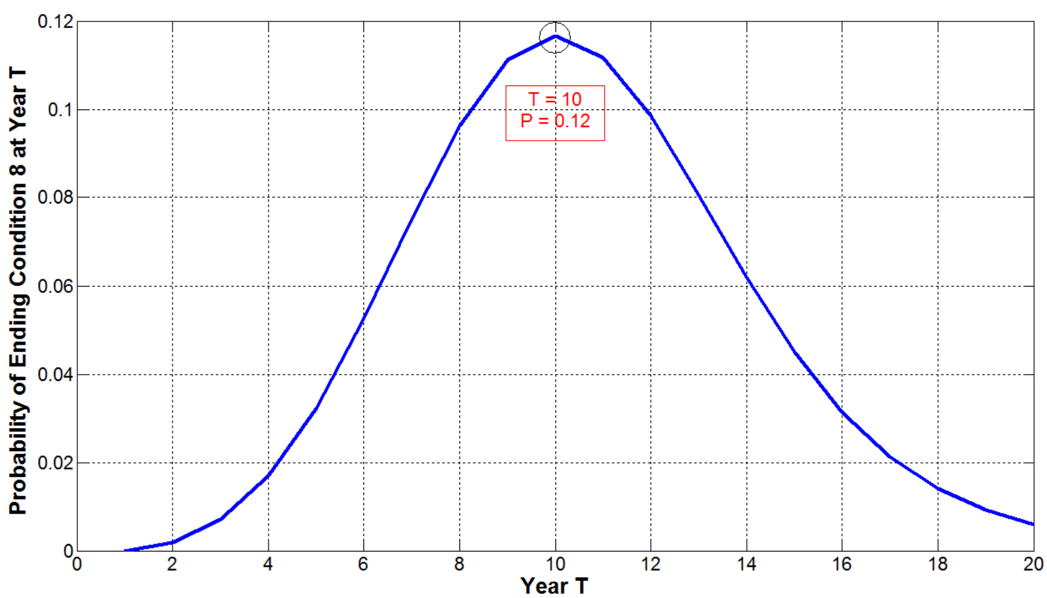


Figure 6.1 Probability Distribution of Sojourn Duration in Condition 8 Ending at Year t
(Year 0 = Beginning of Deck Service Life)

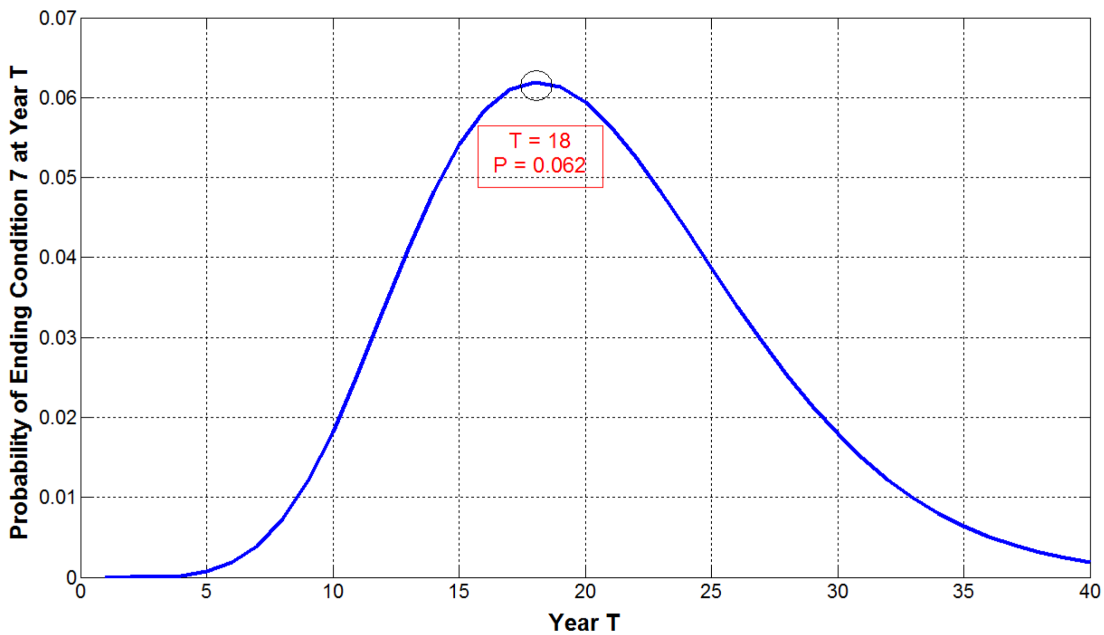


Figure 6.2 Probability Distribution of Sojourn Duration in Condition 7 Ending at Year *t* (Year 0 = Beginning of Deck Service Life)

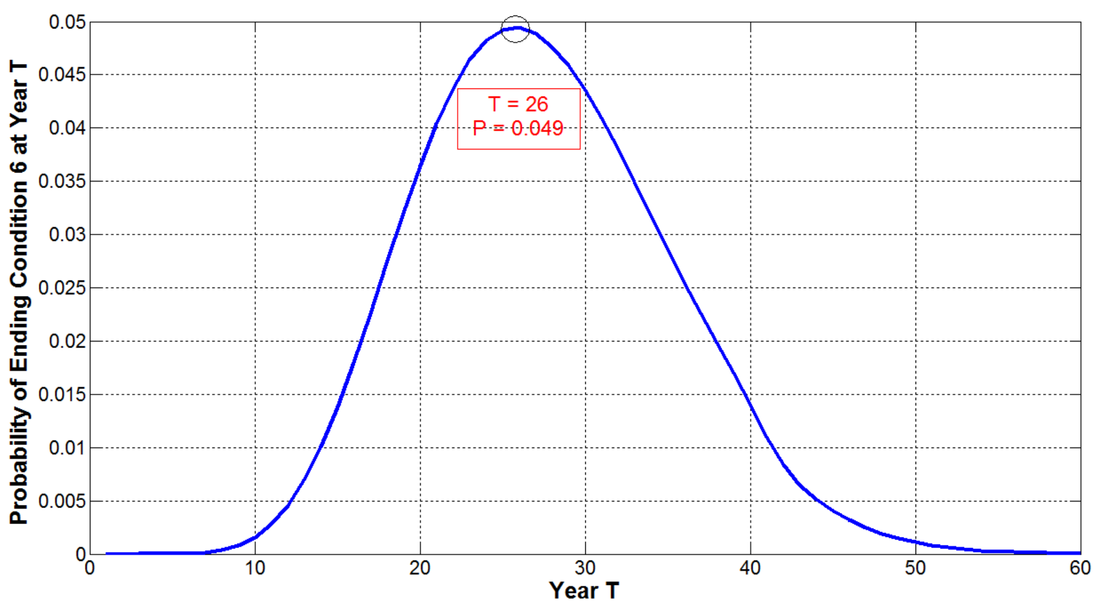


Figure 6.3 Probability Distribution of Sojourn Duration in Condition 6 Ending at Year *t* (Year 0 = Beginning of Deck Service Life)

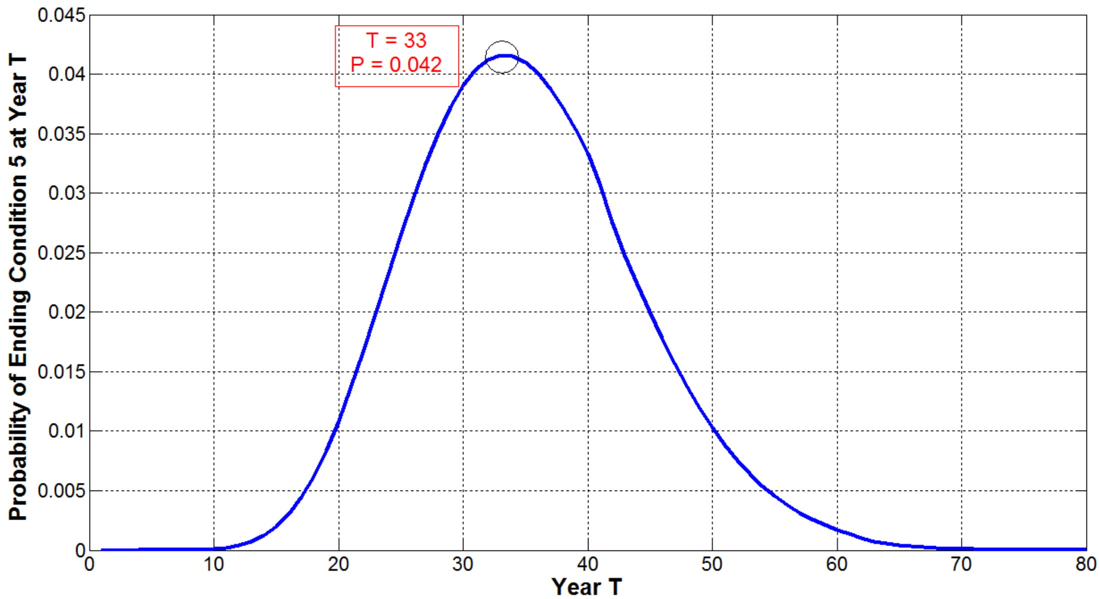


Figure 6.4 Probability Distribution of Sojourn Duration in Condition 5 Ending at Year *t*
(Year 0 = Beginning of Deck Service Life)

Although the duration ranges were e as long as 80 years as shown in Figure 6.4, the probabilities for the upper and lower ends of the durations were extremely low. This indicates that it was highly unlikely that the service life of the deck would be shorter than 20 years or longer than 50 years. Such likelihood is better described using the cumulative probability, which indicates the probability that the duration is less than the specified *t*, or the probability that the duration has ended before the specified *t*. Figure 6.5, Figure 6.6, Figure 6.7, and Figure 6.8 present the cumulative probabilities for condition 8, 7, 6, and 5, respectively. The first quartiles and third quartiles are marked in the figures. The first quartiles are year 8, year 15, year 22, and year 28, and the third quartiles are year 12, year 24, year 32, and year 40, for condition 8, 7, 6, and 5, respectively. For example, in terms of condition 5, the first quartile indicates that there was a 25% probability that condition 5 would end before year 28 or there was a 25% probability that the service life of the deck would be shorter than 28 years; the third quartile indicates that there was a 75% probability that condition 5 would end before year 40 or there was a 75% probability that the service life of the deck would be shorter than 40 years. The shaded areas in the figures indicate there was a 50% probability that the durations would lie in the shaded ranges of the horizontal axes, which suggests that although the total possible duration range was large, most of the possibilities were actually concentrated within a much smaller range.

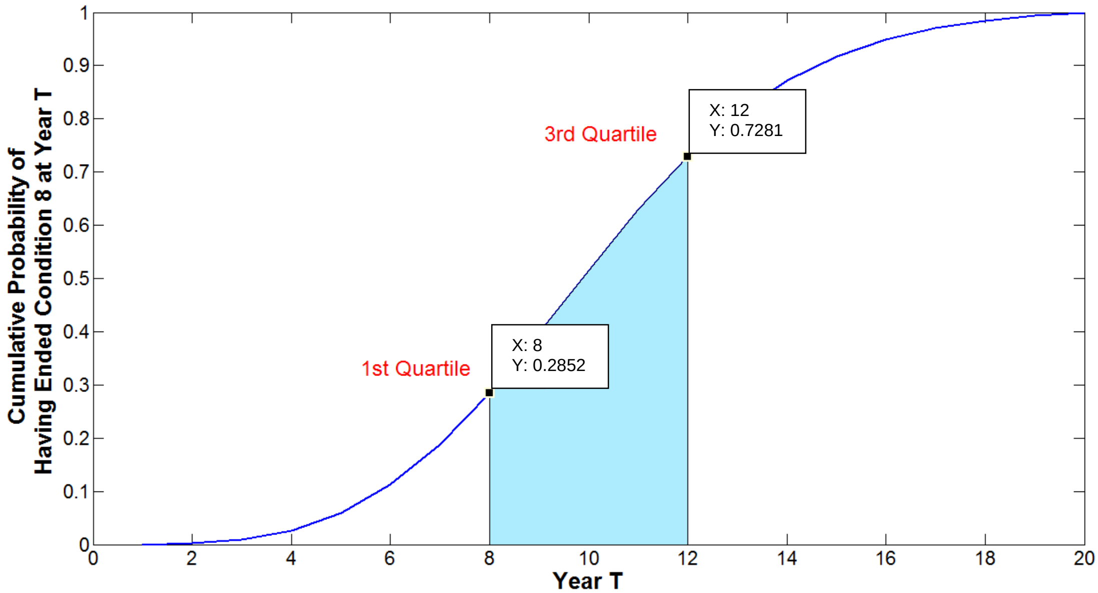


Figure 6.5 Cumulative Probability that the Sojourn Duration in Condition 8 Has Ended Before Year *t* (Year 0 = Beginning of Deck Service Life)

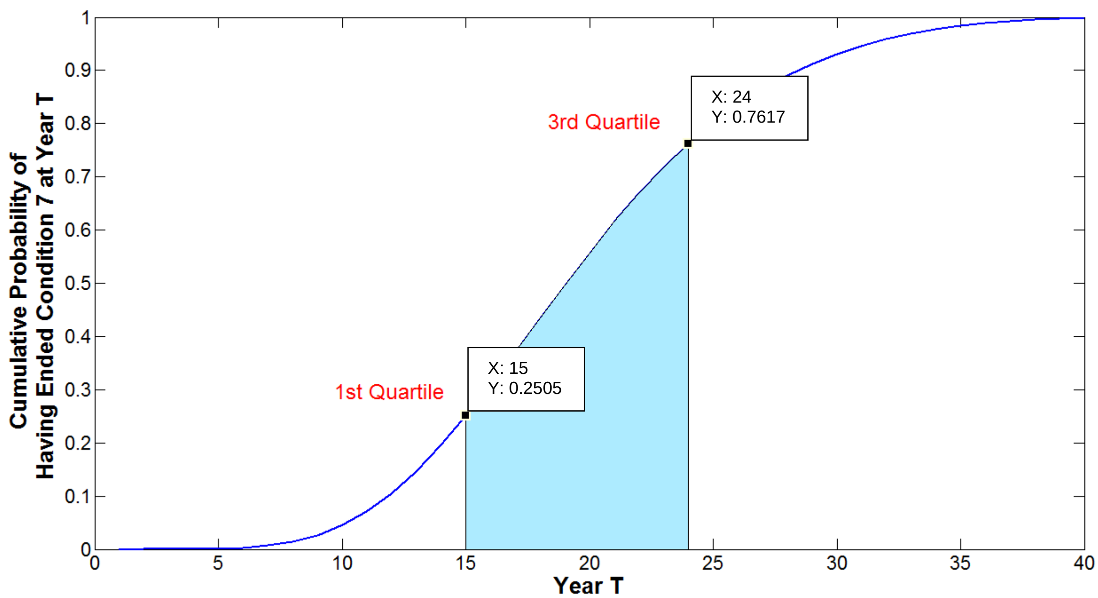


Figure 6.6 Cumulative Probability that the Sojourn Duration in Condition 7 Has Ended Before Year *t* (Year 0 = Beginning of Deck Service Life)

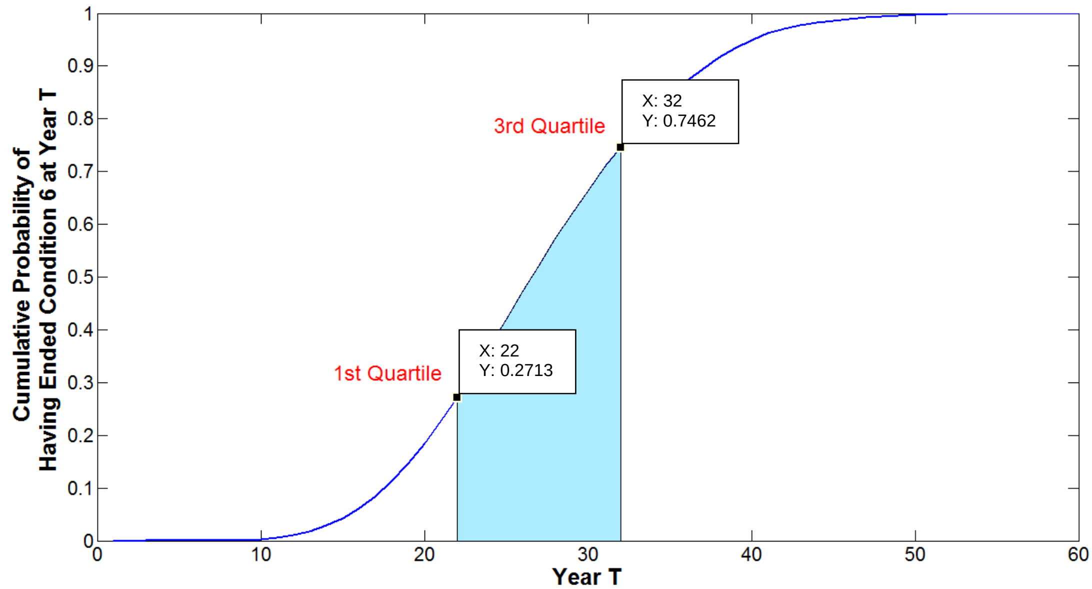


Figure 6.7 Cumulative Probability that the Sojourn Duration in Condition 6 Has Ended Before Year *t* (Year 0 = Beginning of Deck Service Life)

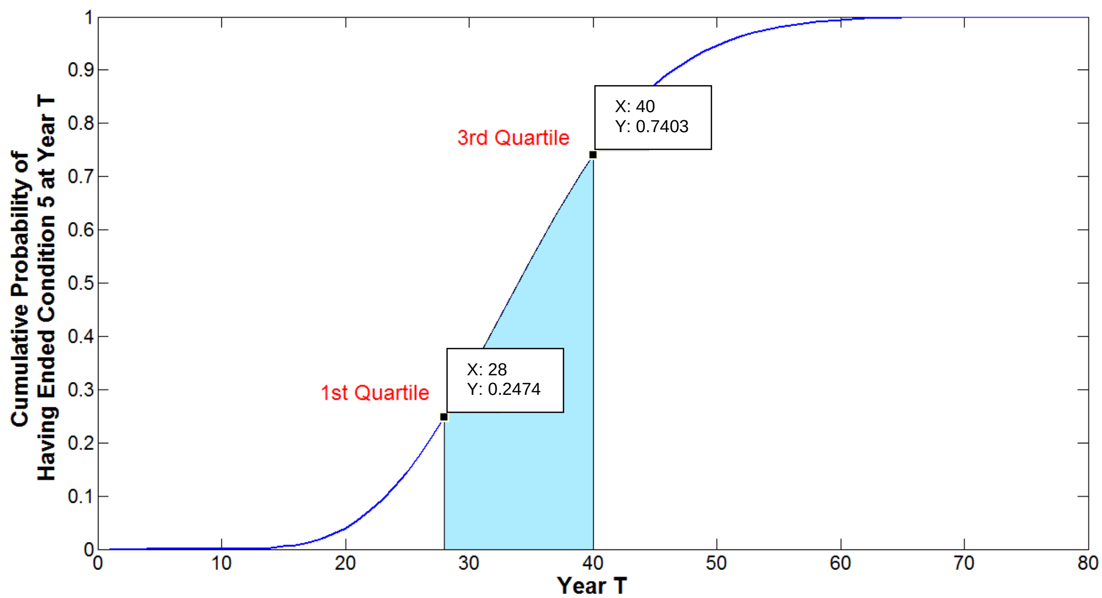


Figure 6.8 Cumulative Probability that the Sojourn Duration in Condition 5 Has Ended Before Year *t* (Year 0 = Beginning of Deck Service Life)

LMC overlays extend the service life of decks. In Chapters 3 and 4, the extension of service life was captured by defining a performance jump in deck condition after the overlay. However, unlike the deterministic situation where deck condition was modeled as a continuous variable, the duration models for the stochastic situation were only defined with respect to integer condition states, such as 8, 7, 6, and 5. Therefore, a non-integer performance jump, such as 0.5, cannot be handled by duration models. For simplicity and without loss of reasonability, it was assumed, for the analysis purposes, the LMC overlay would cause a performance jump to 8 if it is triggered at 7; a performance jump to 7 if it is triggered at 6; and a performance jump to 6 if it is triggered at 5. Such assumptions do not deviate much from the actual performance jump data presented in Figure 3.5 of Chapter 3.

The post-treatment effect after the LMC overlay was captured by the duration models developed for the LMC wearing surface type in Section 5.1.5. For example, if the LMC overlay is triggered at deck condition 6 (implemented immediately after deck condition drops to 6 from 7), the deck condition will revert to 7. The duration of the "new 7" under the LMC overlay was quantified through the estimated duration model for D7LMC (defined in Section 5.1.5). After the "new 7" ends, the durations of 6 and 5 under the LMC overlay were determined through the models for D6LMC and D5LMC, respectively.

As discussed in Chapters 3 and 4, in practice, LMC overlays cannot be triggered and implemented infinitely. Following the results found in the previous chapters, the same assumptions were applied to the analysis in this chapter as follows: if the LMC overlay is triggered at 7, it can be implemented up to three times; if the LMC overlay is triggered at 6, it can be implemented two times; and if the LMC overlay is triggered at 5, it can be implemented only once. The implication is that if the overlay is triggered at a relatively early age of the deck, there will be enough time left for the overlay to be implemented more than once before the deck replacement. On the other hand, if the overlay is triggered at a late age of the deck, there is not much time left before the deck needs to be replaced.

Given the above assumptions, the probability of an LMC-treated deck ends its service life in year *t* were calculated. For example, if the LMC overlay was triggered at condition 6 twice during the deck life, and the deck service life ends (condition 5 ends and drops to 4) at the end of year 10, one of many possibilities of the deterioration process could be: 8-8-7-7-(6)7-7-(6)7-6-5-5-4. The expression (6)7 indicates that the LMC overlay is triggered at the year when the condition drops to 6 and the condition returns back to 7 within the same year after the overlay.

Figure 6.9, Figure 6.10, and Figure 6.11 present the probability distribution of the deck service life (i.e., when condition 5 ends) for the scenarios at which LMC overlay was triggered at 5, 6, and 7. The years in which the deck service life was most likely to end were year 36, year 47, and year 49, with probabilities of 0.041, 0.042, and 0.051, for Trigger = 5, 6, and 7, respectively. It was found that if the LMC overlay was triggered at 5, the deck service life would most likely be extended for only three years (compared with the 33 years without overlays in Figure 6.4), possibly because when the overlay was triggered, the deck was already near the end of its service life and the overlay would not be able to redeem much of its life. In contrast, if the LMC overlay was triggered at 6 and implemented twice, the deck service life likely could be significantly extended (47 years compared with 33 years). Furthermore, it was found that if the LMC overlay was triggered at 7 and implemented three times, the deck service life was likely to increase only two years (49 years compared with 47 years), which may indicate that the implementation of overlays in the early years of the deck would not extend the deck service life much more than implementing overlays during the deck’s middle age. From the figures, it can be seen that the main part of the probability distribution lies within a small range in the middle portion of the horizontal axis; and the probabilities for the upper and lower ends of the range are extremely low.

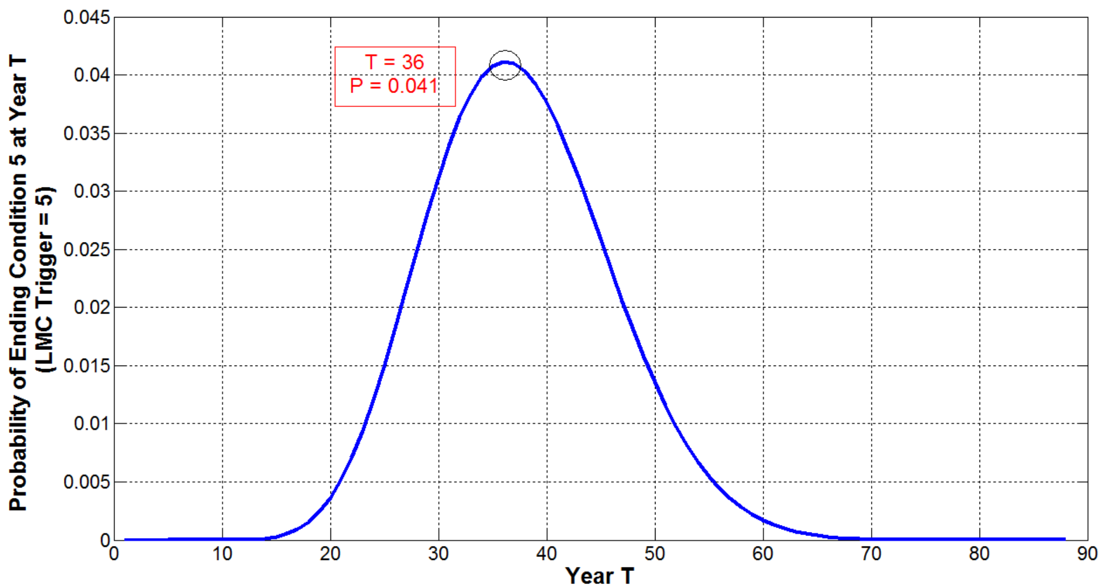


Figure 6.9 Probability Distribution of LMC-Treated Deck Service Life if LMC was Triggered at 5

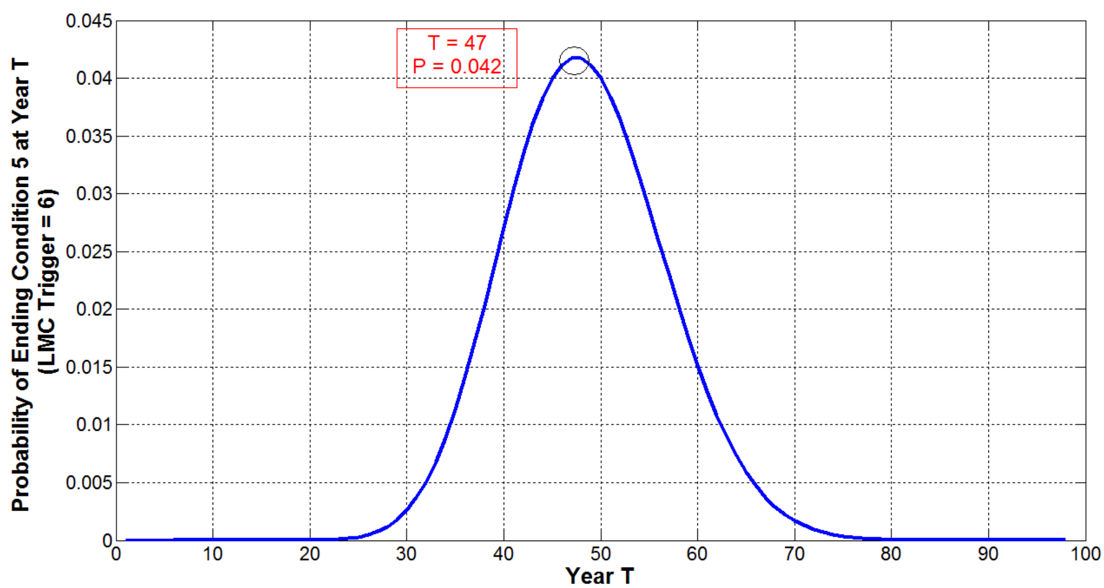


Figure 6.10 Probability Distribution of LMC-Treated Deck Service Life if LMC was Triggered at 6

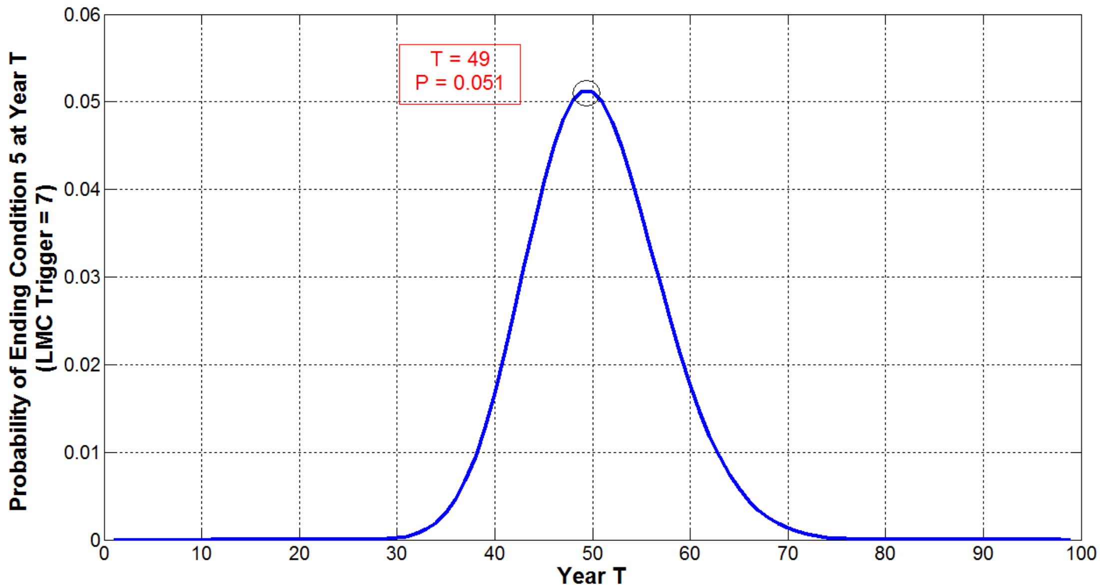


Figure 6.11 Probability Distribution of LMC-Treated Deck Service Life if LMC was Triggered at 7

Figure 6.12, Figure 6.13, and Figure 6.14 present the cumulative probability distribution for the deck service life (when condition 5 ends) for the scenarios that LMC overlay was triggered at 5, 6, and 7. The first quartiles are year 28, year 42, and year 45, and the third quartiles are year 40, year 53, and year 54, for Trigger = 5, 6, and 7, respectively. This means that, if the LMC overlay was triggered, for example, at condition 6, there was a 25% probability that the deck service life would be less than 42 years and 75% probability that the deck service life would be less than 53 years. In fact, the cumulative probability increased rapidly within short ranges, as shown in each of these three figures, indicating that most of the possible scenarios of deck service life are within such ranges. The shaded areas in the figures indicate a 50% probability that the service life of the deck would lie in the shaded ranges of the horizontal axes.

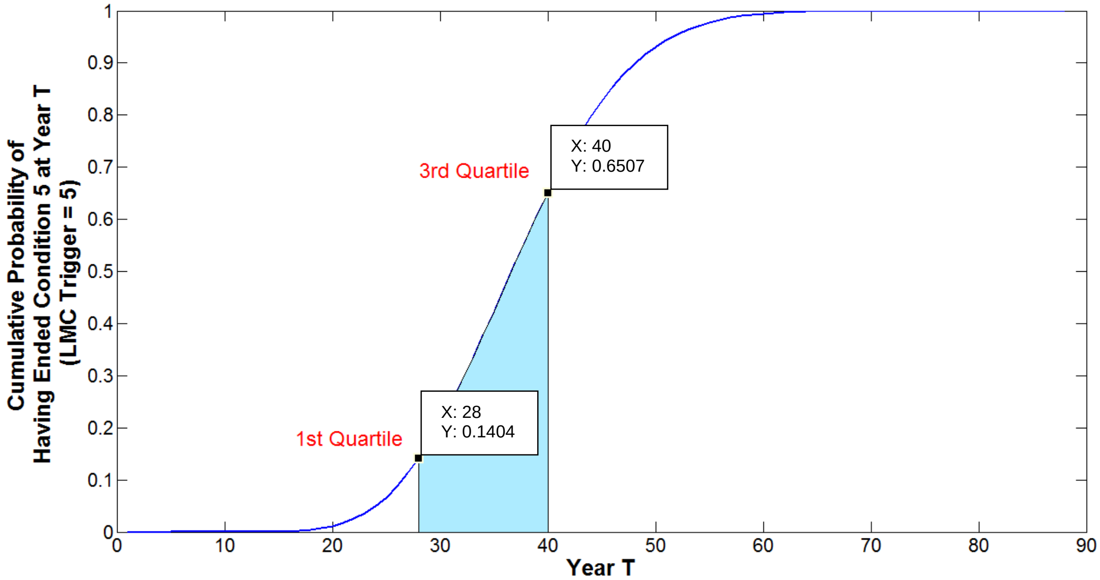


Figure 6.12 Cumulative Probability Distribution of LMC-Treated Deck Service Life if LMC was Triggered at 5

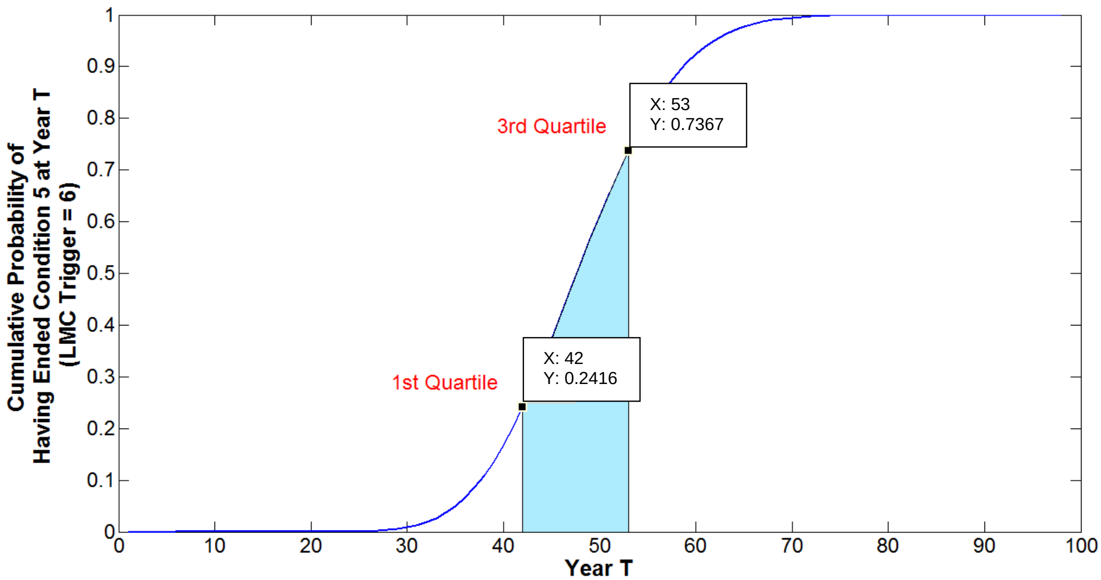


Figure 6.13 Cumulative Probability Distribution of LMC-Treated Deck Service Life if LMC was Triggered at 6

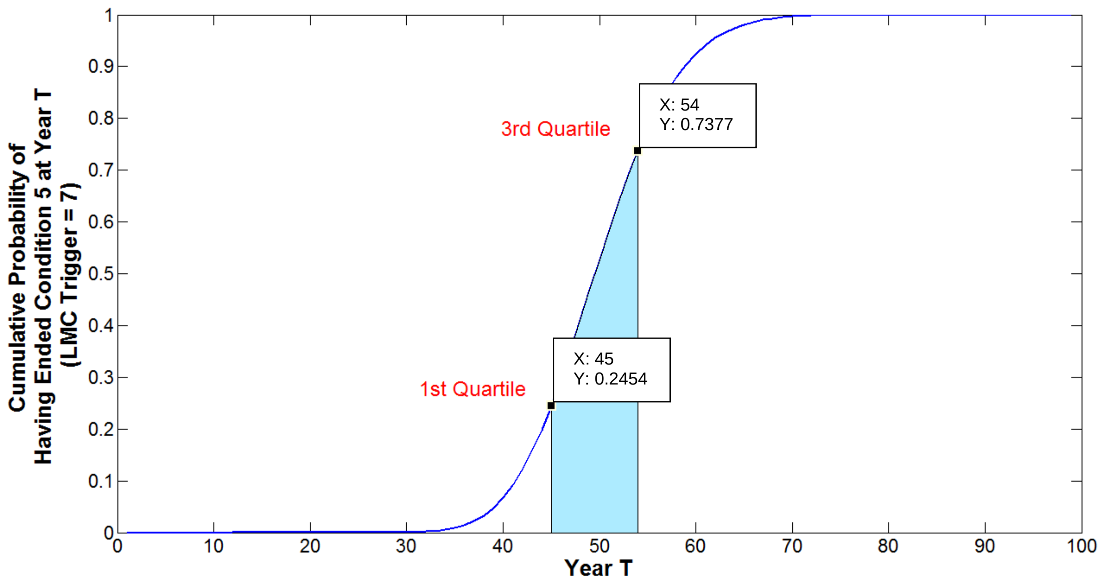


Figure 6.14 Cumulative Probability Distribution of LMC-Treated Deck Service Life if LMC was Triggered at 7

6.2 Life-Cycle Cost Analysis under the Stochastic Situation

In the optimization framework developed in Section 5.3, there was uncertainty in the analysis factors. Probability distributions were developed for some of the inputs, such as the unit cost of LMC overlay, the unit cost of deck replacement, and the traffic growth rate. However, it was determined that in the life-cycle cost analysis of this dissertation, only the uncertainty of the deterioration process was taken into account; while for other factors, including costs, traffic, and inflation rates, only their mean values, or deterministic cost models, were used for the analysis. For agency costs, from the histogram charts in Section 5.2.1, the unit costs of various deck treatments obviously did not follow normal distributions. Although many factors could have possibly influenced the unit costs, the real reasons behind the variations were unclear, and hence the real distribution patterns of the unit costs were unclear. If some types of functional forms are subjectively selected based on the limited available data sets, serious bias may be introduced. For user costs, many more factors with greater uncertainty exist, including traffic volume, vehicle class distributions, work zone durations, and even the scope of the definitions of the travel time value and unit VOC. The distribution patterns behind these factors were unclear and data were not available to establish reliable distributions. Traffic growth and inflation rates are closely related to the macro-economic environment, which is inherently unpredictable in the long term. Therefore, the other factors apart from deck deterioration, including unit costs, traffic, and inflation rates, used the mean values for the deterministic models in Chapters 3 and 4.

The life-cycle cost analysis under the stochastic deterioration process was conducted. The overall algorithm was as follows: for each realization of the deterioration process (e.g., 8-8-8-7-7-(6)7-7-6(7)-7-6-6-5-5-5-4), a life-cycle cost "scenario" (including overlay cost, maintenance and repair cost, deck replacement cost, work zone travel time cost, and incremental VOC) would be incurred. The probability of this particular realization was determined using the duration models; therefore, this probability was attached to this particular life-cycle cost scenario. Then, each life-cycle cost scenario thus corresponded to a probability. The equivalent uniform annual cost (EUAC) was easily determined from the cost scenario. Therefore, the final probability distributions of EUACs (agency, user, and total) were determined. The expected values were calculated as:

$$E(Agency\_EUAC) = \sum_{i \in \Phi} p_i \cdot (EUAC\_LMC_i + EUAC\_RM_i + EUAC\_DR_i) \qquad (6.7)$$

$$E(User\_EUAC) = \sum_{i \in \Phi} p_i \cdot (EUAC\_WZ_i + EUAC\_VOC_i) \qquad (6.8)$$

$$E(Total\_EUAC) = E(Agency\_EUAC) + w \cdot E(User\_EUAC) \qquad (6.9)$$

where Φ refers to the set containing all possible life-cycle cost scenarios; p_i refers to the probability corresponding to the *i*th cost scenario; $EUAC\_LMC_i$, $EUAC\_RM_i$, and $EUAC\_DR_i$ refer to the EUAC of the LMC overlay cost, routine maintenance and minor repair cost, and deck replacement cost, respectively, in the *i*th cost scenario; $EUAC\_WZ_i$ and $EUAC\_VOC_i$ refer to the EUAC of the work zone travel delay cost and the incremental vehicle operating cost due to surface roughness, respectively, in the *i*th cost scenario; the expected value of the EUAC of total cost $E(Total\_EUAC)$ is the weighted sum of the expected value of the EUAC of agency cost $E(Agency\_EUAC)$ and the expected value of the EUAC of user cost *E*(*User_EUAC*), where *w* denotes the weight that decision-makers attach to the user costs.

The set Φ contained 160,000 scenarios for the case Do Nothing (i.e., no overlay was implemented); 1,280,000 scenarios for the case LMC Trigger = 5; 14,400,000 scenarios for the case LMC Trigger = 6; and 82,944,000 scenarios for the case LMC Trigger = 7. All calculations were completed using MATLAB software.

Figure 6.15, Figure 6.16, and Figure 6.17 present the probability distributions of agency EUAC, user EUAC, and total EUAC (with weight = 1:1 between agency cost (AC) and user cost (UC)), for the case of the Do Nothing scenario as an illustration. Each of the three figures actually contains 160,000 points, although the points on the left side are extremely dense and they seem to form “solid” areas. There are no two identical points because each of the points came from a different cost scenario that had a different probability and cost combination. It can be seen that the distributions are obviously right-skewed (or positive-skewed), with the majority of the probabilities concentrated on the lower ends of the EUACs. The probability distributions for other cases (i.e., Triggers 5, 6, and 7) were not plotted because the points would become much more concentrated and they were hard to discern. Their overall distribution patterns were similar.

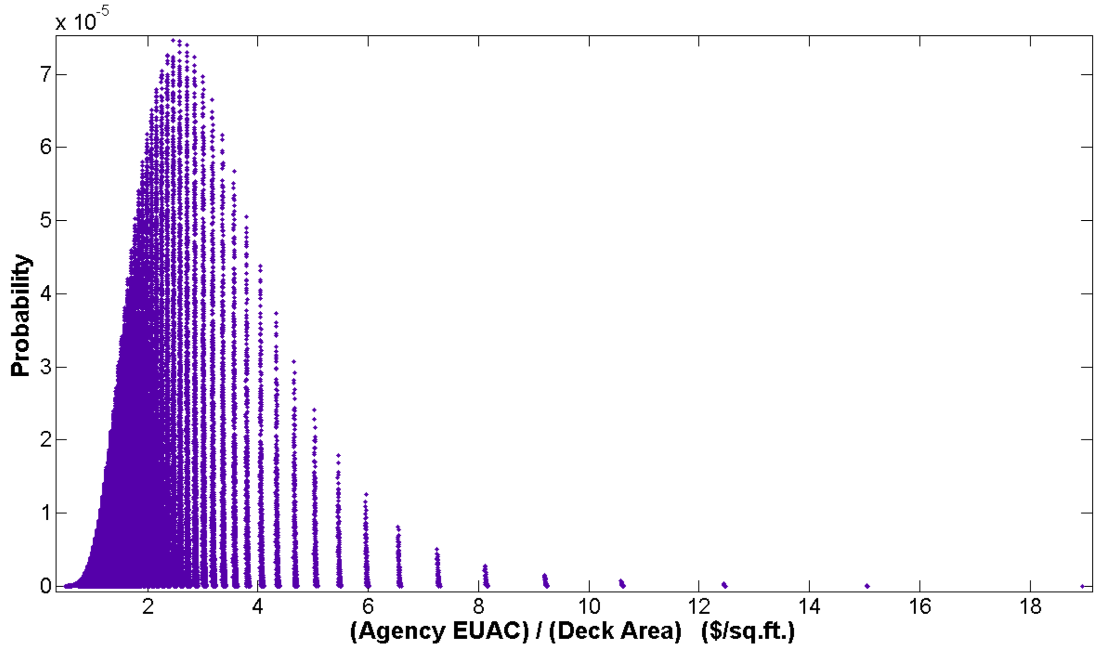


Figure 6.15 Probability Distribution of Life Cycle Agency Cost, Do Nothing Scenario

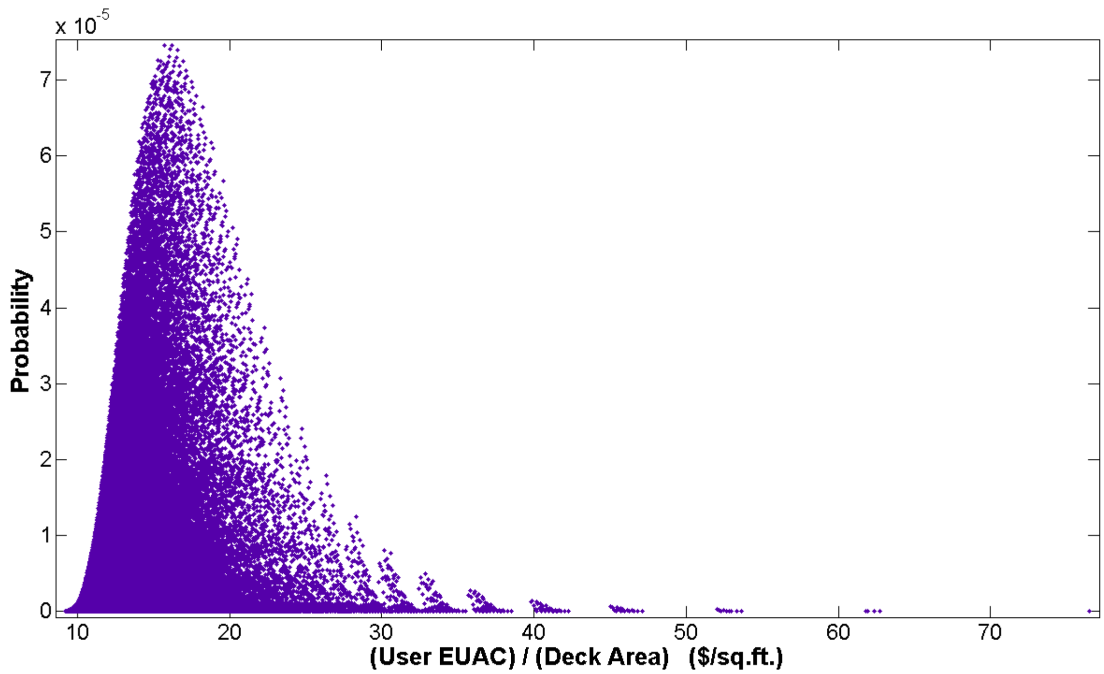


Figure 6.16 Probability Distribution of Life Cycle User Cost, Do Nothing Scenario

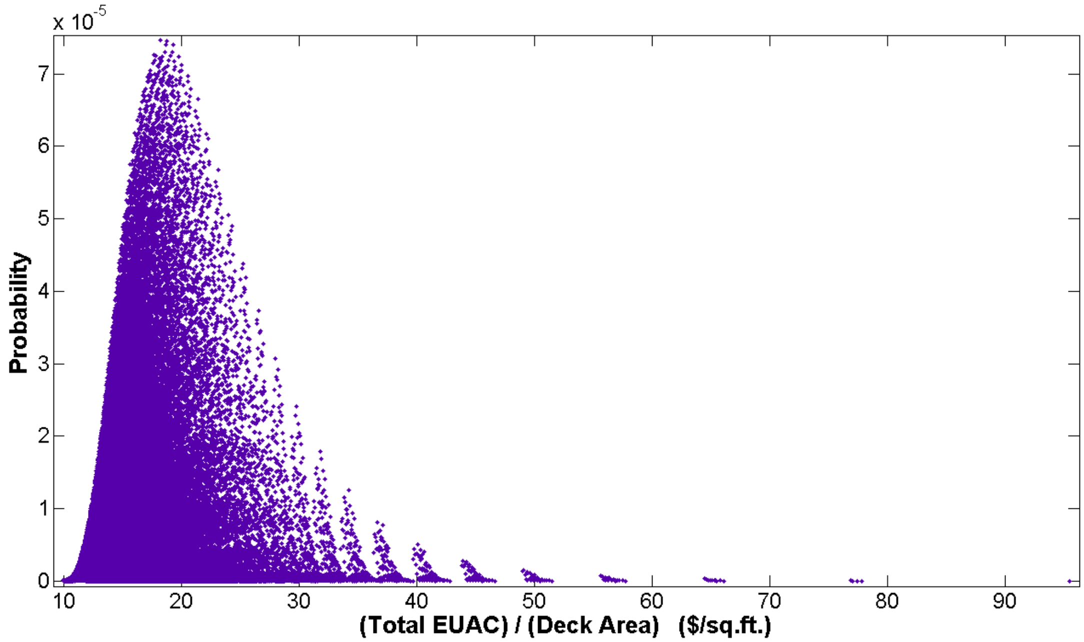


Figure 6.17 Probability Distribution of Life Cycle Total Cost, Do Nothing Scenario

Figure 6.18, Figure 6.19, and Figure 6.20 present the life-cycle results for the EUAC of agency costs, user costs, and total costs for different LMC overlay triggers using box plots. Strictly speaking, they are not the traditional box plots that display the variation of numerical samples. The EUACs are actually random variables, with each value of EUAC corresponding to a certain probability. Strictly, they are discrete random variables because each of their number of scenarios is limited. However, because the number of scenarios was so large with a relatively small range and the probability for each single scenario was so small, they were regarded as continuous random variables.

In the figures, the expected values (E) and five percentiles: 5th, 25th (1st quartile), 50th (median), 75th (3rd quartile), and 95th percentiles are marked and their corresponding EUAC values are presented. The percentiles were calculated through the cumulative probabilities of the ascending sorted EUAC values. These figures present the 5th and 95th percentiles instead of the minimum and maximum because the maximum can be so large that the space for presenting the main results would be squeezed to a small range. In fact, the maximum and minimum were regarded as outliers with extremely small probabilities so it was not necessary to present them. After all, the results between the 5th and the 95th percentiles already included 90% of the EUAC possibilities. It was found that for all the cases, the expected values were greater than the 50th percentile, indicating that the distributions were all right-skewed, as shown in Figure 6.15 through Figure 6.17.

For the results of agency EUAC in Figure 6.18, the expected values for the cases of Do Nothing (no overlay), Trigger = 5, Trigger = 6, and Trigger = 7 were $1.90/ft^2, $2.68/ft^2, $3.26/ft^2, and $5.16/ft^2, respectively. The trend was consistent with the one derived under the deterministic situations. As mentioned earlier, the LMC overlays were triggered and implemented once, twice, and three times for Trigger = 5, 6, and 7, respectively. The EUAC results indicate that, although more frequent triggers could extend the service life of the deck, such extension would not able to compensate for the additional agency costs for the overlays on average (based on the expected values).

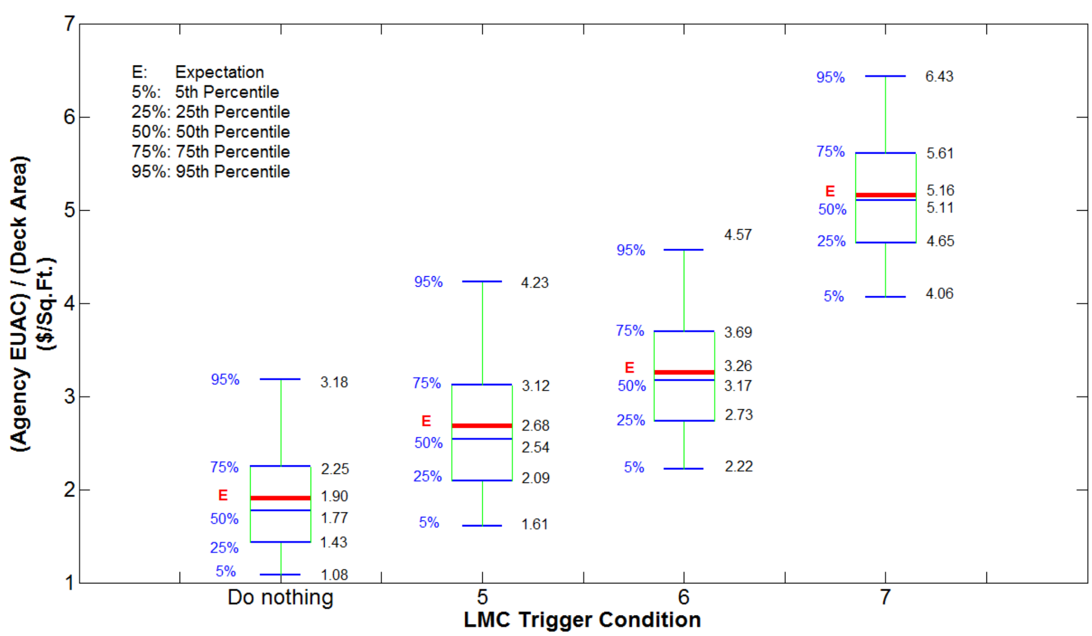


Figure 6.18 Box Plot for Life Cycle Agency Cost for Different Triggers of LMC Treatment

If randomness is considered, there could be overlaps in the range of the life-cycle agency cost between different trigger candidates. Overall, the EUACs for Trigger 7 were significantly higher than the others and was the least overlapping, possibly because its overlay costs are significantly higher but its deck service life was not significantly extended, particularly compared with Trigger 6. On the other hand, in terms of Do Nothing, Trigger 5, and Trigger 6, there were large overlapped portions of the range of the life-cycle agency cost. Specifically, the 75th percentile EUAC of Trigger 5 was at approximately the same level with the 50th percentile EUAC of Trigger 6, indicating that approximately 50% of the EUAC likelihoods of Trigger 6 were higher than 75% of those of Trigger 5. Similarly, approximately 70% of the EUAC likelihoods of Trigger 5 were higher than 75% of those of do nothing; and approximately 95% of the EUAC likelihoods of Trigger 6 were higher than 75% of those of Do Nothing.

However, the upper end and the lower end values of the EUAC are not very likely to happen in reality. The upper end values of the EUAC are produced when the durations of all condition states happen to be short and hence the total service life is short; while the lower end values of EUAC are produced when the durations of all condition states happen to be long and hence the total service life is long. Therefore, the IQR (i.e., the range between the 1st quartile (25th percentile) and the 3rd quartile (75th percentile)) may have more significant implications realistically. Basically, the IQRs of Do Nothing, Trigger 5, Trigger 6, and Trigger 7, ranked from low to high, with small portions of overlapping.

Figure 6.18 indicates that if the agency decides not to consider user costs, then implementing the LMC overlay when the deck condition reaches 5 would yield the lowest EUAC on average. Based on the practices of at least one state agency, bridge decks typically receive at least one overlay during its life cycle (INDOT, 2013). Otherwise the surface roughness may become overly severe for the road users. Therefore, although the Do Nothing scenario provided the lowest EUAC, it was not considered as a feasible strategy.

Figure 6.19 presents the box plots for the results of user EUAC. The expected values for the cases of Do Nothing, Trigger = 5, Trigger = 6, and Trigger = 7 were

$14.17/ft^2, $13.22/ft^2, $10.53/ft^2, and $9.65/ft^2, respectively. This trend was consistent with the one derived under the deterministic situation.

The user costs are the combination of the travel time costs due to the work zone delays and the incremental VOCs due to increased surface roughness. If the overlay was triggered more frequently, there were more work zone delay costs. However, the VOCs were lower due to the superior condition of the deck surface. Therefore, it was not straightforward which trigger strategy would lead to lower user EUAC without data-driven analysis.

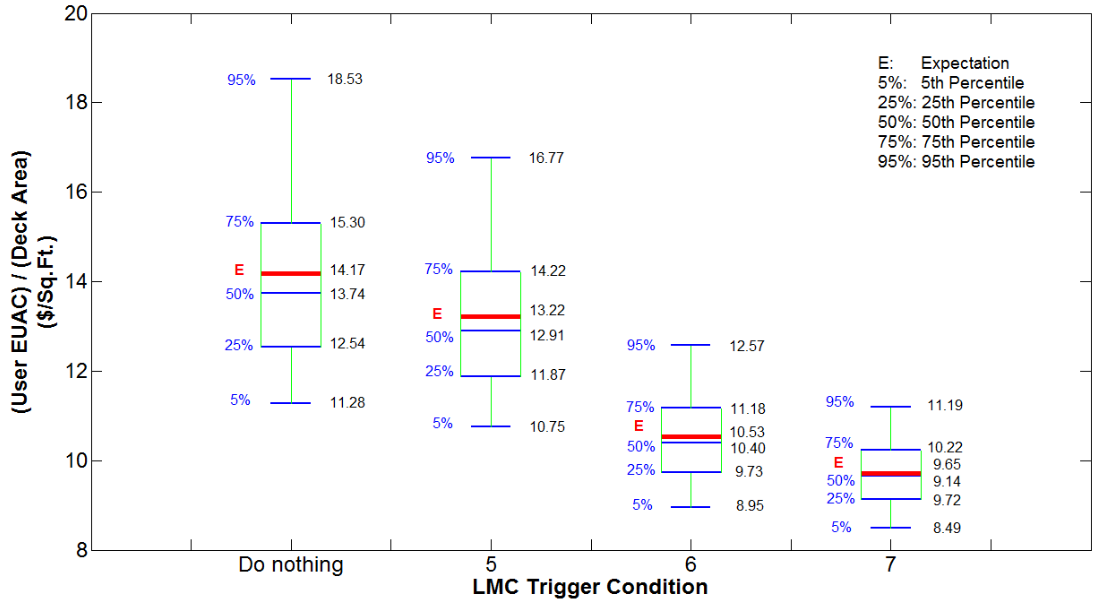


Figure 6.19 Box Plot for Life Cycle User Cost for Different Triggers of LMC Treatment

Figure 6.19 shows that more frequent LMC overlays led to lower user EUAC, which possibly were due to the fact that the magnitudes of the life-cycle VOCs were significantly greater than those of the life-cycle travel time costs. This result was due to the fact that travel time costs were only incurred during the overlay implementation whereas the VOCs were incurred during all the normal operations periods. The possible explanation for the obvious greater variations in the Do Nothing scenario and the Trigger 5 case, compared to Triggers 6 and 7, was the relatively small magnitudes of total user costs for Triggers 6 and 7, which were further discounted by their significantly longer average deck service life when the user costs were transformed into EUACs. Thus, the difference between the discounted upper end and lower end of EUACs for the Trigger 6 and 7 scenarios were not as large as that for the Trigger 5 and Do Nothing scenarios.

As mentioned earlier, more attention was paid to the IQR. Figure 6.19 shows that the IQRs of the Do Nothing and Trigger 5 scenarios overlapped for a large portion, while approximately half of the IQRs of the Trigger 6 and Trigger 7 scenarios overlapped. Overall, the IQRs of Trigger 6 and Trigger 7 turned out to be significantly lower than the other two, indicating that Trigger 6 and 7 were more likely to result in lower life cycle user costs.

Figure 6.20 presents the box plots for the total life cycle cost results. The total EUAC was calculated as the simple sum of the agency EUAC and the user EUAC (i.e., the weight between the agency cost (AC) and the user cost (UC) was 1:1), meaning that one dollar of agency cost was considered equal to one dollar of user cost. Sensitivity analysis was conducted by changing this weight ratio, and the results are presented in a subsequent section of this chapter.

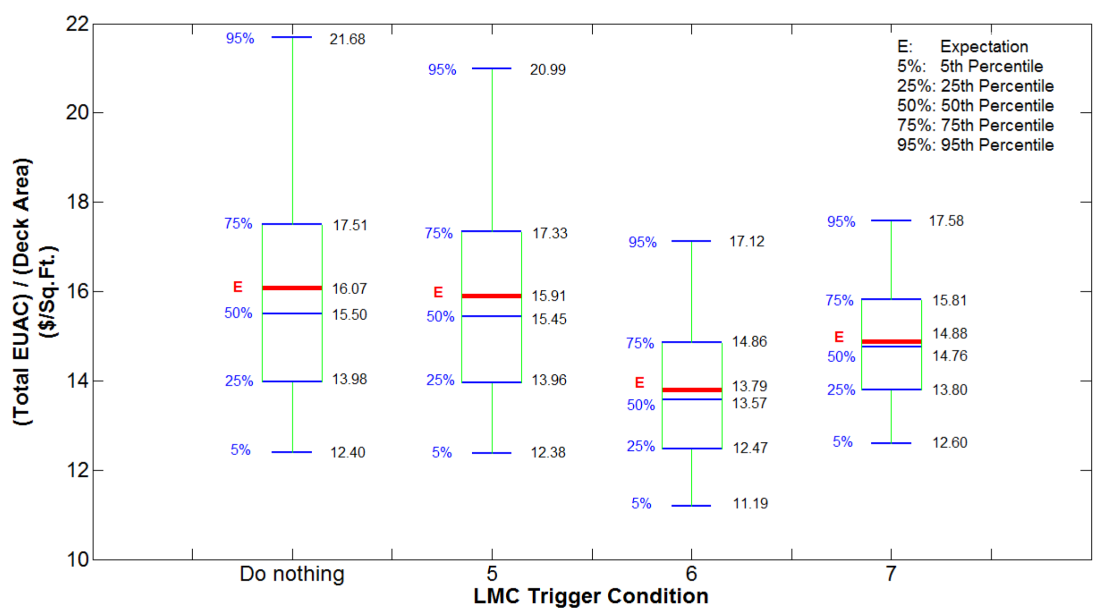


Figure 6.20 Box Plot for Total Life Cycle Cost for Different Triggers of LMC Treatment (AC:UC = 1:1)

From Figure 6.20, the expected values of the total life cycle cost for the Do Nothing, Trigger = 5, Trigger = 6, and Trigger = 7 scenarios were $\$16.07/ft^2$, $\$15.91/ft^2$, $\$13.79/ft^2$, and $\$14.88/ft^2$, respectively. The trend here was consistent with the one derived under the deterministic situation. It can be seen that the variations for all four cases became larger because they combined the variabilities from the both agency EUAC and the user EUAC. With significant variations, the difference between Do Nothing and Trigger 5 seems ambiguous. It could be inferred that the means of these two cases were not statistically significantly different. Trigger 6 basically led to the lowest total EUAC, although it still had some portions overlapped with other trigger scenarios. Why the differences in total EUAC between the four scenarios became less significant was straightforward: for the agency EUAC, the order of EUAC from low to high was: Do Nothing, Trigger 5, Trigger 6, and Trigger 7; however, for the user EUAC, the order was completely the opposite: Trigger 7, Trigger 6, Trigger 5, and Do Nothing. With uncertainties incorporated, the recommendation that can be made from Figure 6.20 is that given a weight of 1:1 between the agency and user costs, it was most likely that the implementation of LMC overlay at condition 6 would yield the lowest total life cycle cost.

6.3 Sensitivity Analysis

As discussed in Section 4.5, changing the values of various input factors could affect the analysis results. The purpose of the sensitivity analysis was to investigate the impacts of such change on the final results. Section 4.5 focused on two factors that could have relatively significant impacts on the EUAC: the weight between the agency cost and user cost, and the traffic volume. In this section, the impact of traffic was not investigated because a) traffic was not found to be a statistically significant variable in many of the developed duration models, thus the impact of traffic on the overall deterioration process could not be determined; and b) the main impact of traffic would lie in the user costs instead of the agency costs, and the impact of traffic therefore would be similar to the impact of changing the weight between the agency and user costs. This makes the sensitivity analysis in terms of traffic less necessary. Therefore, the only factor of interest in the sensitivity analysis in this section was the weight between the agency and user costs. Because the magnitude of the user cost amount could be several times greater than that of the agency cost, the change of the weight between them could significantly affect the total life cycle cost and hence the selection of the appropriate trigger.

Table 6.1 presents the sensitivity analysis results of changing the weight (AC:UC ratio) from 1:1 to 8:1. Weights higher than 8:1 were not investigated because the trend for ratios exceeding 5:1 was found to be consistent. The total EUAC results presented in th table are the expected values derived from the stochastic life-cycle cost analysis. The bold values indicate that the corresponding trigger led to the lowest expected total EUAC. From the table, if the Do Nothing scenario was not considered as a feasible strategy, when the weight ratio was less than 4:1, Trigger = 6 led to the lowest expected total EUAC. When the weight ratio was greater than 5:1, Trigger = 5 was found to yield the lowest expected life cycle cost. This trend is intuitive because if higher weights are attached to the agency costs, the magnitude of agency EUAC would dominate the total EUAC. Thus, the trigger with a lower agency EUAC would result in lower total EUAC.

Table 6.1 Sensitivity of Life Cycle Cost to the Agency cost and User Cost Relative Weights

	Weight (AC:UC)	**Do Nothing**	**Trigger = 5**	**Trigger = 6**	**Trigger = 7**
Expected Values of (Total EUAC) / (Deck Area) ($\$/ft^2$)	1:1	16.07	15.91	**13.79**	14.88
	2:1	8.99	9.30	**8.52**	10.02
	3:1	6.63	7.09	**6.77**	8.40
	4:1	5.45	5.99	**5.89**	7.59
	5:1	4.74	**5.33**	5.36	7.10
	6:1	4.27	**4.89**	5.01	6.78
	7:1	3.93	**4.57**	4.76	6.55
	8:1	3.68	**4.34**	4.57	6.37

Figure 6.21 illustrates graphically the information presented in the above table. The marked diamond points refer to the triggers that yielded the lowest expected life cycle cost under different weights. It was found that as the weight increased, the lowest total EUAC shifted from Trigger = 6 to Trigger = 5, if Do Nothing was not considered.

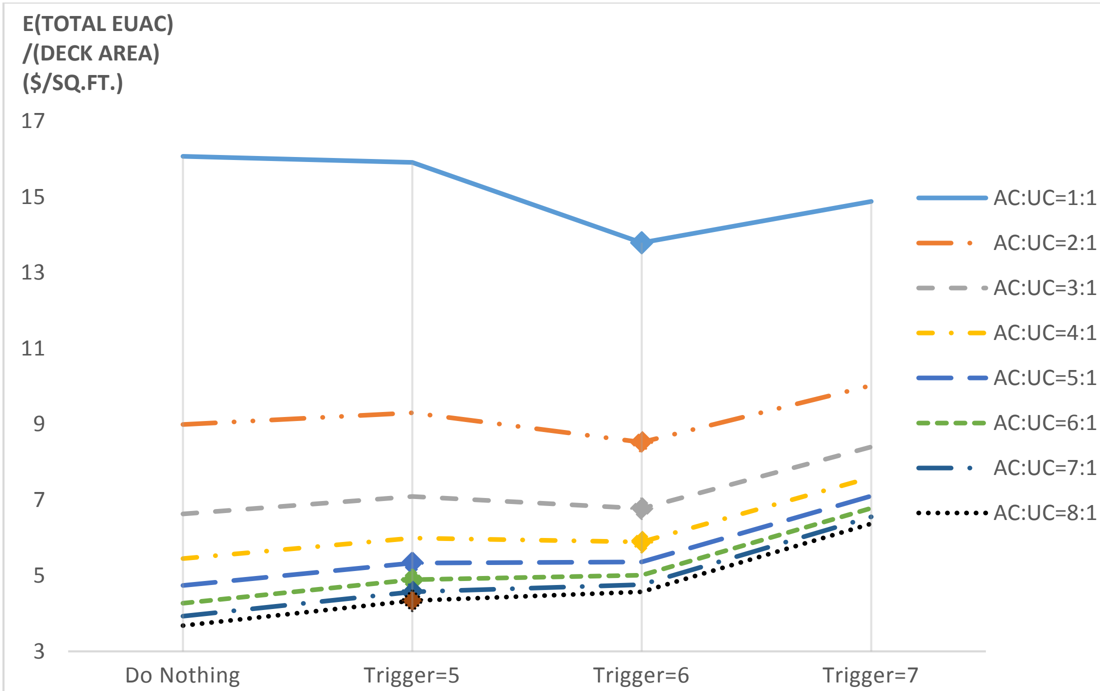


Figure 6.21 Sensitivity of Life Cycle Cost to the Agency Cost and User Cost Relative Weights

The accurate "critical" weights were calculated. The critical weight indicates the ratio that the optimal trigger changes if the weight is greater than or less than this ratio. It was found that if AC:UC > 4.69, Trigger = 5 would yield the lowest expected life cycle cost; if 0.43 < AC:UC < 4.69, Trigger = 6 would yield the lowest expected life cycle cost; and if 0 ≤ AC:UC < 0.43, Trigger = 7 would yield the lowest expected life cycle cost.

Figure 6.22, Figure 6.23, Figure 6.24, and Figure 6.25 present the box plots for the sensitivity analysis, which illustrate the variations in the stochastic life cycle cost in response to different triggers and AC:UC weights. Only four representative weights, 1:1, 3:1, 5:1, and 8:1, were presented because their results adequately show the change of the optimal triggers. The box plots show the interquartile ranges (IQR) only because, as mentioned previously, the IQRs could have more important implications. Besides, the difference among the box plots could be shown more clearly without the interference of the large variations caused by the 5th and 95th percentiles.

The overall trend is consistent with the results presented in Table 6.1 and Figure 6.21. When the weight AC:UC is greater than 5:1 (the exact ratio is 4.69:1), Trigger = 5 led to the lowest expected total EUAC. However, with randomness taken into account, significant overlapped portions were found between Trigger 5 and 6 for the weights of 3:1, 5:1, and 8:1. This may indicate that, in practice, where many risks and uncertainties exist, there may not be a significant difference between the life cycle costs associated with Trigger 5 and Trigger 6 regardless of the agency/user cost weight ratio. Even if the user cost were excluded, there could still be large overlapped portions, as shown earlier in Figure 6.18. In addition, the box plots show that the overall variations became smaller as the weight for agency cost became greater because there was smaller uncertainty in the life cycle agency cost compared with the life cycle user cost.

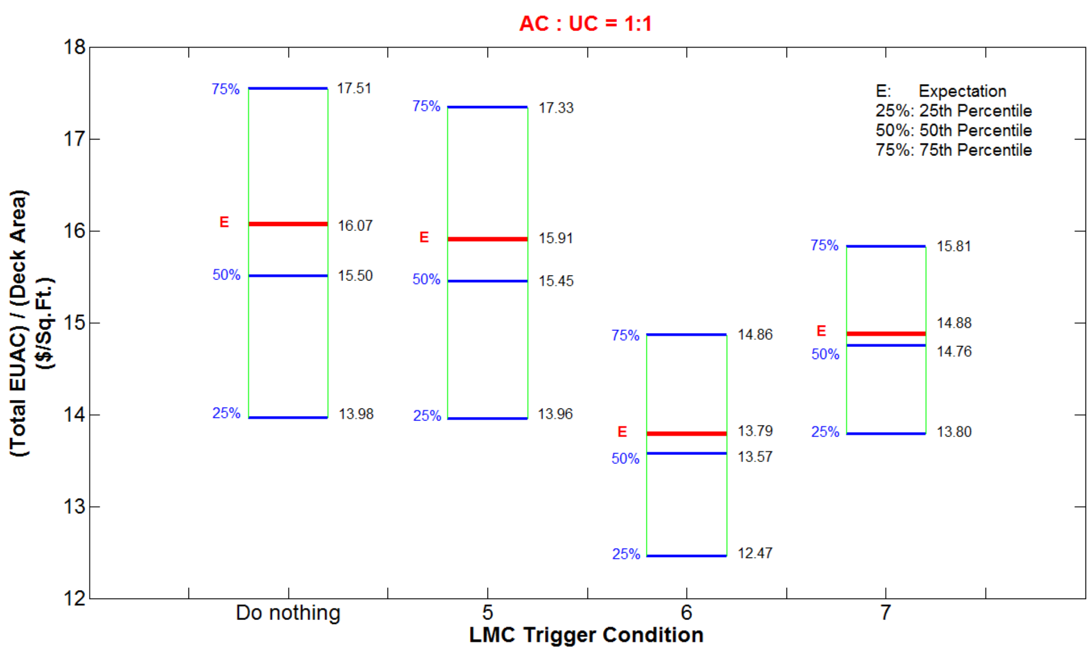


Figure 6.22 Box Plot for Total Life Cycle Cost (AC:UC = 1:1)

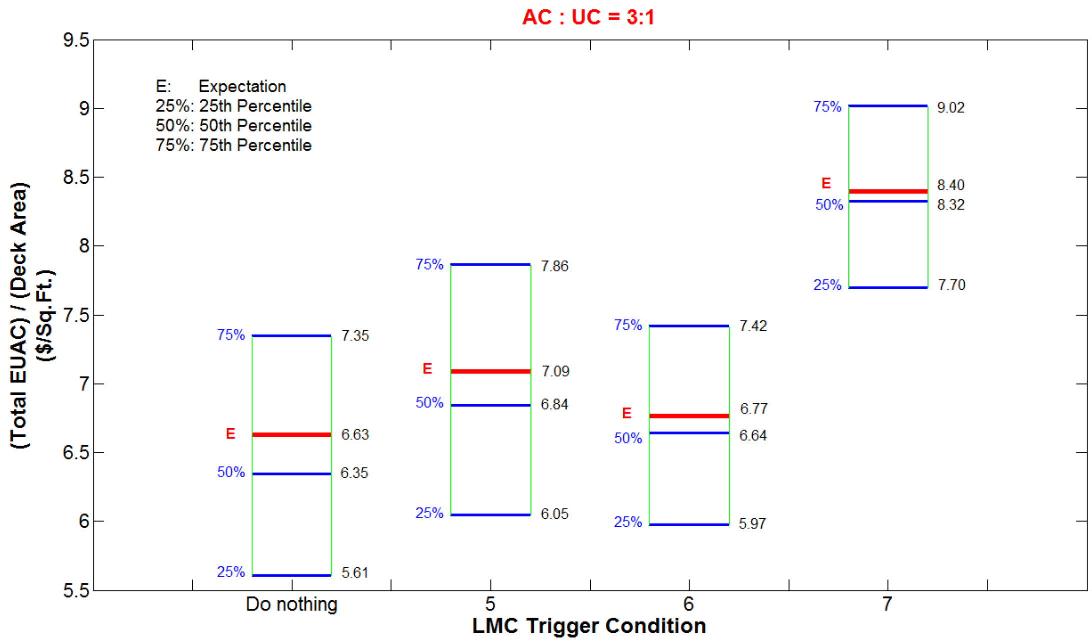


Figure 6.23 Box Plot for Total Life Cycle Cost (AC:UC = 3:1)

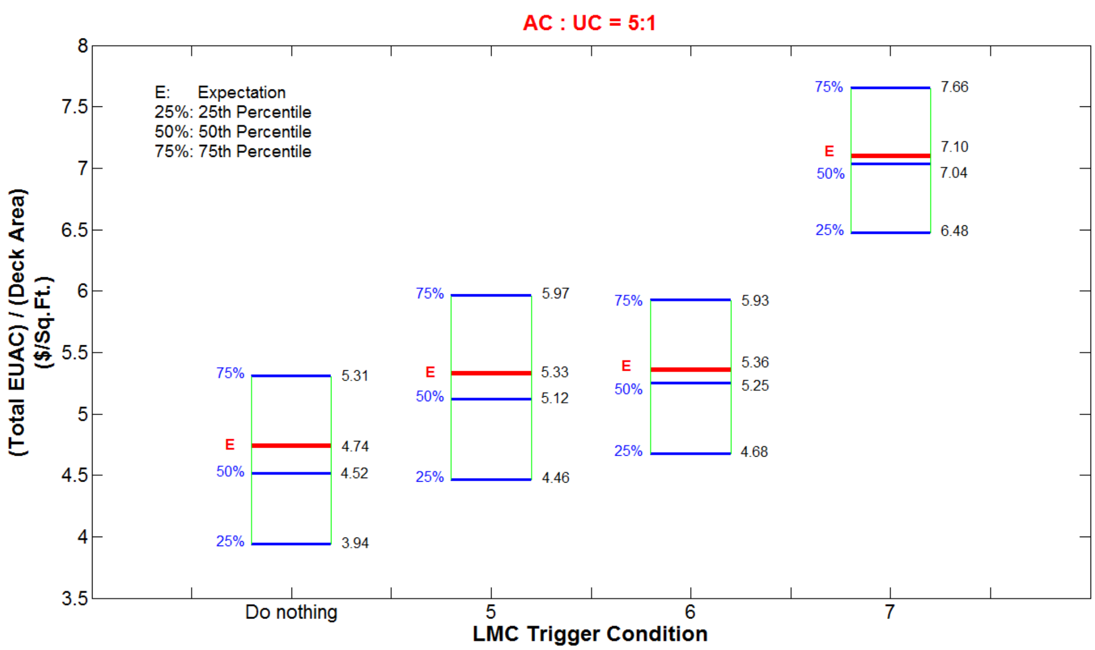


Figure 6.24 Box Plot for Total Life Cycle Cost (AC:UC = 5:1)

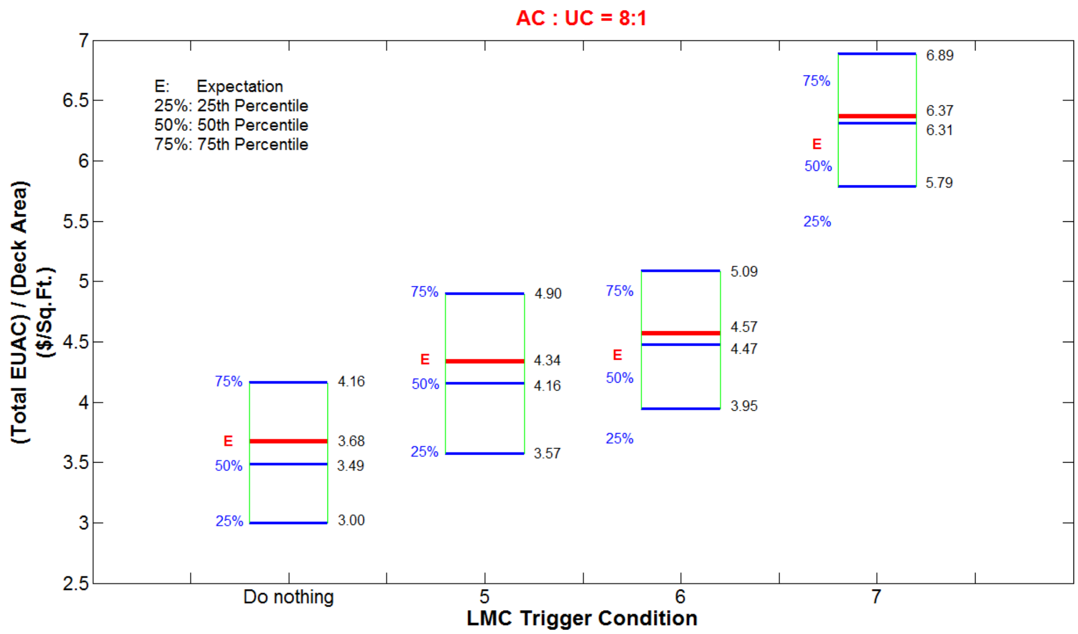


Figure 6.25 Box Plot for Total Life Cycle Cost (AC:UC = 8:1)

6.4 Proposed Bridge Deck Life-Cycle M&R Strategies

Based on the results from the sensitivity analysis, if each agency cost dollar weight is at least 4.69 times as much as each user cost dollar (i.e., AC:UC > 4.69:1), implementation of the LMC overlay is recommended when the deck condition reaches 5 (Trigger = 5). Also, if each agency cost dollar weight is greater than 0.43 times but smaller than 4.69 times of each user cost dollar (i.e., 0.43:1 < AC:UC < 4.69:1), implementation of the LMC overlay is recommended when the deck condition reaches 6 (Trigger = 6). Typically, an agency would not assign a higher weight to the user cost than to the agency cost. Therefore, Trigger = 7 would not be recommended under the typical practice of AC:UC ≥ 1:1.

Figure 6.26 and Figure 6.27 illustrate the recommended life-cycle deck maintenance and repair strategies under stochastic situations for LMC overlay Trigger = 5 and Trigger = 6, respectively. The duration of each condition state is stochastic; therefore, the most likely duration (duration with the highest probability) was selected to be used in the profiles for illustration purposes.

In the figures, the blue solid lines indicate the condition states and their durations before the implementation of the LMC overlay while the red solid lines indicate the condition states and their durations after the implementation of the LMC overlays. The numbers in boxes refer to their most likely durations. For example, in Figure 6.26, condition 6 was most likely to last for about eight years before the LMC overlay. On the other hand, post-treatment condition 6 was most likely to last for about six years, two years shorter than the pre-treatment duration. These durations were calculated based on the duration models developed for the monolithic concrete and the LMC wearing surface in Section 5.1.

In Figure 6.26, the LMC overlay was implemented when the deck condition reached 5, possibly about year 26. The exact years for implementing the overlay and deck replacement are not marked in the figures because a) this dissertation aimed to establish a condition-based strategy instead of a time-based strategy and b) time is actually stochastic and the figures only present one possibility for the implementation time. After the overlay, the performance jump was assumed to be 1 (condition reverting to 6) and the deck continued to deteriorate until its condition reached 4, possibly about year 36. Then, the deck was replaced at condition 4 and a new life cycle began. It was assumed that routine maintenance and minor repairs were conducted on a regular basis or triggered whenever needed, and thus are not shown in the figure.

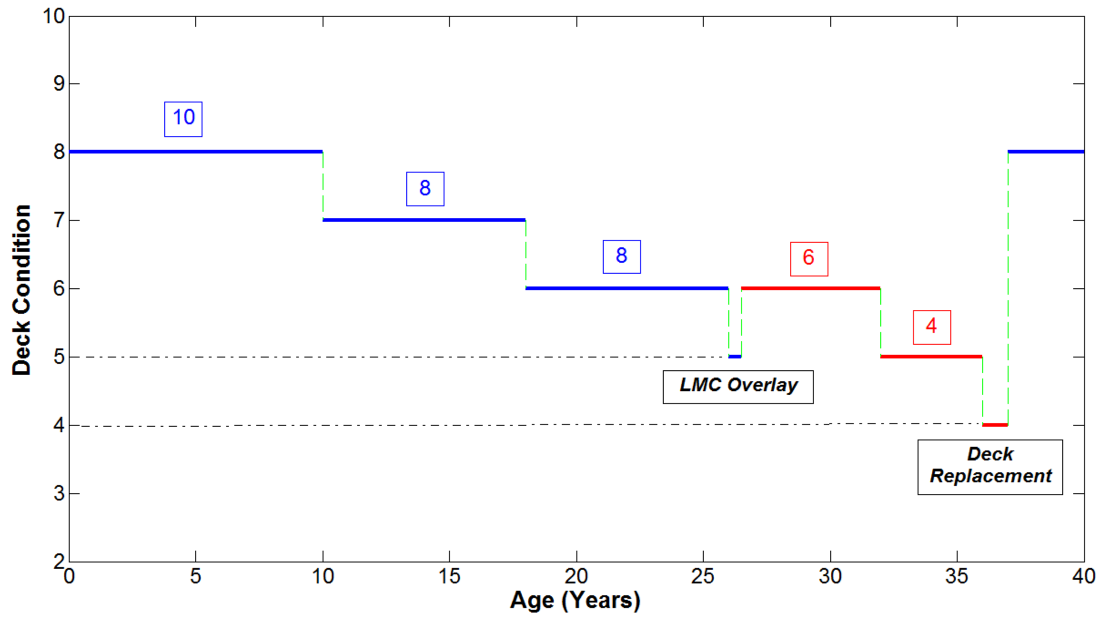


Figure 6.26 Proposed Bridge Deck Life-Cycle Condition-Based M&R Strategy (Trigger = 5)

In Figure 6.27, where the LMC overlay trigger was 6 and was triggered twice, the first recommended overlay took place when the deck condition reached 6, possibly at year 18. The performance jump was assumed to be 1 (condition reverting to 7) and the deck continued to deteriorate until its condition reached 6 again after possibly nine years from the first overlay. Then, the second overlay was triggered and improved the deck condition to 7 again. There were no more major treatments until the deck condition reached 4, which triggered a possible deck replacement about year 46, followed by a new service cycle. It was assumed that routine maintenance and minor repairs were conducted on a regular basis or triggered whenever needed, and thus are not shown in the figure.

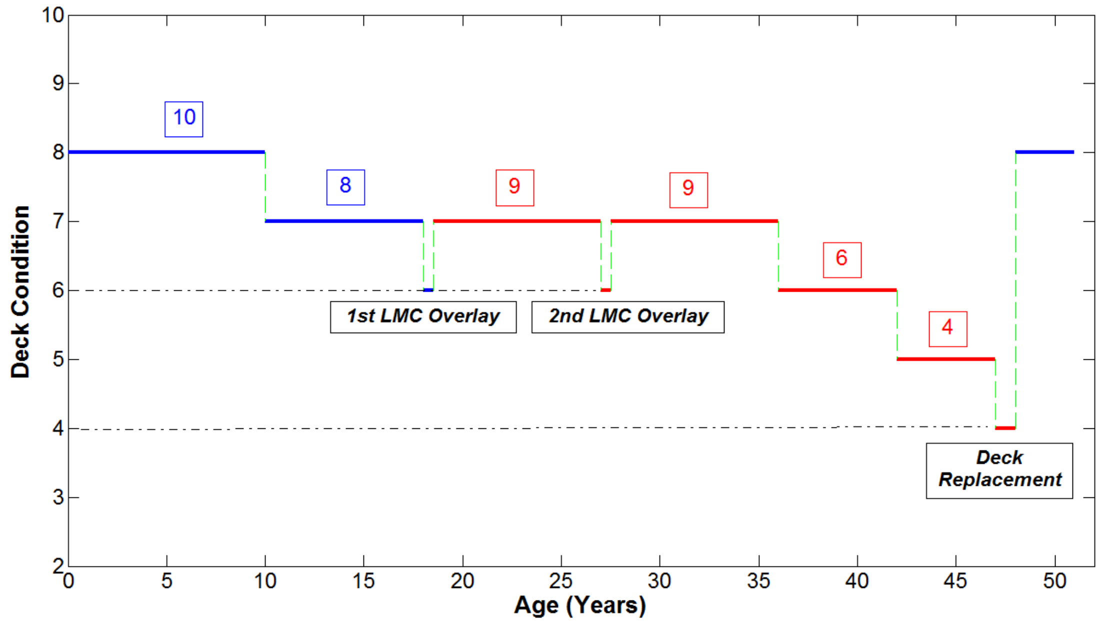


Figure 6.27 Proposed Bridge Deck Life-Cycle Condition-Based M&R Strategy (Trigger = 6)

6.5 Comparison between Results under Deterministic and Stochastic Situations

Chapter 4 discussed the life-cycle analysis results under deterministic situations and Chapter 6 discussed the life-cycle analysis results under stochastic situations. It is worthwhile to make some comparisons in terms of the results derived from these two situations. Their general differences include:

a) The analysis for the deterministic situation was carried out for different climate regions and functional classes separately. The analysis for the stochastic situation did not separately consider the regions and functional classes, mainly because the variables for the climate regions and function class were not consistently found to be statistically significant variables in all the models developed in Chapter 5. For those models that did not include these two variables, the impacts of climate region and functional class could not be captured.

b) Polymeric overlay was included as an additional deck treatment in the analysis for the deterministic situation. The stochastic situation did not incorporate the polymeric overlay into the analysis primarily because the available data were inadequate to develop stochastic duration models for the polymeric overlay.

c) In the deterministic situation, the trigger thresholds were established in terms of the wearing surface condition and the interactions between the wearing surface condition and the deck condition were considered. On the other hand, in the stochastic situation, only the deck condition was considered. This was again mainly due to the issue of data availability. In the NBI database, the wearing surface condition was not recorded as an item. Although ten years of data for the wearing surface condition were collected for this dissertation, the time span of the data was not long enough to develop reliable stochastic duration models. Although the wearing surface condition is a more appropriate trigger for the deck overlay because the overlay is a treatment that mainly deals with the deck surface, it was not unfeasible that overall deck condition was used as a trigger.

d) In the deterministic situation, both the deck and wearing surface were modeled as continuous deterioration. This appropriately captured the nature of the deterioration of infrastructure, which develops gradually and continuously. However, the modeling technique was not as appropriate because the recorded condition data were discrete count data instead of continuous variables. In contrast, the stochastic situation modeled the deck deterioration in terms of discrete condition states. The modeling technique was appropriate for the discrete count data type, but it did not adequately describe the natural infrastructure deterioration process because, in reality, bridge decks or other components do not suddenly drop from one condition state to another.

With regard to the specific results, Table 6.2 presents the results from the deterministic analysis (shown in column D) and the stochastic analysis (shown in column S) for comparison. For the deterministic situation, only a representative result for moderate region NHS is presented as an example for comparison. The overall trend, as mentioned in Section 6.2, was exactly the same in terms of these two analyses. Specifically, for the life cycle agency cost, the Do Nothing, Trigger 5, Trigger 6, and Trigger 7 ranked from low to high; for the life cycle user cost, the Do Nothing, Trigger 5, Trigger 6, and Trigger 7 ranked from high to low; and for life cycle agency cost (AC:UC=1:1), Trigger 6 had the lowest EUAC value in both analyses, followed by Trigger 7, Trigger 5, and Do Nothing.

The magnitudes of the EUACs turned out to be generally consistent. Given the fact that these two analyses used two different deterioration model forms, the disparities in their results, in terms of the magnitudes, can be regarded as acceptable. It is noted that the magnitudes of the life cycle agency cost only had minor disparities, while the life cycle user cost from the deterministic analysis were higher than those from the stochastic analysis. The reason for this difference was possibly due to the deterministic models using a continuously deteriorated condition, which caused the VOCs to continually increase with the deterioration while, for the stochastic analysis in which the conditions were integers, it was assumed that the VOCs maintained the same level as long as the deck condition stayed at a certain state. The VOCs contributed to the majority of the user costs. Therefore, the differences in the magnitudes of the VOCs may have led to the disparities between the two analyses.

Table 6.2 Comparison between Results from Deterministic Analysis (D) and Stochastic Analysis (S)

	Do Nothing		**Trigger = 5**		**Trigger = 6**		**Trigger = 7**	
	D	S	D	S	D	S	D	S
(Agency EUAC) / (Deck Area) ($/ft^2)	1.78	1.90	2.69	2.68	3.85	3.26	5.14	5.16
(User EUAC) / (Deck Area) ($/ft^2)	17.33	14.17	15.14	13.22	13.24	10.53	12.36	9.72
(Total EUAC) / (Deck Area) ($/ft^2)	19.11	16.07	17.83	15.91	17.09	13.79	17.50	14.88
Deck Service Life (years)	35	33	43	36	47	47	53	49

In addition, comparisons of deck service life also were made based on Table 6.2. The service life for the case of do nothing, Trigger = 6, and Trigger = 7 were similar (35 years vs. 33 years, 47 vs. 47 years, and 53 vs. 49 years, respectively). The only relative greater difference was for Trigger = 5 (43 vs. 36 years). The reason for this disparity could be due to the assumptions for the performance jump. In the stochastic analysis, a performance jump of one was assumed for all pre-treatment condition states. On the other hand, in the deterministic analysis, a performance jump model was developed and, based on the model, the performance jump was greater than one for condition 5.

The years in which the LMC overlays were triggered also were roughly compared even though this dissertation focused on condition-based instead of time-based strategies. If the LMC overlay was triggered at condition 5, both the deterministic analysis and the stochastic analysis happened to result in the same triggering age (expected age for the latter) was Year 26. If the LMC overlay was triggered at condition 6, the deterministic analysis recommended the triggering age to be approximately Year 17 for the first overlay and Year 30 for the second overlay; while the stochastic analysis recommended Year 18 and Year 27 (expected values). The two analyses generally led to similar ages for triggering the LMC overlays.

Finally, one more comparison could be made between the "critical" weights between agency cost and user cost found in the two analyses (i.e., the weights that would make the total EUAC of one trigger equal to that of another trigger). Under the deterministic situations, the critical weight that would make Trigger = 5 and Trigger = 6 indifferent was AC:UC=1.64:1 (moderate region, NHS), whereas such weight was AC:UC=4.69:1 (on average) for the stochastic situations. For Trigger = 6 and Trigger = 7 to be indifferent, the critical weight for the deterministic analysis was AC:UC=0.68:1 (moderate region, NHS), while the weight was AC:UC=0.43:1 (on average) for the stochastic analysis. The discrepancy in the critical weights, particularly between Triggers 5 and 6, could be mainly due to the difference in the magnitudes of the life cycle agency and user costs determined from the two analyses.

6.6 Chapter Summary

In this chapter, the life-cycle cost analysis results under the stochastic situation were presented and discussed. First, the probability distributions that the deck sojourns in specific condition states were calculated and the corresponding cumulative distributions were also presented. The stochastic life-cycle cost analysis results were presented using box plots that showed the expected values and various percentiles of the distributions. Significant variations existed in terms of some scenarios. The overall trend of the expected EUACs proved to be consistent with what was found under the deterministic situations. The sensitivity of the life cycle cost to the weights between agency and user costs, was investigated. Specifically, it was found that if AC:UC > 4.69:1, triggering LMC overlay at condition 5 would result in the lowest expected value of total life cycle cost; if 0.43:1 < AC:UC < 4.69:1, triggering LMC overlay at condition 6 would result in the lowest expected value of total life cycle cost; and if 0 ≤ AC:UC < 0.43:1, triggering LMC overlay at condition 7 would result in the lowest expected value of total life cycle cost. Because of the existence of uncertainties and the assignment of different weights to the user costs, both Trigger = 5 and Trigger = 6 were likely to result in the lowest total EUAC. Therefore, two recommended life-cycle condition-based deck M&R strategies were provided and illustrated. Finally, comparisons in terms of methodologies and results between the deterministic analysis and stochastic analysis were conducted. It was found that although the magnitudes of the EUAC results had some differences due to the different modeling techniques, the overall conclusions derived from these two analyses largely remained consistent.

CHAPTER 7. UPDATING THE DECISION TREE IN THE INDIANA BRIDGE MANAGEMENT SYSTEM

In the current Indiana Bridge Management System (IBMS), a decision tree, named DTREE, has been used for decision-making on treatment selection for all bridge components including deck, superstructure, and substructure. The DTREE provides suggestions with regard to what type of treatment should be implemented given the current condition ratings of deck, wearing surface, superstructure, substructure, deck geometry, etc. The latest version of the DTREE can be found in Sinha et al. (2009), and it is included in the Appendix E of this dissertation. However, the thresholds developed in the DTREE are based on expert opinion. Therefore, the data-driven thresholds developed in this dissertation can be used to verify or update, if necessary, those deck-related thresholds in the existing DTREE.

7.1 Issues with regard to the Existing DTREE

Figure 7.1 presents the portion of the existing DTREE that is related to bridge deck treatments for NHS bridges. Through investigation, several problems were found for this portion of the DTREE. The following paragraphs use the node numbers and action numbers that are originally marked in the DTREE to point out where the problems are located. Besides, these problems are also marked in Figure 7.2 using boxes and bold lines.

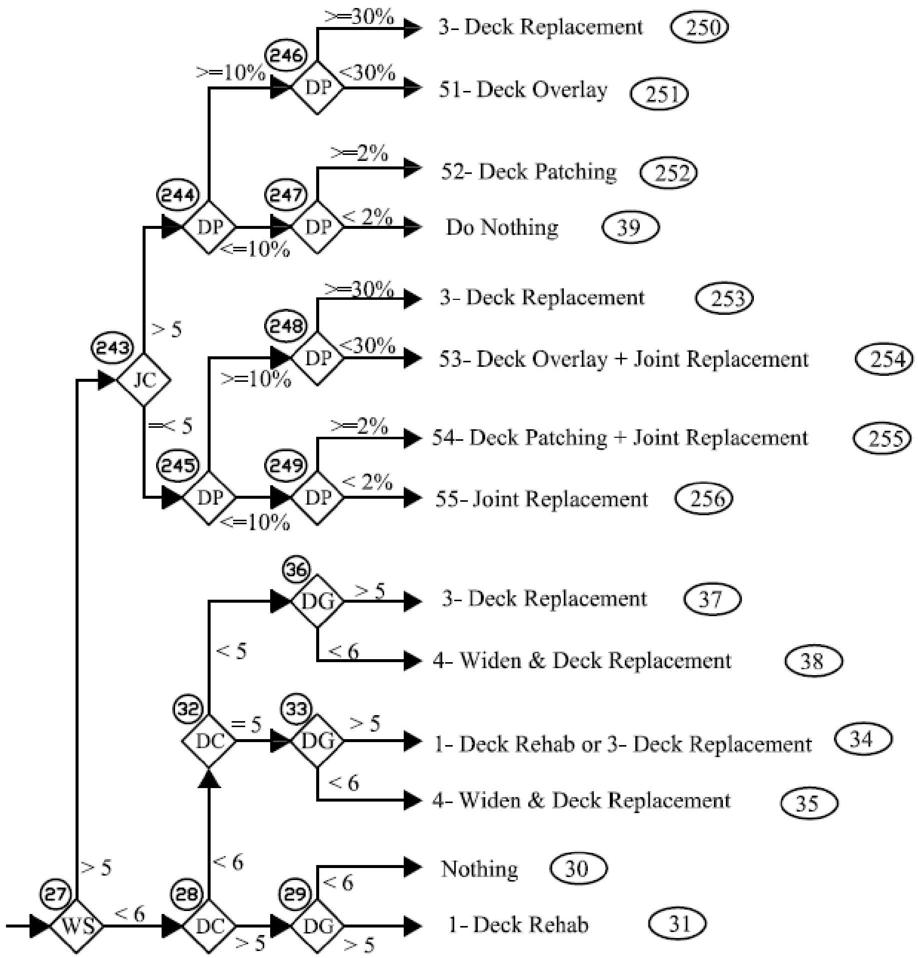


Figure 7.1 Existing DTREE for Bridge Deck M&R Treatments in the IBMS
(Source: Sinha et al., 2009)

Generally, the upper part of the DTREE (within the green dotted-line box in Figure 7.2) was actually an updated part in the 2009 version DTREE as an addition to the original lower part (within the blue solid-line box in Figure 7.2). However, such combination caused some problems in terms of the logic and the decision variables, listed as follows:

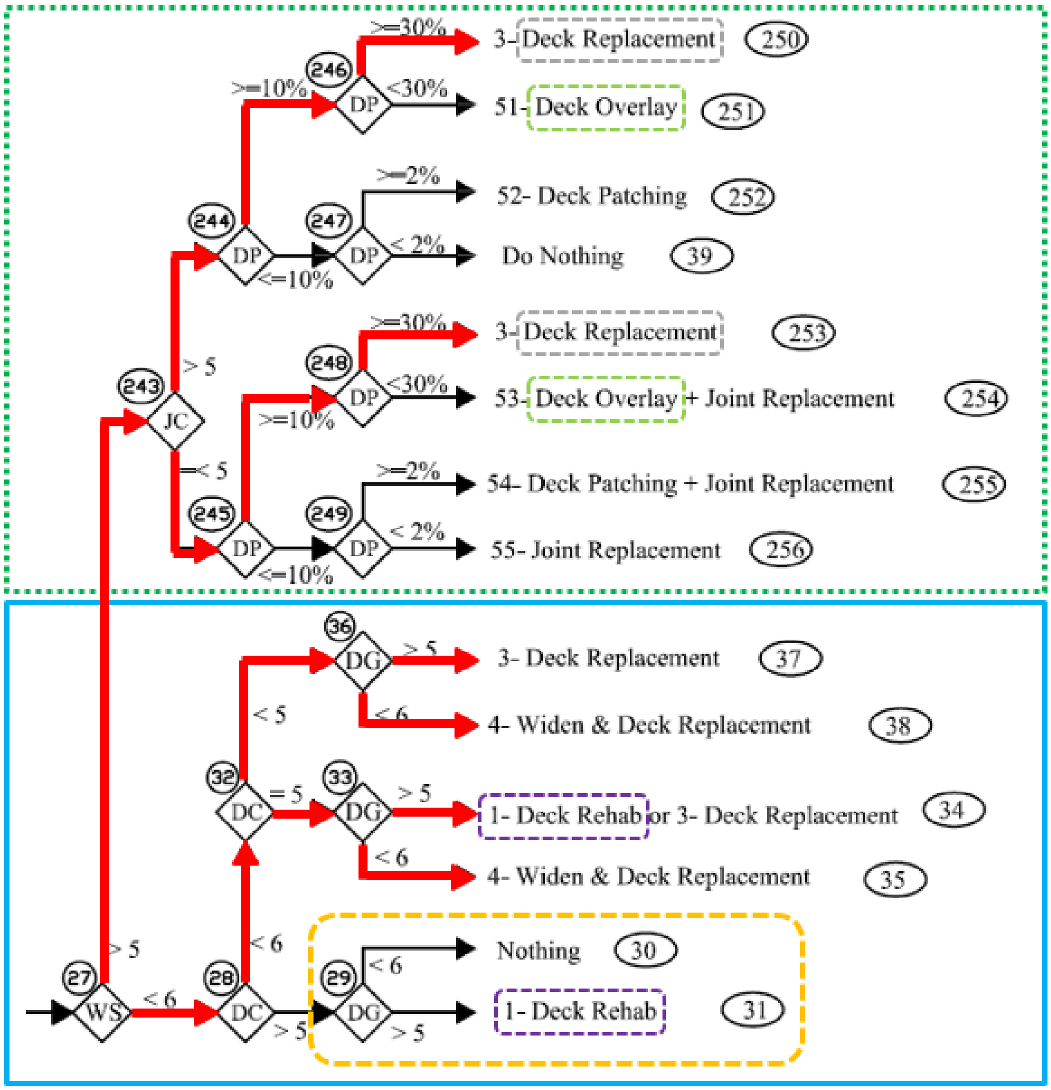


Figure 7.2 Issues with regard to the Existing DTREE

(a) The lower part of the DTREE is activated only when the wearing surface condition is lower than 6 (WS < 6). However, in the upper part of the DTREE, the candidate treatments include deck overlay and deck replacement. Both these two treatments will actually create a new wearing surface. Therefore, the wearing surface condition (WS) will always revert back to 9 after going through the upper part of the DTREE. In fact, a loop is formed within the upper part and the lower part will never have a chance to be activated any more.

(b) The deck replacement treatment (Action 250 and Action 253) in the upper part of the DTREE (marked with bold red lines in Figure 7.2) is simply determined by the deck patching area percentage (DP). Deck condition (DC) is not included as a decision variable in the upper part. Besides, all the upper part is under the condition that wearing surface condition is greater than 5 (WS>5). Therefore, it is saying that with a wearing surface condition of 6 or higher, without considering deck condition rating, as long as the patching area is greater than 30%, then the deck needs to be replaced. Two problems exist herein: 1) deck condition rating should be considered because the patching area percentage can only reflect the condition of the deck surface, instead of the overall deck condition; 2) it seems that DP>30% can contradict with the premise that WS>5. Would a wearing surface with more than 30% patching area be rated as 6 or higher?

(c) In the lower part of the DTREE, there seems to be an error on Node 29. Intuitively, DG>5 should correspond to Do Nothing and DG<6 should correspond to Deck Rehab. However, even if this error is corrected, the deck geometry rating (DG) should only determine whether the deck needs widening. The current Note 29 indicates that when wearing surface condition is worse than 6 but deck condition is better than 5, if deck geometry rating is worse than 6, do nothing; if better than 5, do deck rehabilitation. In fact, given that wearing surface condition is 5 or lower, it makes no sense that deck rehabilitation is given up because deck geometry rating is good. Therefore, Node 29 seems incorrect and unnecessary.

(d) The deck rehabilitation treatment (Action 31 and Action 34) in the lower part of the DTREE does not specify which type of deck rehabilitation should be used. Perhaps the DTREE leaves the flexibility to the decision makers regarding what rehabilitation treatments to be used. Similarly, the deck overlay treatment (Action 251 and Action 254) in the upper part of the DTREE does not specify which type of deck overlay should be used. In fact, deck overlay belongs to the deck rehabilitation techniques. The terms deck overlay and deck rehabilitation should not be mixed used.

(e) The upper part of the DTREE actually defines some threshold ranges, rather than specific threshold values, to trigger deck treatments. For example, based on the upper part, the deck overlay can be triggered at any threshold between DP = 10% and DP = 30%. However, there could be a large interval between the time when DP = 10% and the time when DP = 30%. This can cause significant variability in terms of the life-cycle cost for the deck overlay, because the discounted present value of the overlay cost significantly depends on the year when it is implemented.

7.2 Updates to the Existing DTREE

This dissertation attempts to resolve the aforementioned issues by proposing an updated DTREE for the portion related to deck treatments. The proposed DTREE is presented in Figure 7.3.

The updated DTREE integrates the upper part and the lower part of the existing DTREE and incorporates two specific types of deck overlay treatments. The overall flow process is simplified. Deck condition rating (DC) is assured to be an important decision variable in the entire DTREE. Patching area percentage (DP) will not determine a major deck treatment by itself. Deck geometry rating (DG) plays its role only when it is in the range that triggers deck widening. The overall decision flow process is demonstrated as follows:

First, check the deck geometry rating (DG); if it is lower than or equal to 5 (this threshold follows the one in the existing DTREE), the deck needs to be replaced and widened. If the deck geometry rating (DG) is fair or above (≥ 6), go ahead and check the deck condition (DC). If the deck condition (DC) is lower than or equal to 4, the deck needs to be replaced. If the deck condition (DC) is higher than or equal to 5, go ahead and check the joint condition (JC). If the joint condition (JC) is higher than or equal to 6, check the wearing surface condition (WS) and the patching area percentage (DP) to determine the final treatment type: if WS ≥ 7 and DP < 2%, no action is needed at the moment; if WS ≥ 7 and DP ≥ 2%, deck patching is suggested; if WS = 6, the polymeric overlay is recommended; if WS = 5, the LMC overlay is the proposed treatment. If the joint condition (JC) is less than or equal to 5, then joint replacement is required in addition to any other suggested treatments. It is suggested that this updated DTREE is used for the deck treatment decision-making once every year or once every two years, depending on the frequency of the bridge inspection carried out by the agency.

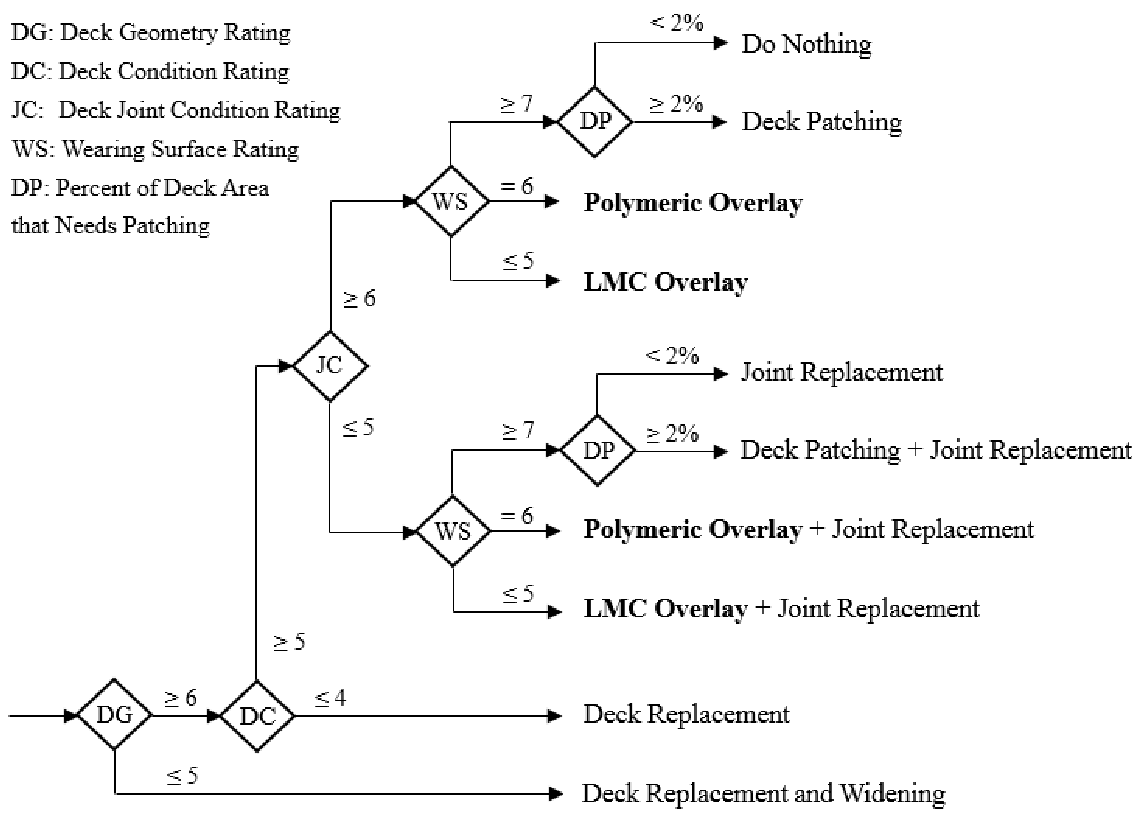


Figure 7.3 Updated DTREE for Bridge Deck M&R Treatments

The updated DTREE includes both the LMC overlay and the polymeric overlay as treatment candidates. However, if the polymeric overlay is not an available option for some agency, the LMC overlay can be triggered at either WS = 6 or WS = 5, depending on the agency’s preference with regard to the relative weights between the agency cost and the user cost.

7.3 Comparison between the Updated DTREE and the Existing DTREE in terms of Life-Cycle Cost Using Examples

Although the updated DTREE addresses the issues in the existing DTREE, it is worth investigating that whether the updated DTREE is superior to the existing DTREE in terms of the life-cycle cost of the decision-makings based on these two DTREEs.

A representative bridge, is used in this section as an example to demonstrate the life-cycle strategies and costs based on the two different DTREES. The characteristics of this bridge represent the average level of the characteristics of bridges from moderate climate region of Indiana, NHS highways. The statistics are: structure length 165ft, structure width 40ft, average daily traffic 7,300, heavy vehicle percentage 12.5%, and detour length 4.5 miles. The data for agency and user costs are taken from Chapter 4 and the average values are used here. The deterioration models and the performance jumps models for the corresponding bridge are taken from Chapter 3. With regard to existing DTREE, patching area information is need. The data for the annual increase in the patching area is taken from the IBMS manual (Sinha et al., 2009).

Based on the performance thresholds developed in the updated DTREE, the yielded life-cycle deck M&R strategy is presented in Figure 7.4. Please note that this figure is not drawn to scale, and the deterioration curves and performance jumps plotted in this figure do not represent the exact developed models. The purpose of this figure is for illustration only. In addition, deck geometry rating is not considered as a constraint herein because deck geometry depends on the traffic instead the bridge itself. It is assumed that the deck geometry satisfies the traffic requirement over its life cycle. It can be seen that the yielded strategy is actually similar to the strategy for the P6L5 scenario developed in Chapter 4. When wearing surface condition is higher than or equal to 7, deck patching is recommended if the area that needs patching is greater than 2% of the deck area. Polymeric overlay is suggested when wearing surface condition reaches 6 at approximately the 14^{th} year. Then, LMC overlay is triggered if the wearing surface condition drops to 5 at approximately the 29^{th} year. Finally, deck replacement is needed when the deck condition reaches 4 at approximately the 45^{th} year.

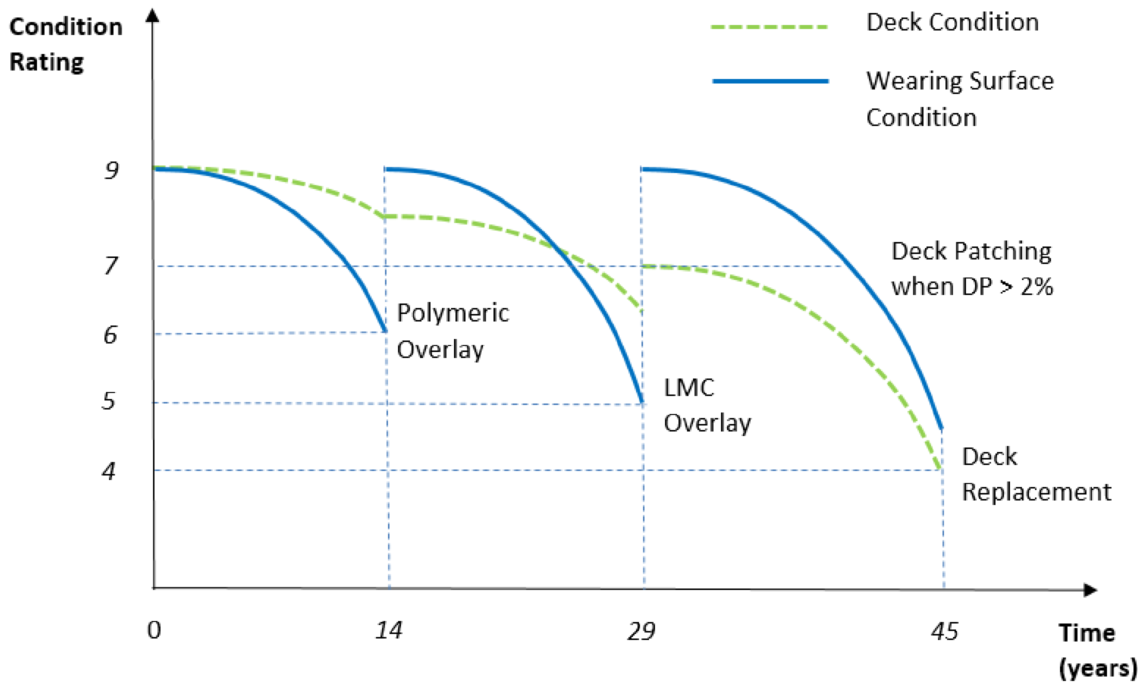


Figure 7.4 Life-Cycle Deck M&R Strategy based on the Updated DTREE for a Representative Bridge

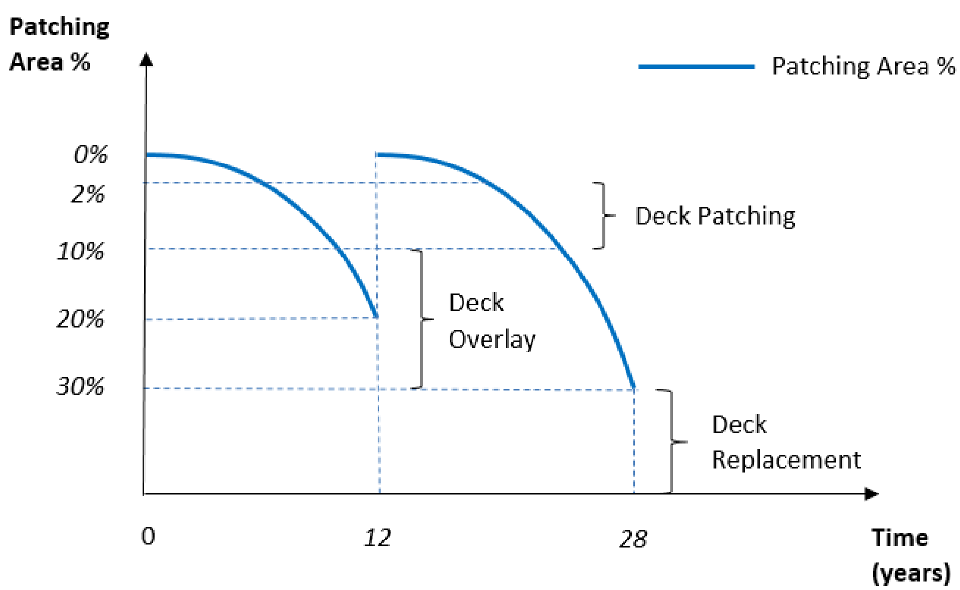


Figure 7.5 Life-Cycle Deck M&R Strategy based on the Existing DTREE (Upper Part) for a Representative Bridge

The yielded life-cycle deck M&R strategy based on the existing DTREE is illustrated in Figure 7.5. Similarly, this figure is not drawn to scale and is for illustration purpose only. As mentioned in Section 7.1, one issue of the existing DTREE is that the upper part forms a loop within itself. Therefore, the strategy presented in Figure 7.5 is based on the upper part of the existing DTREE only. This part of the DTREE only suggests threshold ranges instead of specified fixed thresholds. The trigger for the deck overlay plotted in the figure is marked at 20%, which is the average of the range 10% - 30%. Based on the data in the IBMS, the total patching area (i.e., the area that needs patching and is already patched) reaches 20% in approximately the 12th year, and the deck overlay is triggered (because it does not specify the type of the overlay, LMC overlay is assumed for the cost analysis). The total patching area reaches 30% in approximately the 28th year, and the deck should be replaced. It can be found that the total deck service life from the existing DTREE is significantly shorter than that from the updated DTREE. This is partly because this upper part of the DTREE only uses the patching area as the main decision variable. When the patching area reaches 30%, the overall deck may still be in fair condition.

With regard to the lower part of the existing DTREE, if deck geometry rating is not considered, it is simply indicating that if deck condition is lower than 5, deck should be replaced; if deck condition is equal to 5, decision maker can choose either deck rehabilitation or deck replacement; if deck condition is greater than 5 but wearing surface condition lower than 6, deck rehabilitation should be carried out. This is actually similar to the LMC Trigger = 5 strategy developed in Chapter 4, if the deck rehabilitation in this part of DTREE mainly refers to deck overlay.

Given the life-cycle strategies developed from the three DTREES (the updated DTREE, upper part of the existing DTREE, and lower part of the existing DTREE), the life-cycle agency and user costs can be calculated using data for the representative bridge. The results are presented in Table 7.1. It turned out that the updated DTREE yielded the lowest total life-cycle cost (agency and user cost combined with 1:1 ratio), lowest life-cycle user cost, and longest deck service life. The agency cost from the lower part of the existing DTREE was the lowest because only one deck rehabilitation treatment is triggered over the life cycle. However, it would lead to higher user costs due to surface roughness, compared with the strategy recommended from the updated DTREE. With respect to the results from the upper part of the existing DTREE, its life-cycle agency cost, user cost, and total cost were all found to be the highest compared with the other two candidates. This was largely due to its short deck service life because it used the deck patching area as the decision variable. Besides, frequent patching treatments would incur higher unit agency cost and higher user cost due to work zone.

Table 7.1 Comparison of Life-Cycle Costs based on the Updated DTREE and the Existing DTREE for a Representative Bridge

	Updated DTREE	**Upper Part of Existing DTREE**	**Lower Part of Existing DTREE**
Life-Cycle Agency Cost (Agency EUAC/Deck Area) ($\$/ft^2$)	3.06	6.36	**2.71**
Life-Cycle User Cost (User EUAC/Deck Area) ($\$/ft^2$)	**13.52**	14.42	15.19
Life-Cycle Total Cost (Total EUAC/Deck Area) ($\$/ft^2$)	**16.58**	20.78	17.90
Deck Service Life (years)	**45**	28	41

Although the updated DTREE showed its advantage in the example using a representative bridge, it is still not perfectly designed. Only a limited number of treatment types is incorporated, and it does not reflect the possible change in the recommended thresholds if the relative weight between agency and user cost changes. In future research, if more deck treatment types could be investigated, the DTREE could be further improved.

CHAPTER 8. SUMMARY AND RECOMMENDATIONS

8.1 Summary and Findings

This dissertation sought to establish data-driven condition-based performance thresholds for triggering bridge deck M&R treatments. The methodology framework was developed and analysis was conducted under both deterministic and stochastic situations. Under the deterministic situation, statistical models were developed, including bridge deck and wearing surface deterioration models, performance jump (sudden improvement in condition) models, and deck treatment cost models. 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 during the deck work. Two types of bridge user costs were taken into account, including travel time costs due to work zone delays and the incremental VOC during normal operations due to the increased roughness of the bridge deck surface. An optimization framework that involved life-cycle costs was developed, which was demonstrated using bridge data from Indiana. Separate analyses were conducted with respect to different climate regions in Indiana (cold, moderate, and warm) and different highway functional classes (national highway system (NHS) and non-NHS). Sensitivity analysis was carried out to investigate the impacts of the agency cost and user cost weights and the traffic volume on the life-cycle cost. It was found that different weights and traffic volumes significantly impacted the optimal trigger associated with the lowest life-cycle cost for some scenarios. In addition, life-cycle condition-based deck M&R strategies for various scenarios were proposed and illustrated. The proposed life-cycle M&R strategies based on the deterministic analyses are presented in this chapter again by Figure 8.1, Figure 8.2, and Figure 8.3, which are identical to the figures in Section 4.4). These figures present the strategies for only the

NHS bridges in the moderate climate region. Additional strategies for other climate regions and functional classes can be found in Appendix B of this dissertation.

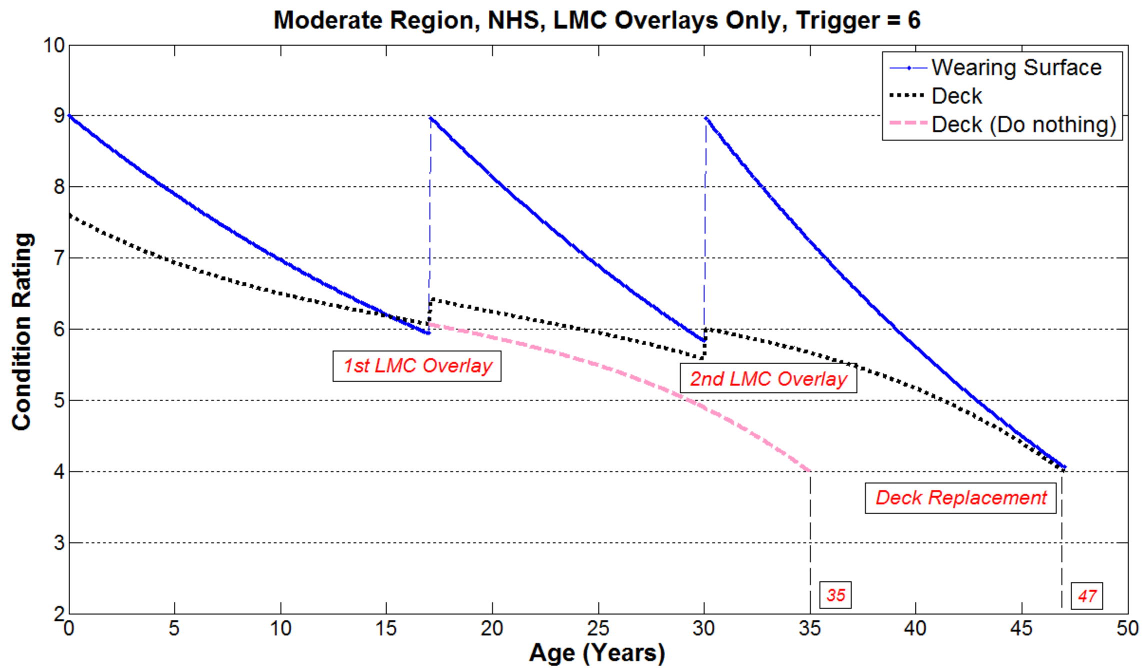


Figure 8.1 Proposed Condition-Based Bridge Deck M&R Strategy for Moderate Region, NHS, LMC Overlays Only, Trigger = 6

Under the stochastic situation, hazard-based duration models were developed to estimate the probabilistic duration for each expected deck condition state. Various functional forms for the hazard distribution were attempted, including exponential distribution, Weibull distribution, Weibull distribution with gamma heterogeneity, and log-logistic distribution. The estimation results indicated that state dependence existed in all condition states, meaning that the probability of the duration of a condition state ending soon was related to the time duration. Separate duration models were developed for three different types of wearing surface (monolithic concrete, latex-modified concrete (LMC), and asphalt) to investigate the post-treatment effect of the LMC overlay and the potential protection effect of the asphalt wearing surface. The underlying uncertainties existing in terms of agency costs, user costs, traffic, and inflation rates were discussed.

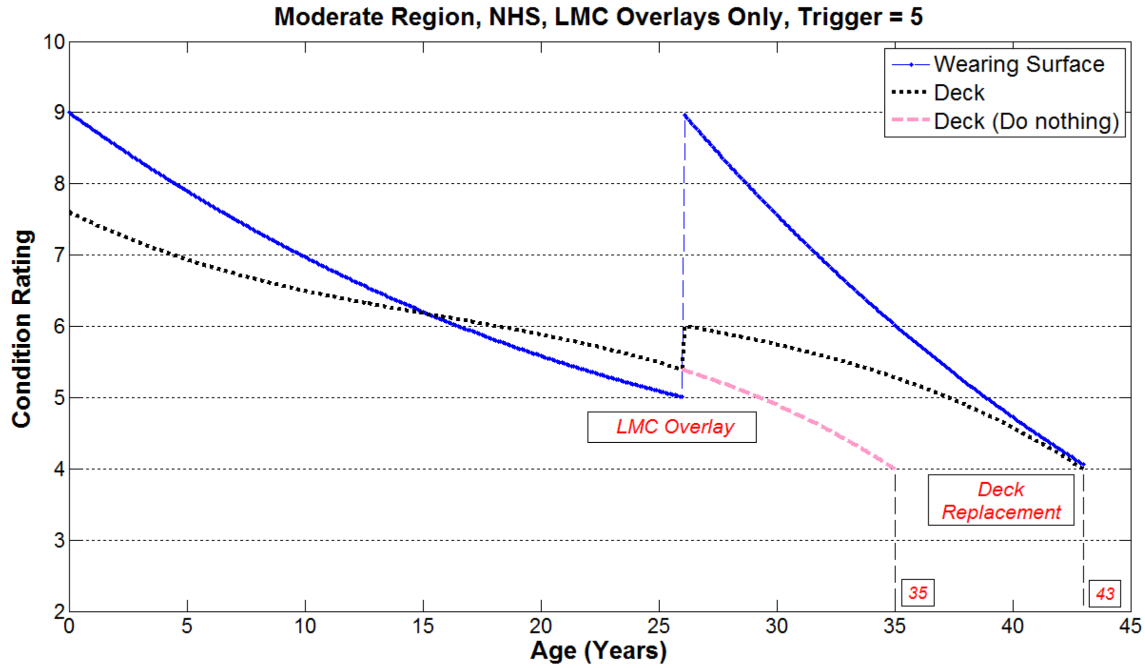


Figure 8.2 Proposed Condition-Based Bridge Deck M&R Strategy based on Deterministic Analysis, for Moderate Region, NHS, LMC Overlays Only, Trigger = 5

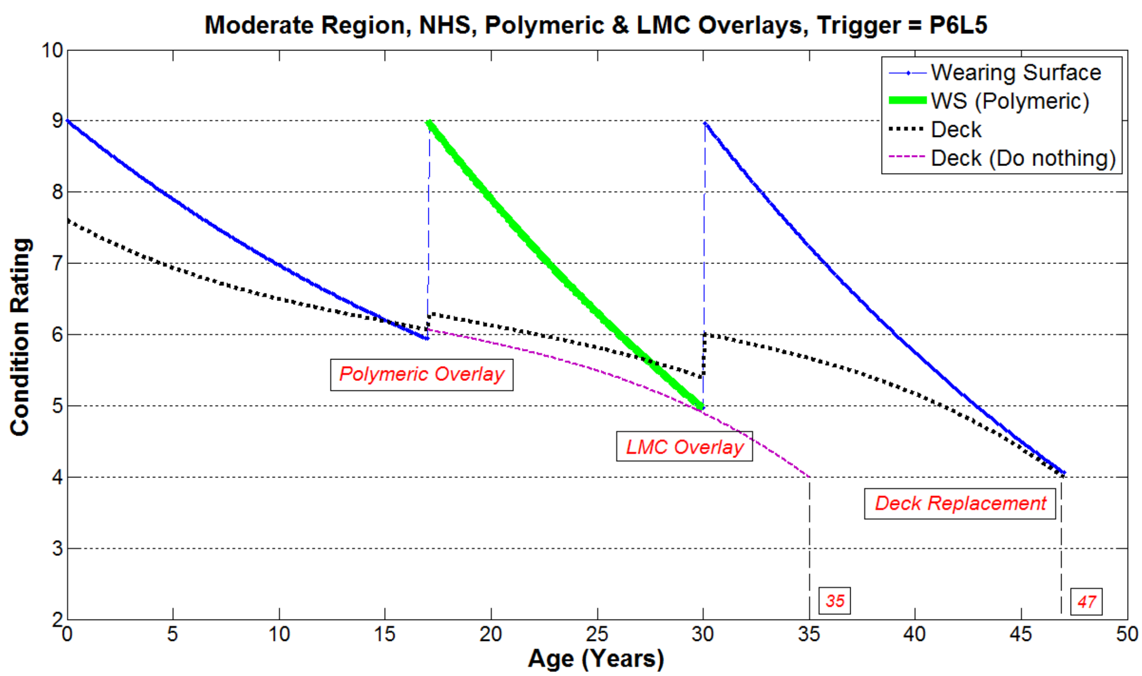


Figure 8.3 Proposed Condition-Based Bridge Deck M&R Strategy based on Deterministic Analysis, for Moderate Region, NHS, LMC Overlays Only, Trigger = Polymer6-LMC5

The optimization framework under the stochastic situation was established. The objective function was to minimize the expected value of the life-cycle weighted sum of the agency cost and the user cost. Life-cycle cost analysis was carried out under the stochastic situation. The stochastic life-cycle cost results are presented using box plots that show the expected values and various percentiles of the distributions. There were significant variations in the results for some of the scenarios. The overall trend of the expected life-cycle cost proved to be consistent with the results under the deterministic situation. In addition, the recommended life-cycle condition-based deck M&R strategies were proposed and illustrated. Finally, comparisons between the deterministic analysis and stochastic analysis in terms of the methodologies and the results were conducted. It was found that, although the magnitudes of the EUAC results had minor differences, the overall conclusions derived from these two analyses remained consistent. The proposed life-cycle M&R strategies based on the deterministic analyses are presented in this chapter in Figure 8.4 and Figure 8.5 (identical to figures in Section 6.4).

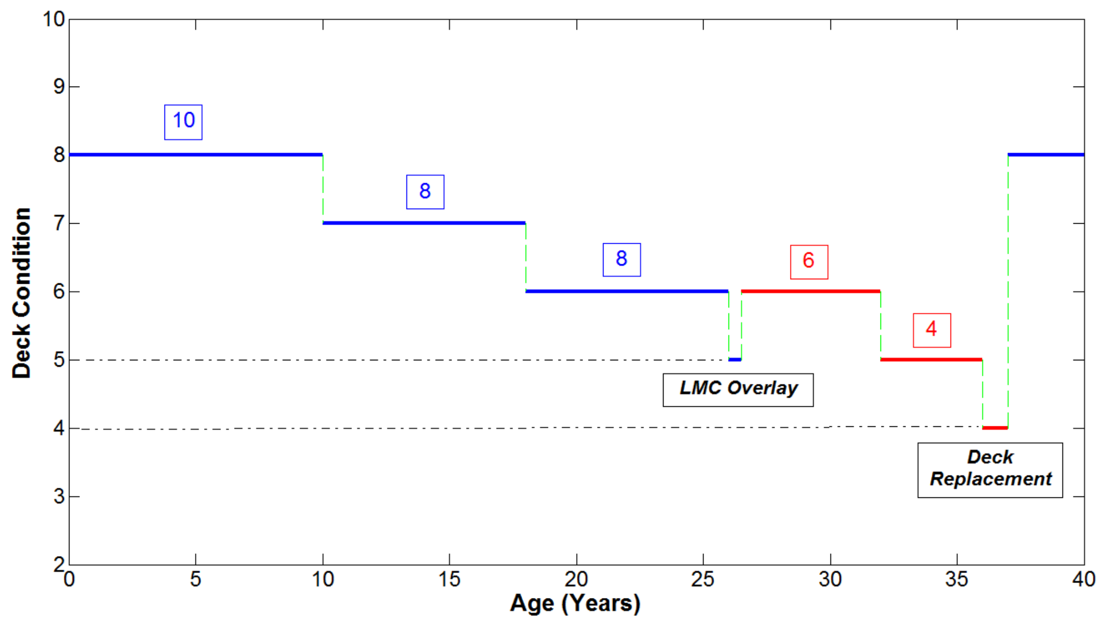


Figure 8.4 Proposed Condition-Based Bridge Deck M&R Strategy based on Stochastic Analysis, for NHS, LMC Overlays Only, Trigger = 5

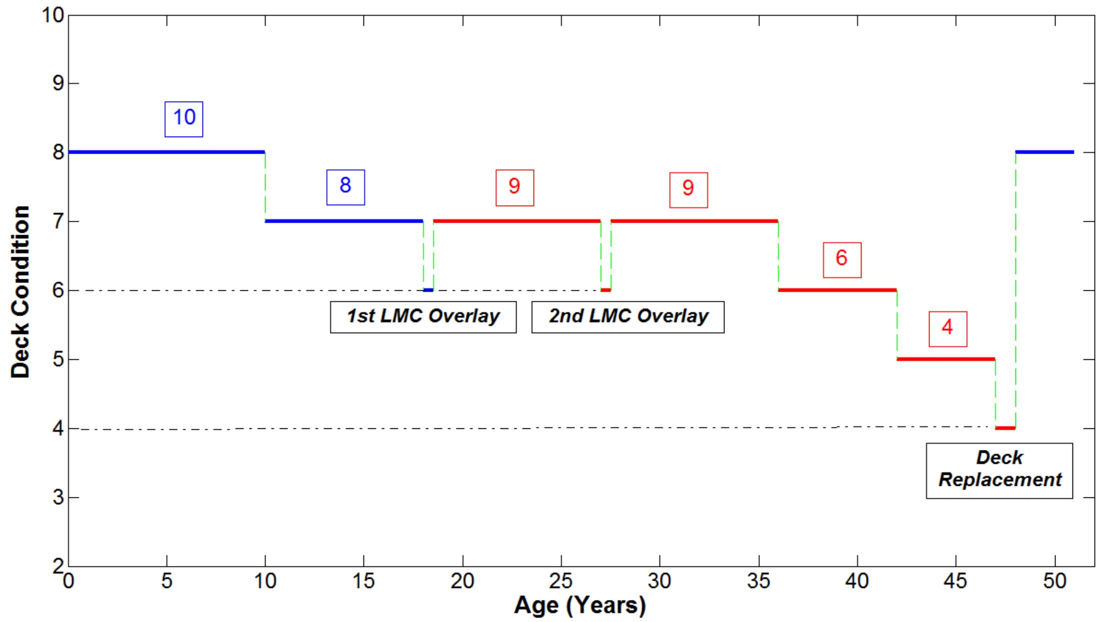


Figure 8.5 Proposed Condition-Based Bridge Deck M&R Strategy based on Stochastic Analysis, for NHS, LMC Overlays Only, Trigger = 6

Although the developed triggers and the proposed strategies in this dissertation were based on the data obtained from the state of Indiana, the established framework can be readily applied to any state or agency that uses similar deck M&R treatments. Generally, it is expected that this dissertation's data-driven analysis and results will enhance the state of bridge management practice and decision-making with respect to the condition-based timing of bridge deck M&R treatments.

8.2 Contributions of this Dissertation

a) This dissertation developed condition-based performance thresholds for triggering certain bridge deck treatments based on analytical approaches. In current practice, such thresholds are generally determined using expert opinion. In previous academic research, very few projects addressed the issue of triggers for specific bridge deck treatments.

b) This dissertation proposed condition-based life-cycle bridge deck M&R strategies that are expected to be more reasonable and applicable in real practice compared to the time-based strategies commonly proposed in previous studies and adopted by highway agencies.

c) This dissertation investigated two specific deck overlay treatments that have not been studied much in the past: latex-modified concrete (LMC) overlay and polymeric overlay. LMC overlay is one of the most commonly-used and important overlay techniques in the U.S., and polymeric overlay has gained increasing popularity in recent years. Therefore, this dissertation contributes greatly to the state of the practice knowledge for these two techniques.

d) This dissertation developed stochastic hazard-based duration models to estimate the durations of each deck condition state. Separate models were developed for three types of wearing surface (i.e., monolithic concrete, LMC, and asphalt). The LMC models captured the impact of LMC overlay on post-treatment deterioration. The asphalt wearing surface models analyzed the potential protection effect of the asphalt. Stochastics models for these three wearing surface types were not found in the past literature.

e) This dissertation conducted stochastic life-cycle cost analysis. Probability distributions of deck service life and life-cycle agency costs, user costs, and total costs for different candidate LMC overlay trigger thresholds were determined on the basis of the stochastic deck deterioration models developed in this dissertation.

f) This dissertation quantified the impact of the weighting between the agency cost and the user cost. The results indicated that when different weights were assigned to the user cost, the optimal trigger threshold changed.

g) This dissertation proposed an updated decision tree on the basis of the existing decision tree (DTREE) related to deck M&R treatments in the IBMS. The updated DTREE incorporates the recommended triggers based on the results of this dissertation and improved the logic flows of the decision tree compared to the existing.

8.3 Recommendations for Future Research

The following future research is recommended to address the limitations of this dissertation.

a) In the optimization framework of this dissertation, the objective function only considered the life-cycle cost. In future research, performance measures that represent the benefits for the agency and the user may be developed. These performance measures for benefits should not double count the effect that is already captured by the agency and user costs. Then, a cost-effectiveness optimization or multi-objective optimization can be formulated. In addition, in the optimization framework, the decision variable was restricted at a fixed level (i.e., a fixed trigger threshold was assumed to be applied over the life cycle of the deck). In future research, it would be worthwhile to investigate whether flexible trigger thresholds (i.e., different trigger thresholds in one life cycle) would yield lower life-cycle costs. Moreover, the condition-based threshold used in this dissertation was based on the NBI ratings (the wearing surface condition rating and the deck condition rating). However, in real practice, the decision-making for triggering deck treatments may also depend on other performance indicators besides the NBI ratings, such as patches, delamination, and other deck distresses. In future research, the threshold could be developed in terms of an index that combines the NBI ratings and other performance indicators.

b) In this dissertation, only two major bridge deck overlay treatments, LMC overlay and polymeric overlay, were included in the analysis. Other treatments were not considered for the following reasons: 1) unlike deck overlays that can be triggered and implemented on a relatively regular basis, the majority of other treatments, such as deck patching, joint repair and replacement, and railing repair, are basically triggered whenever needed in practice; and 2) the effects of many other treatments on the deterioration of the deck or wearing surface cannot be well captured by the current inspection record data. For example, the effect of minor patching or deck crack sealing typically would not be reflected by a change in deck condition or wearing surface condition. Thus, the impacts of these treatments on the life-cycle costs could not be well defined and accommodated in the analysis in this dissertation.

c) Some highway agencies have begun using polymeric overlays more often in recent years, which caused a lack of adequate data in some cases. For example, in Indiana, there was less than eight years of condition data available for most of their polymeric overlay projects. Consequently, it was not possible to capture the effects of polymeric overlays (as well as LMC overlays) on the deck, such as a performance jump and post-treatment effects, and some estimates therefore had to be made. For the stochastic situation, deterioration models were not developed due to inadequate data. In the future, if more polymeric overlay contract data are available, new models could be developed and the proposed trigger results could be reexamined.

d) Duration models were not developed in the stochastic analysis for wearing surface deterioration because of limited wearing surface data. Therefore, the deck condition was used instead as the performance measure for the trigger. Although it would still be feasible to trigger the overlay based on deck condition, the wearing surface condition may be a more appropriate performance measure because a deck overlay mainly deals with the deck surface. In future research, if more wearing surface deterioration data are available, stochastic deterioration models could be developed for the wearing surface, allowing the stochastic life-cycle analysis to be revisited with respect to the wearing surface condition.

LIST OF REFERENCES

LIST OF REFERENCES

Agrawal, A. K., Kawaguchi, A, and Chen, Z. (2009). Bridge Element Deterioration Rates. Report No. C-01-51. The City College of New York, New York, NY.

American Society of Civil Engineers (ASCE). (2013). 2013 Report Card for America's Infrastructure. Retrieved Oct. 25, 2015, from http://www.infrastructurereportcard.org/a/#p/bridges/overview

Bai, Q., Labi, S., Sinha, K. C., and Thompson, P. (2011). Bridge User Cost Estimation – A Synthesis of Existing Methods and Addressing the Issues of Multiple Counting, Work Zones and Traffic Capacity Limitation. *Structure and Infrastructure Engineering: Maintenance, Management, Life-Cycle Design and Performance*, Vol. 9, Issue 9, pp. 849-859.

Bai, Q., Labi, S., and Sinha, K. C. (2012). Trade-Off Analysis for Multiobjective Optimization in Transportation Asset Management by Generating Pareto Frontiers Using Extreme Points Nondominated Sorting Genetic Algorithm II. *Journal of Transportation Engineering*, ASCE, Vol. 138, No. 6, pp. 798-808.

Bai, Q., Labi, S., Sinha, K. C., and Thompson, P. (2013). Multiobjective Optimization for Project Selection in Network-Level Bridge Management Incorporating Decision-Maker's Preference Using the Concept of Holism. *Journal of Bridge Engineering*, ASCE, Vol. 18, No. 9, pp. 879-889.

Barnes, G. and Langworthy, P. (2003). The Per-Mile Costs of Operating Automobiles and Trucks. Rep. MN/RC 2003-19, University of Minnesota, Minneapolis, MN.

Ben-Akiva, M., Humplick, F., Madanat, S., and Ramaswamy, R. (1993). Infrastructure Management Under Uncertainty: Latent Performance Approach. *Journal of Transportation Engineering*, ASCE, Vol. 119, No. 1, pp. 43-58.

Ben-Akiva, M. and Ramaswamy, R. (1993). An Approach for Predicting Latent Infrastructure Facility Deterioration. *Transportation Science*, Vol. 27, No. 2, pp. 174-193.

Bulusu, S. and Sinha, K. C. (1997). Comparison of Methodologies to Predict Bridge Deterioration. Transportation Research Record: Journal of the Transportation Research Board, No. 1597, Transportation Research Board of the National Academies, Washington D.C., pp. 34-42.

Bureau of Labor Statistics. (2016). Consumer Price Index. Retrieved Jan. 15, 2016, from http://www.bls.gov/cpi/#tables and http://www.usinflationcalculator.com/inflation/consumer-price-index-and-annual-percent-changes-from-1913-to-2008/

Cavalline, T. L., Whelan, M. J., Tempest, B. Q., Goyal, R., and Ramsey, J. D. (2015). Determination of Bridge Deterioration Models and Bridge User Costs for the NCDOT Bridge Management System. Report No. FHWA/NC/2014-07. University of North Carolina at Charlotte, Charlotte, NC.

Cesare, M. A., Santamarina, C., Turkstra, C., and Vanmarcke, E. H. (1992). Modeling Bridge Deterioration with Markov Chains. *Journal of Transportation Engineering*, ASCE, Vol. 118, No. 6, pp. 820-833.

Cox, D. (1972). Regression Models and Life Tables. *Journal of the Royal Statistical Society*, B34, pp. 187-200.

Durango, P. L. and Madanat, S. M. (2002). Optimal Maintenance and Repair Policies in Infrastructure Management Under Uncertain Facility Deterioration Rates: An Adaptive Control Approach. *Transportation Research Part A*, Vol. 36, pp. 763-778.

Durango, P. L. and Madanat, S. M. (2008). Optimization of Inspection and Maintenance Decisions for Infrastructure Facilities Under Performance Model Uncertainty: A Quasi-Bayes Approach. *Transportation Research Part A*, Vol. 42, pp. 1074-1085.

Elbehairy, H., Elbeltagi, E., Hegazy, T., and Soudki, K. (2006). Comparison of Two Evolutionary Algorithms for Optimization of Bridge Deck Repairs. *Computer-Aided Civil and Infrastructure Engineering*, Vol. 21, pp. 561-572.

FHWA. (1995). Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges. Report No. FHWA-PD-96-001. Office of Engineering, Bridge Division.

FHWA. (2002). Life-Cycle Cost Analysis Primer. Office of Asset Management, U.S. Department of Transportation.

FHWA. (2010). 2010 Conditions and Performance Report. Retrieved Oct. 30, 2015, from http://www.fhwa.dot.gov/policy/2010cpr/

FHWA. (2011). Bridge Preservation Guide: Maintaining a State of Good Repair Using Cost Effective Investment Strategies. Federal Highway Administration, Washington D.C.

FHWA. (2014). National Bridge Inventory (NBI). Retrieved Oct. 30, 2015, from http://www.fhwa.dot.gov/bridge/nbi.cfm

FHWA. (2015). National Highway Construction Cost Index (NHCCI). Retrieved Jan. 12, 2016, from https://www.fhwa.dot.gov/policyinformation/nhcci/pt1.cfm

Fleming, T. and Harrington D. (1991). *Counting Processes and Survival Analysis*. Jon Wiley & Sons, New York.

Fricker, J. D., Xiong, Y., and Labi, S. (2016). Bundling or Grouping Pavement and Bridge Projects: Analysis and Strategies. *Transportation Research Record: Journal of the Transportation Research Board*, Transportation Research Board of the National Academies, Washington D. C. (in press)

Frosch, R. J., Kreger, M. E., and Strandquist, B. V. (2013). Implementation of Performance-Based Bridge Deck Protective Systems. Publication FHWA/IN/JTRP-2013/12. Joint Transportation Research Program, Indiana Department of Transportation and Purdue University, West Lafayette, Indiana.

Gourieroux, C., Monfort, A., and Trogon, A. (1984). Pseudo Maximum Likelihood Methods: Theory. *Econometrica*, Vol. 52, pp. 681-700.

Greene, W. H. (1997). *Econometric Analysis*. Prentice Hall, Inc., Third Edition, Upper Saddle River, NJ.

Guillaumot, V., Durango-Cohen, P. L., and Madanat, S. M. (2003). Adaptive Optimization of Infrastructure Maintenance and Inspection Decisions under Performance Model Uncertainty. *Journal of Infrastructure Systems*, ASCE, Vol. 9, No. 4, pp. 133-139.

Gutkowski, R. M. and Arenella, N. D. (1998). Investigation of Pontis - A Bridge Management Software.

Hawk, H. (1995). BRIDGIT Deterioration Models. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1490, Transportation Research Board of the National Academies, Washington D.C., pp. 19-22.

Hawk, H. (2003). Bridge Life-Cycle Cost Analysis. NCHRP Report 483, Transportation Research Board, Washington, D.C.

Heckman, J. and Singer, B. (1984). A Method for Minimizing the Impact of Distributional Assumptions in Econometric Models for Duration Data. *Econometrica*, Vol. 52, pp. 271-320.

Hensher, D. and Mannering, F. (1994). Hazard-Based Duration Models and Their Application to Transport Analysis. *Transport Reviews*, Vol. 14, pp. 63-82.

Hollar, D. A., Rasdorf, W., Liu, M., Hummer, J. E., Arocho, I., and Hsiang, S. M. (2013). Preliminary Engineering Cost Estimation Model for Bridge Projects. *Journal of Construction Engineering and Management*, ASCE, Vol. 139, No. 9, pp. 1259-1267.

Hong, T. and Hastak, M. (2007). Evaluation and Determination of Optimal MR&R Strategies in Concrete Bridge Decks. *Automation in Construction*, Vol. 16, pp. 165-175.

Hosmer, D. W. J. and Lemeshow, S. (1999). *Applied Survival Analysis: Regression Modeling of Time to Event Data*. John Wiley & Sons, Inc., New York, NY.

Indiana Department of Transportation (INDOT). (2013). Indiana Design Manual 2013. Chapter 72 – Bridge Rehabilitation.

Indiana Department of Transportation (INDOT). (2014). Bridge and Culvert Preservation Initiative, Policy Statement.

Indiana Department of Transportation (INDOT). (2015). Latest INDOT Traffic Adjustment Factors.

Infrastructure Australia. (2008). National Public Private Partnership Guidelines, Volume 5: Discount Rate Methodology Guidance. Australian Government.

Irfan, M. (2010). A Framework for Developing Optimal Pavement Life-Cycle Treatment Profiles. Ph.D. Dissertation, Purdue University, West Lafayette, IN.

Irfan, M., Khurshid, M. B., Labi, S., and Flora, W. (2009). Evaluating the Cost Effectiveness of Flexible Rehabilitation Treatments Using Different Performance Criteria. *Journal of Transportation Engineering*, ASCE, Vol 135, No. 10, pp. 753-763.

Jiang, Y., Saito, M., and Sinha, K.C. (1987). Bridge performance prediction model using the Markov chain. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1180, Transportation Research Board of the National Academies, Washington D.C., pp. 25-32.

Jiang, Y. and Sinha, K. C. (1989a). The Development of Optimal Strategies for Maintenance, Rehabilitation and Replacement of Highway Bridges, Final Report Vol. 6: Performance Analysis and Optimization. Report No. FHWA/IN/JHRP-89/13, Joint Highway Research Project, Purdue University, West Lafayette, Indiana.

Jiang, Y. and Sinha, K. C. (1989b). Bridge Service Life Prediction Model Using the Markov Chain. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1223, Transportation Research Board of the National Academies, Washington D.C., pp. 24-30.

Jiang, Y., Zhao, G., and Li, S. (2013). An Economic Analysis Methodology for Project Evaluation and Programming. Publication FHWA/IN/JTRP-2013/17. Joint Transportation Research Program, Indiana Department of Transportation and Purdue University, West Lafayette, Indiana.

Kalbfleisch, J. and Prentice R. (1980). The Statistical Analysis of Failure Time Data. John Wiley & Sons, New York.

Kaplan, E. and Meier, P. (1958). Nonparametric Estimation from Incomplete Observations. *Journal of the American Statistical Association*, Vol. 53, pp. 457-481.

Khurshid, M. B. (2010). A Framework for Establishing Optimal Performance Thresholds for Highway Asset Interventions. Ph.D. Dissertation, Purdue University, West Lafayette, IN.

Khurshid, M. B., Irfan, M., Labi, S., and Sinha, K. C. (2008). Cost Effectiveness of Rigid Pavement Rehabilitation Treatments. 7th International Conference on Managing Pavements and Other Roadway Assets, Calgary, Alberta, Canada.

Kiefer, N. (1988). Economic Duration Data and Hazard Functions. *Journal of Economic Literature*, Vol. 26, pp. 646-679.

Krauss, P. D., Lawler, J. S., and Steiner, K. A. (2009). Guidelines for Selection of Bridge Deck Overlays, Sealers and Treatments. NCHRP Project 20-07, Task 234. Transportation Research Board, Washington, D.C.

Lamptey, G., Ahmad, M., Labi, S., and Sinha, K. C. (2005). Life Cycle Cost Analysis for INDOT Pavement Design Procedures. Report No. FHWA/IN/JHRP -2004/28, Joint Highway Research Project, Purdue University, West Lafayette, Indiana.

Lamptey, G., Labi, S., and Li, Z. (2008). Decision Support for Optimal Scheduling of Highway Pavement Preventive Maintenance within Resurfacing Cycle. *Decision Support Systems*, Vol. 46, pp. 376-387.

Lee, E. (1992). Statistical Methods for Survival Data Analysis, Second Edition. John Wiley & Sons, New York.

Lee, C. K. and Kim, S. K. (2007). GA-based Algorithm for Selecting Optimal Repair and Rehabilitation Methods for Reinforced Concrete (RC) Bridge Decks. *Automation in Construction*, Vol. 16, pp. 153-164.

Li, L., Sun, L., and Ning, G. (2014). Deterioration Prediction of Urban Bridges on Network Level Using Markov-Chain Model. Mathematical Problems in Engineering, Vol. 2014, pp. 1-10.

Liu, C., Hammad, A., and Itoh, Y. (1997). Maintenance Strategy Optimization of Bridge Decks using Genetic Algorithm. *Journal of Transportation Engineering*, ASCE, Vol. 123, No. 2, pp. 91-100.

Liu, M. and Frangopol D. M. (2005a). Bridge Annual Maintenance Prioritization under Uncertainty by Multiobjective Combinatorial Optimization. *Computer- Aided Civil and Infrastructure Engineering*, Vol. 20, pp. 343-353.

Liu, M. and Frangopol D. M. (2005b). Multiobjective Maintenance Planning Optimization for Deteriorating Bridges Considering Condition, Safety, and Life-Cycle Cost. *Journal of Structural Engineering*, ASCE, Vol. 131, No. 5, pp. 833-842.

Madanat, S. (1993). Optimal Infrastructure Management Decisions under Uncertainty. *Transportation Research Part C*, Vol. 1, No.1, pp. 77-88.

Madanat, S. and Ben-Akiva, M. (1994). Optimal Inspection and Repair Policies for Infrastructure Facilities. *Transportation Science*, Vol. 28, No. 1, pp. 55-62.

Madanat, S. and Wan Ibrahim, W. H. (1995). Poisson Regression Models of Infrastructure Transition Probabilities. *Journal of Transportation Engineering*, ASCE, Vol. 121, No. 3, pp. 267-272.

Madanat, S., Mishalani, R., and Wan Ibrahim, W. H. (1995). Estimation of Infrastructure Transition Probabilities from Condition Rating Data. *Journal of Infrastructure Systems*, ASCE, Vol. 1, No. 2, pp. 120-125.

Madanat, S., Karlaftis, M. G., McCarthy, P. S. (1997). Probabilistic Infrastructure Deterioration Models with Panel Data. *Journal of Infrastructure Systems*, ASCE, Vol. 3, No. 1, pp. 4-9.

Mannering, F. (1993). Male/Female Driver Characteristics and Accident Risk: Some New Evidence. *Accident Analysis and Prevention*, Vol. 25, pp. 77-84.

Markow, M. J. and Hyman, W. A. (2009). Bridge Management Systems for Transportation Agency Decision Making: A Synthesis of Highway Practice. NCHRP Synthesis 397, Transportation Research Board, Washington D.C.

Mauch, M. and Madanat, S. (2001). Semiparametric Hazard Rate Models of Reinforced Concrete Bridge Deck Deterioration. *Journal of Infrastructure Systems*, ASCE, Vol. 7, No. 2, pp. 49-57.

Mishalani, R. G. and Madanat, S. (2002). Computation of Infrastructure Transition Probabilities Using Stochastic Duration Models. *Journal of Infrastructure Systems*, ASCE, Vol. 8, No. 4, pp. 139-148.

Miyamoto, A., Kawamura, K., and Nakamura, H. (2000). Bridge Management System and Maintenance Optimization for Existing Bridges. *Computer-Aided Civil and Infrastructure Engineering*, Vol. 15, pp. 45-55.

Moomen, M., Qiao, Y., Agbelie, B., Labi, S., and Sinha, K. C. (2015). Bridge Deterioration Models to Support Indiana's Bridge Management System. Final Report Volume II, Joint Transportation Research Program, Purdue University, West Lafayette, Indiana. (In Press)

Morcous, G. (2006). Performance Prediction of Bridge Deck Systems Using Markov Chains. *Journal of Performance of Constructed Facilities*, ASCE, Vol. 20, No. 2, pp. 146-155.

Nam, D. and Mannering, F. (2000). Hazard-Based Analysis of Highway Incident Duration. *Transportation Research Part A*, Vol. 34, pp. 85-102.

Nevada Department of Transportation DOT. (2008). NDOT Structures Manual. Chapter 22, Bridge Rehabilitation.

Neves, L. C., Frangopol, D. M., and Cruz, P. J. S. (2006a). Probabilistic Lifetime-Oriented Multiobjective Optimization of Bridge Maintenance: Single Maintenance Type. *Journal of Structural Engineering*, ASCE, Vol. 132, No. 6, pp. 991-1005.

Neves, L. C., Frangopol, D. M., and Petcherdchoo, A. (2006b). Probabilistic Lifetime-Oriented Multiobjective Optimization of Bridge Maintenance: Combination of Maintenance Types. *Journal of Structural Engineering*, ASCE, Vol. 132, No. 11, pp. 1821-1834.

Oh, C. D., Park, C., and Kim, K. J. (2013). An Approximate Cost Estimation Model based on Standard Quantities of Steel Box Girder Bridge Substructure. KSCE *Journal of Civil Engineering*, Vol. 17, No. 5, pp. 877-885.

Pasupathy, R., Labi, S., and Sinha, K. C. (2007). Optimal Reconstruction Periods for Stochastically Deteriorating Infrastructures. *Computer-Aided Civil and Infrastructure Engineering*, Vol. 22, pp. 389-399.

Patidar, V., Labi, S., Sinha, K. C., and Thompson, P. (2007). Multi-Objective Optimization for Bridge Management Systems. NCHRP Report 590, Transportation Research Board, Washington, D. C.

Robelin, C. A. and Madanat, S. (2007). History-Dependent Bridge Deck Maintenance and Replacement Optimization with Markov Decision Processes. *Journal of Infrastructure Systems*, ASCE, Vol. 13, No. 3, pp. 195-201.

Saito, M. and Sinha, K. C. (1989a). The Development of Optimal Strategies for Maintenance, Rehabilitation and Replacement of Highway Bridges, Final Report Vol. 4: Cost Analysis. Report No. FHWA/IN/JHRP-89/11, Joint Highway Research Project, Purdue University, West Lafayette, Indiana.

Saito, M. and Sinha, K. C. (1989b). The Development of Optimal Strategies for Maintenance, Rehabilitation and Replacement of Highway Bridges, Final Report Vol. 5: Priority Ranking Method. Report No. FHWA/IN/JHRP-89/12, Joint Highway Research Project, Purdue University, West Lafayette, Indiana.

Sinha, K. C. and Labi, S. (2007). *Transportation Decision Making: Principles of Project Evaluation and Programming*. John Wiley & Sons, Inc.

Sinha, K. C., Labi, S., Hodge, S., Tine, G., and Shah, H. (2009). An Assessment of Highway Financing Needs in Indiana. Report No. FHWA/IN/JTRP-2005/9, Joint Transportation Research Project, Purdue University, West Lafayette, Indiana.

Sinha, K. C., Labi, S., McCullouch, B. G., Bhargava, A., and Bai, Q. (2009). Updating and Enhancing the Indiana Bridge Management System (IBMS). Report No. FHWA/IN/JTRP-2008/30, Joint Transportation Research Project, Purdue University, West Lafayette, Indiana.

Sinha, K. C., Labi, S., Rodriguez, M., Tine, G., and Dutta, R. (2005). Procedures for the Estimation of Pavement and Bridge Preservation Costs for Fiscal Planning. Report No. FHWA/IN/JTRP-2005/17, Joint Transportation Research Project, Purdue University, West Lafayette, Indiana.

Sinha, K. C., Saito, M., Jiang, Y., Murthy, S., Tee, A.B., and Bowman, M. D. (1988). The Development of Optimal Strategies for Maintenance, Rehabilitation and Replacement of Highway Bridges, Final Report Vol. 1: The Elements of the Indiana Bridge Management System. Report No. FHWA/IN/JHRP-88/15, Joint Highway Research Project, Purdue University, West Lafayette, Indiana.

Son, Y. and Sinha, K. C. (1997). Methodology to Estimate User Costs in Indiana Bridge Management System. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1597, Transportation Research Board of the National Academies, Washington D.C., pp. 43-51.

Thompson, P. D. and Johnson, M. B. (2005). Markovian Bridge Deterioration: Developing Models from Historical Data. *Structure and Infrastructure Engineering*, Vol. 1, No. 1, pp. 85-91.

Transportation Research Board. (2013). *Design Guide for Bridges for Service Life*. SHRP 2 Renewal Project R19A. Transportation Research Board of the National Academies, Washington D.C.

Washington, S. P., Karlaftis, M. G., and Mannering, F. L. (2011). *Statistical and Econometric Methods for Transportation Data Analysis*, Second Edition, Chapman & Hall/CRC, Boca Raton, FL.

Zayed, T. M., Chang, L. M., and Fricker, J. D. (2002). Life-cycle Cost Analysis Using Deterministic and Stochastic Methods: Conflicting Results. *Journal of Performance of Constructed Facilities*, ASCE, Vol. 16, No. 2, pp. 63-74.

APPENDICES

Appendix A Additional Life-Cycle Cost Analysis Results

Appendix A presents the life-cycle cost analysis results for the other climate regions and functional classes, including moderate region non-NHS, cold region NHS and non-NHS, and warm region NHS and non-NHS. It was determined that the optimal triggers varied between the NHS and non-NHS classes but remained consistent across the climate regions. The total EUAC values in all the tables and figures used the weight of AC:UC=1:1 (i.e., Total EUAC = Agency EUAC + User EUAC).

Table A.8.1 Life-Cycle Agency and User EUAC Results for Moderate Region, 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

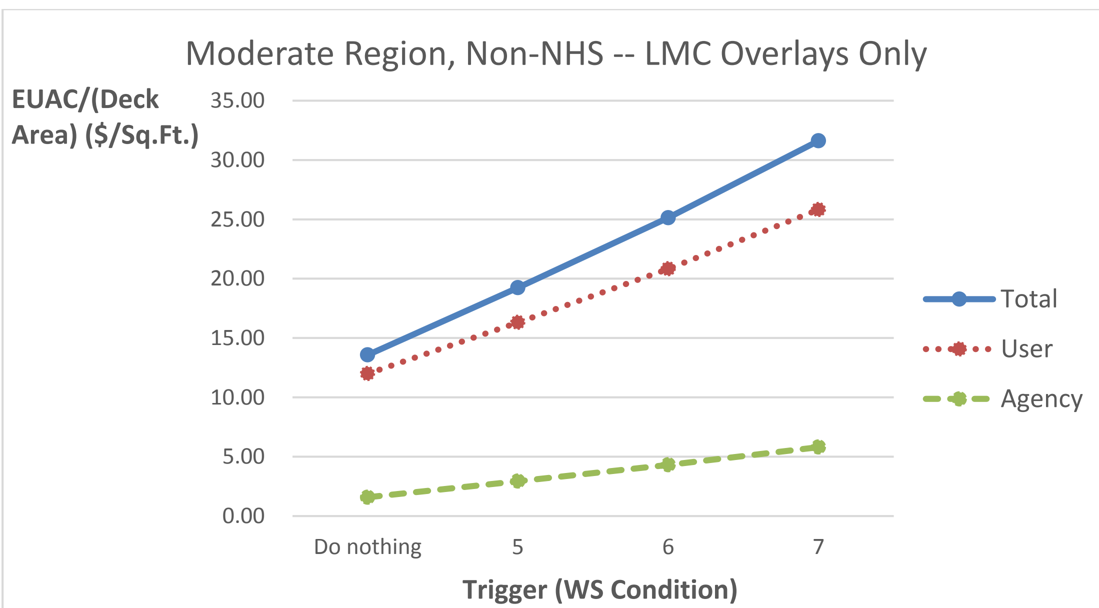


Figure A.1 Life-Cycle Agency and User EUAC Results for Moderate Region, Non-NHS, LMC Overlays Only

Table A.8.2 Life-Cycle Agency and User EUAC Results for Moderate Region, 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	20.93	19.02

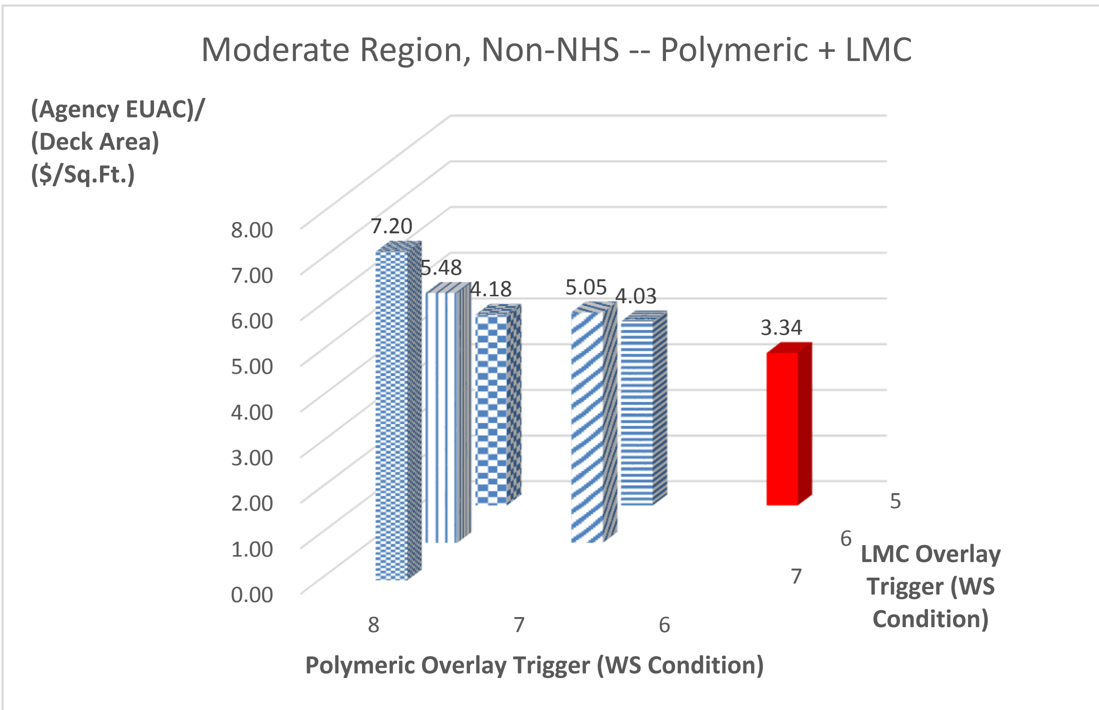


Figure A.2 Life-Cycle Agency EUAC Results for Moderate Region, Non-NHS, Polymeric and LMC Overlays

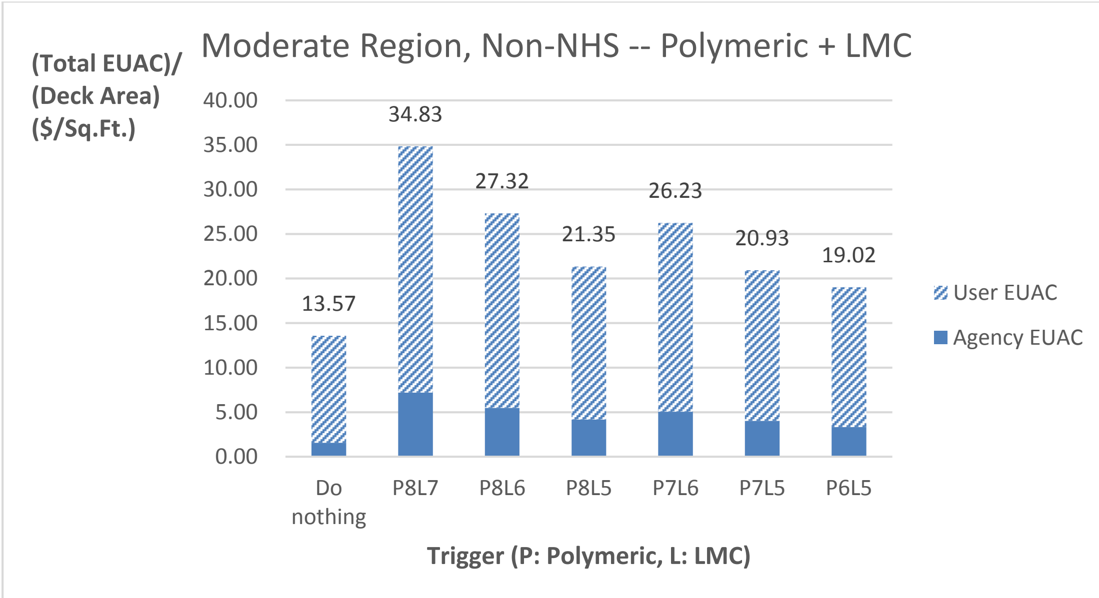


Figure A.3 Life-Cycle Total EUAC Results for Moderate Region, Non-NHS, Polymeric and LMC Overlays

Table A.8.3 Life-Cycle Agency and User EUAC Results for Cold Region, 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

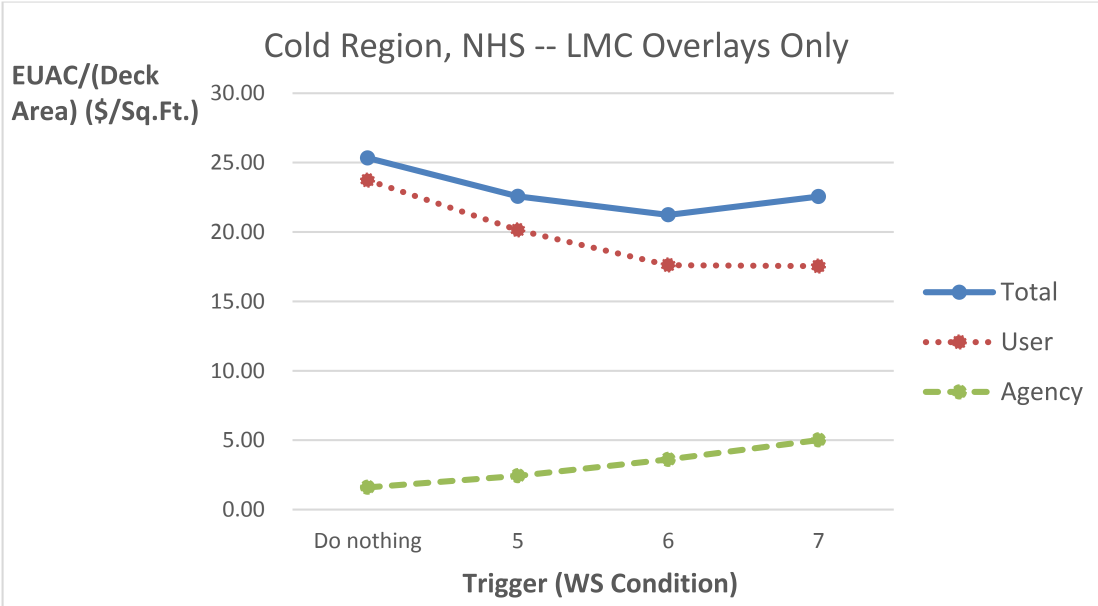


Figure A.4 Life-Cycle Agency and User EUAC Results for Cold Region, NHS, LMC Overlays Only

Table A.8.4 Life-Cycle Agency and User EUAC Results for Cold Region, 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

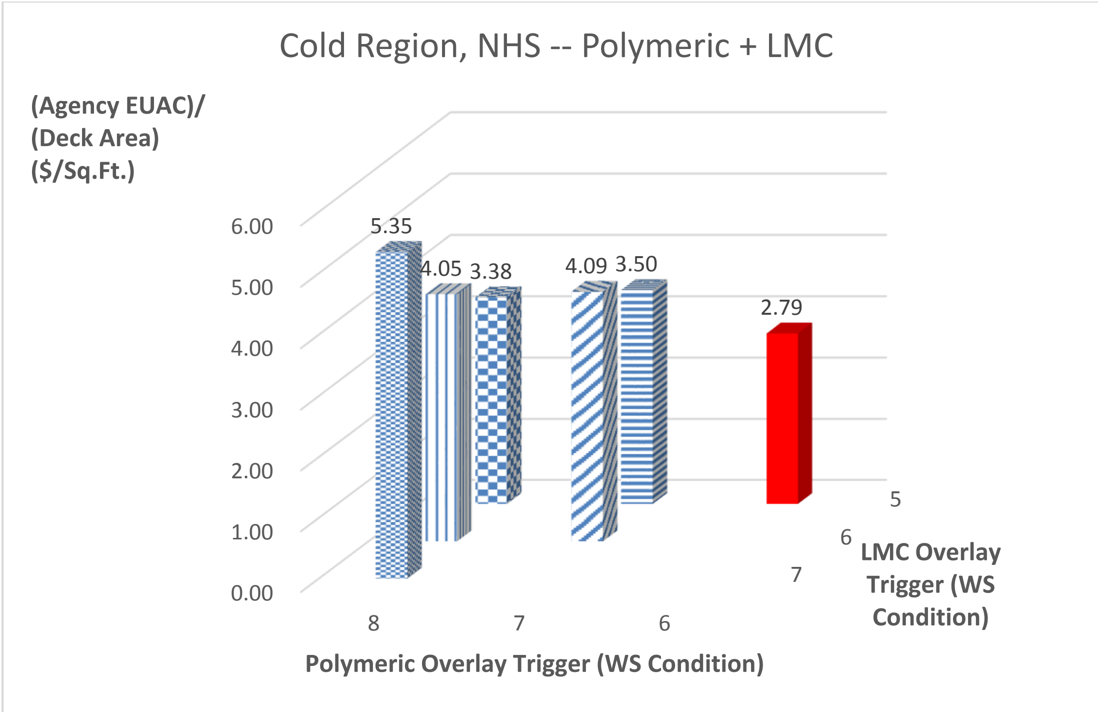


Figure A.5 Life-Cycle Agency EUAC Results for Cold Region, NHS, Polymeric and LMC Overlays

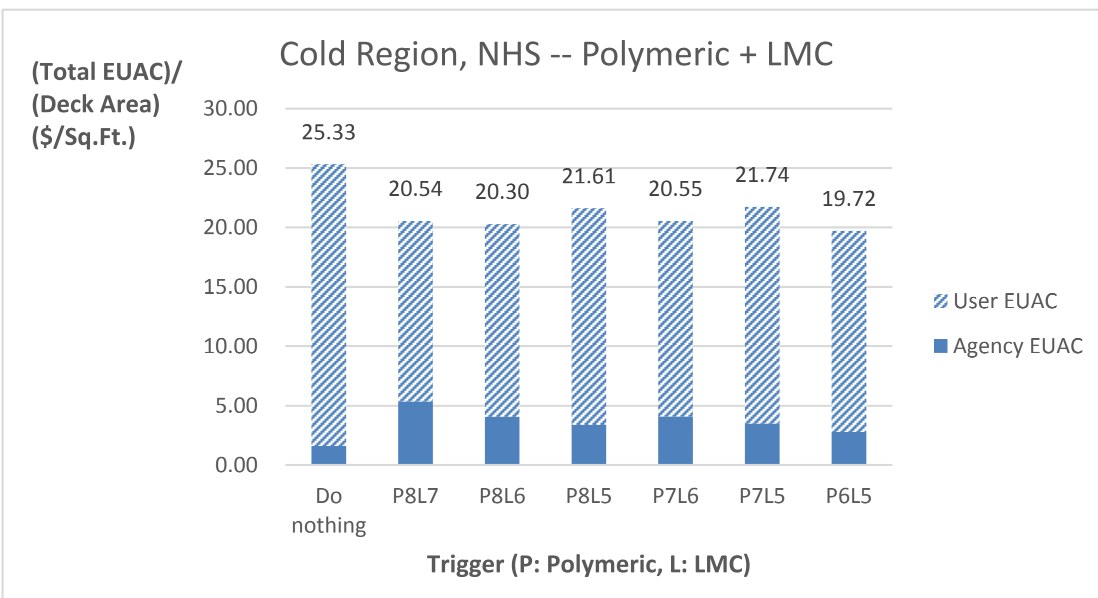


Figure A.6 Life-Cycle Total EUAC Results for Cold Region, NHS, Polymeric and LMC Overlays

Table A.8.5 Life-Cycle Agency and User EUAC Results for Cold Region, 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

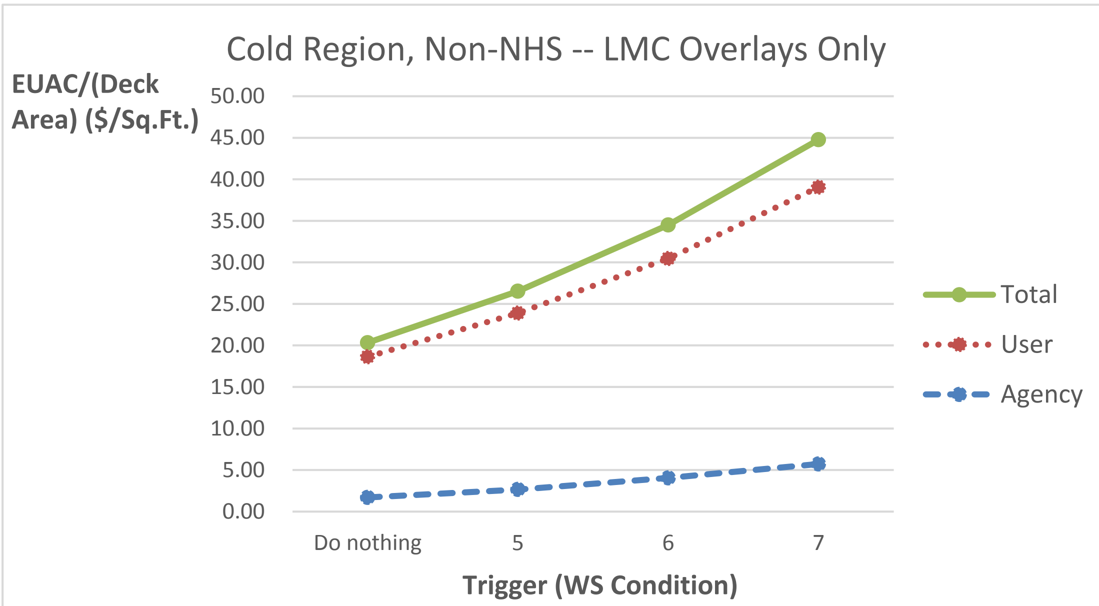


Figure A.7 Life-Cycle Agency and User EUAC Results for Cold Region, Non-NHS, LMC Overlays Only

Table A.8.6 Life-Cycle Agency and User EUAC Results for Cold Region, 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

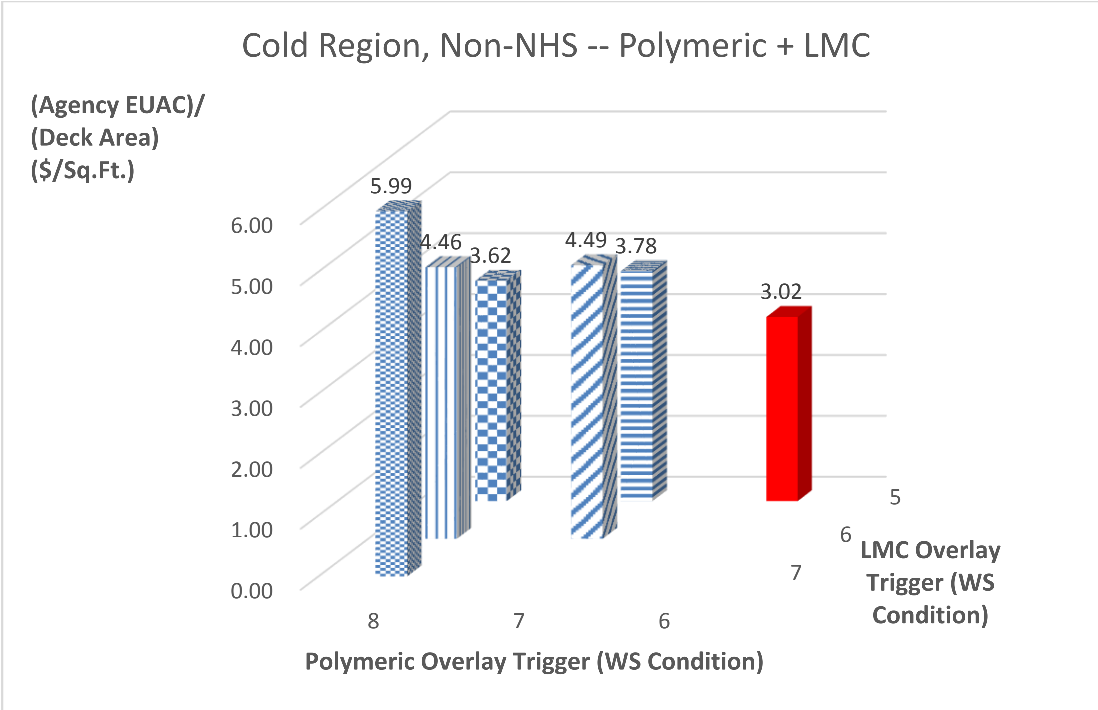


Figure A.8 Life-Cycle Agency EUAC Results for Cold Region, Non-NHS, Polymeric and LMC Overlays

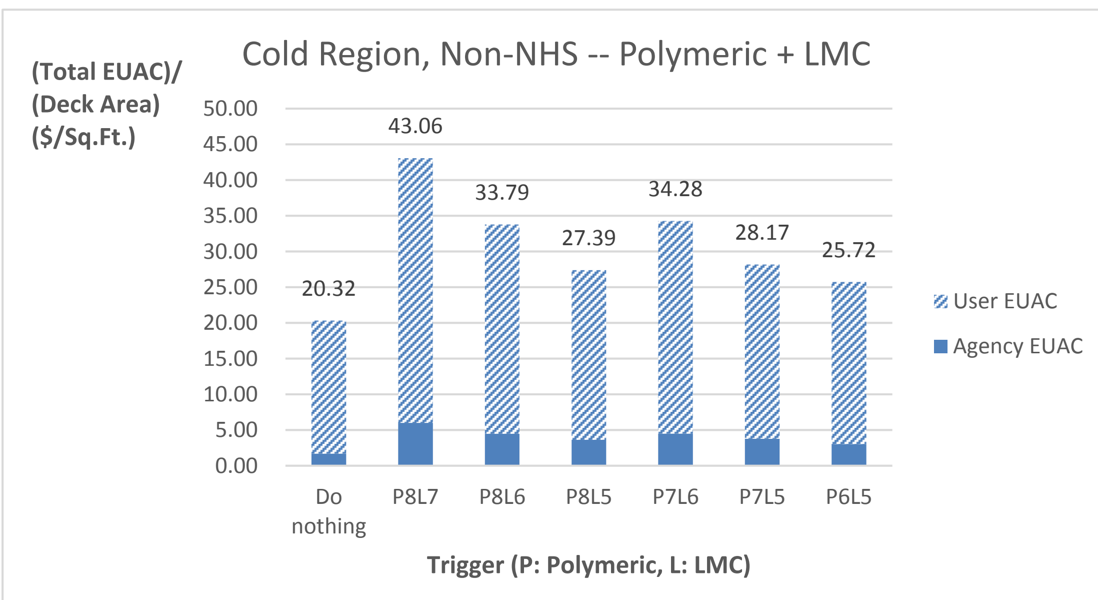


Figure A.9 Life-Cycle Total EUAC Results for Cold Region, Non-NHS, Polymeric and LMC Overlays

Table A.8.7 Life-Cycle Agency and User EUAC Results for Warm Region, 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

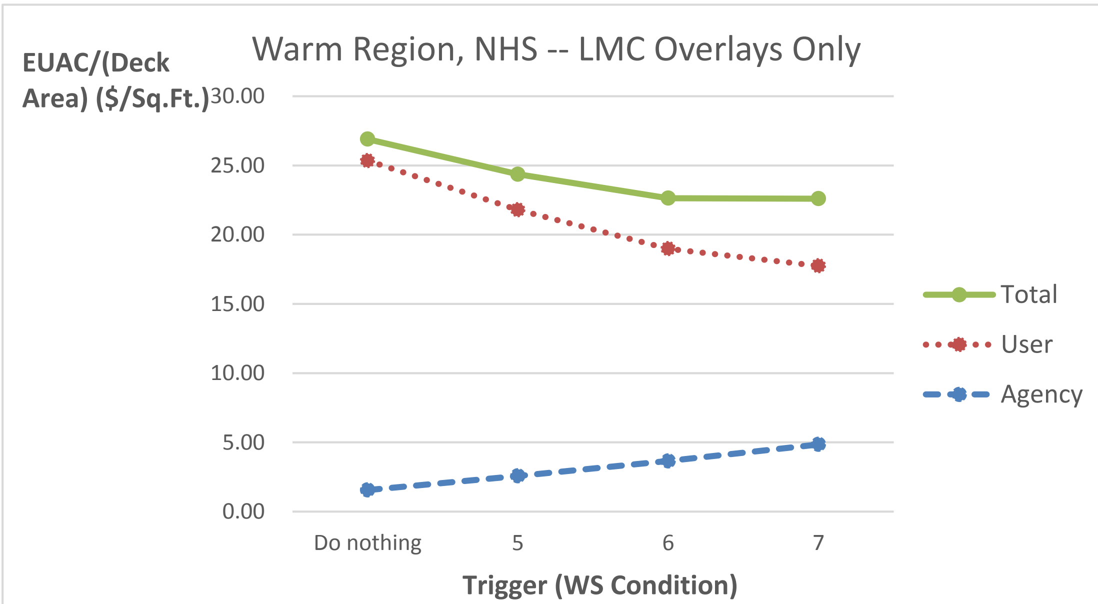


Figure A.10 Life-Cycle Agency and User EUAC Results for Warm Region, NHS, LMC Overlays Only

Table A.8.8 Life-Cycle Agency and User EUAC Results for Warm Region, 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

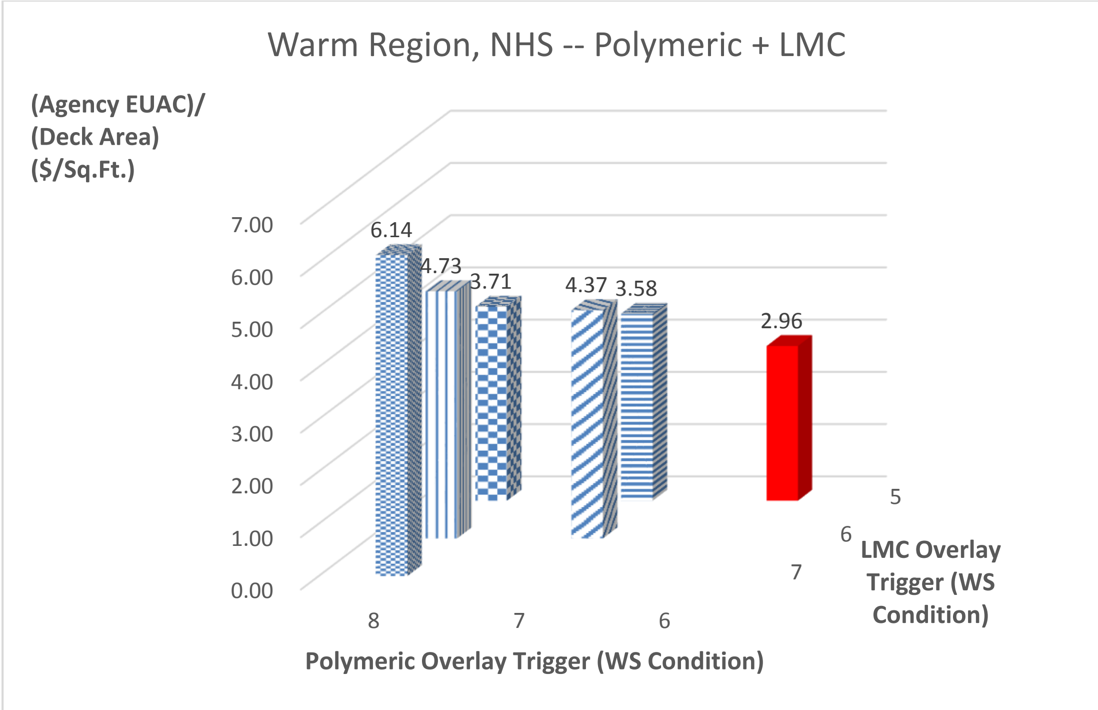


Figure A.11 Life-Cycle Agency EUAC Results for Warm Region, NHS, Polymeric and LMC Overlays

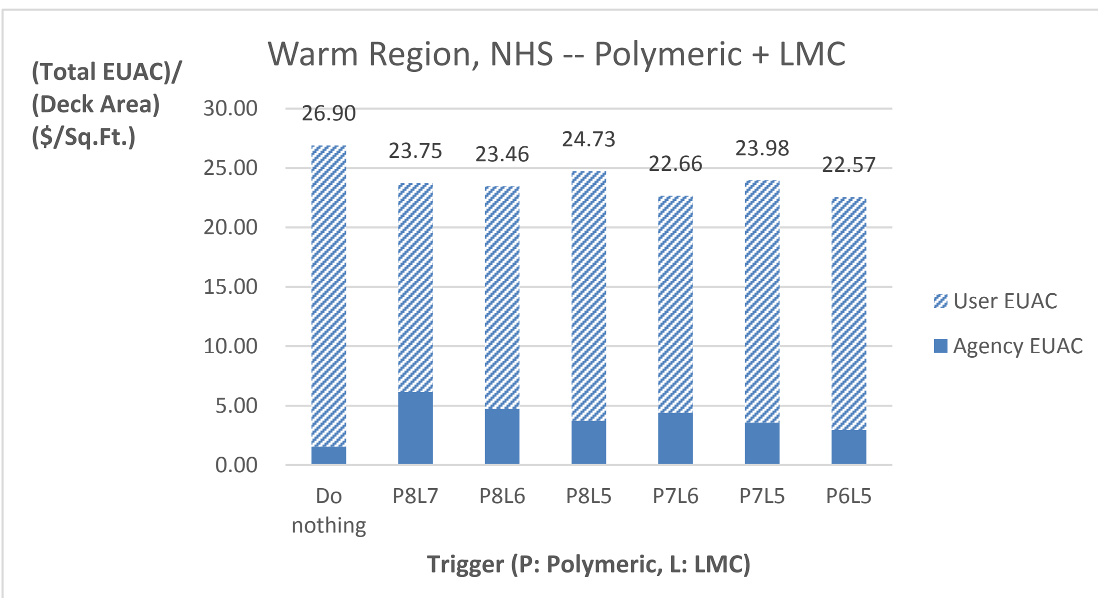


Figure A.12 Life-Cycle Total EUAC Results for Warm Region, NHS, Polymeric and LMC Overlays

Table A.8.9 Life-Cycle Agency and User EUAC Results for Warm Region, 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

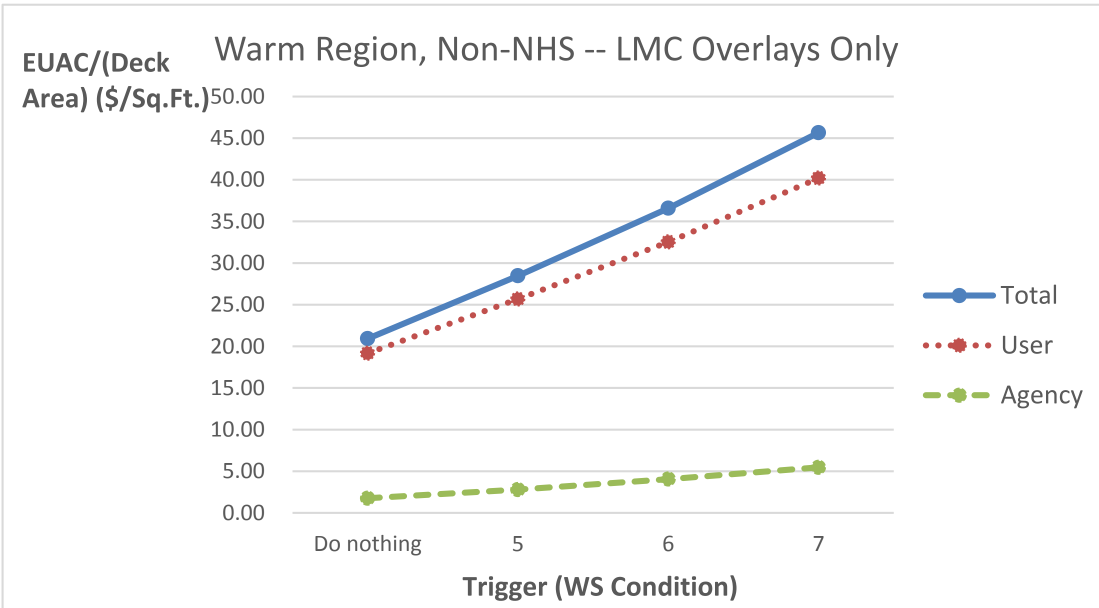


Figure A.13 Life-Cycle Agency and User EUAC Results for Warm Region, Non-NHS, LMC Overlays Only

Table A.8.10 Life-Cycle Agency and User EUAC Results for Warm Region, 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

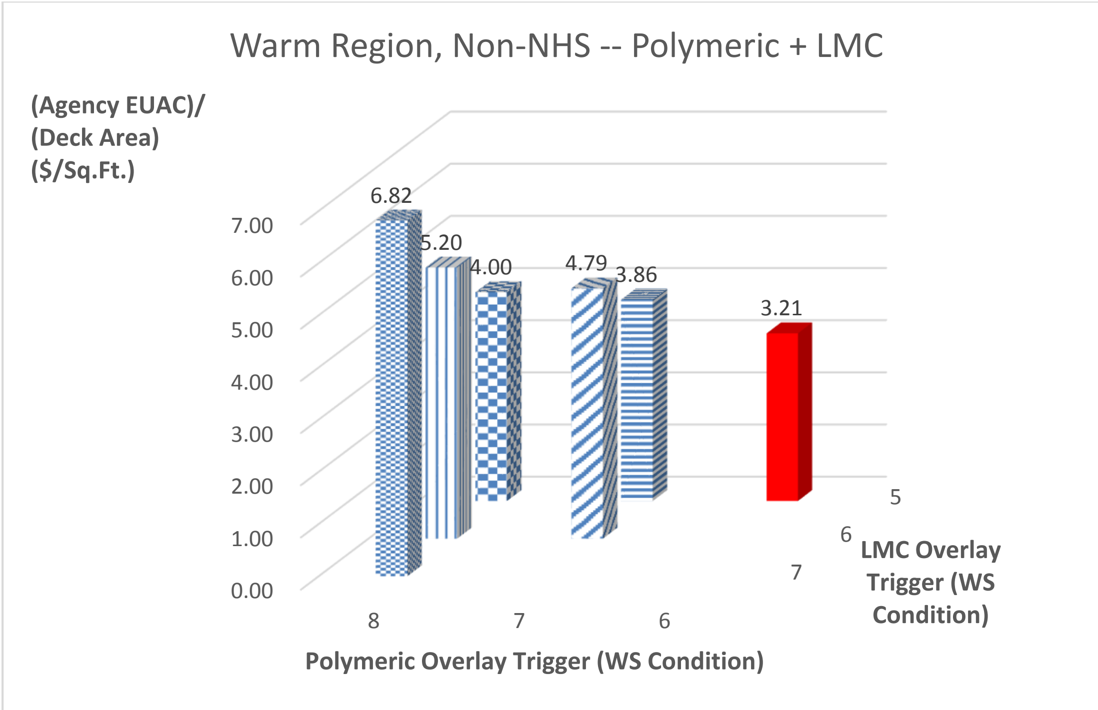


Figure A.14 Life-Cycle Agency EUAC Results for Warm Region, Non-NHS, Polymeric and LMC Overlays

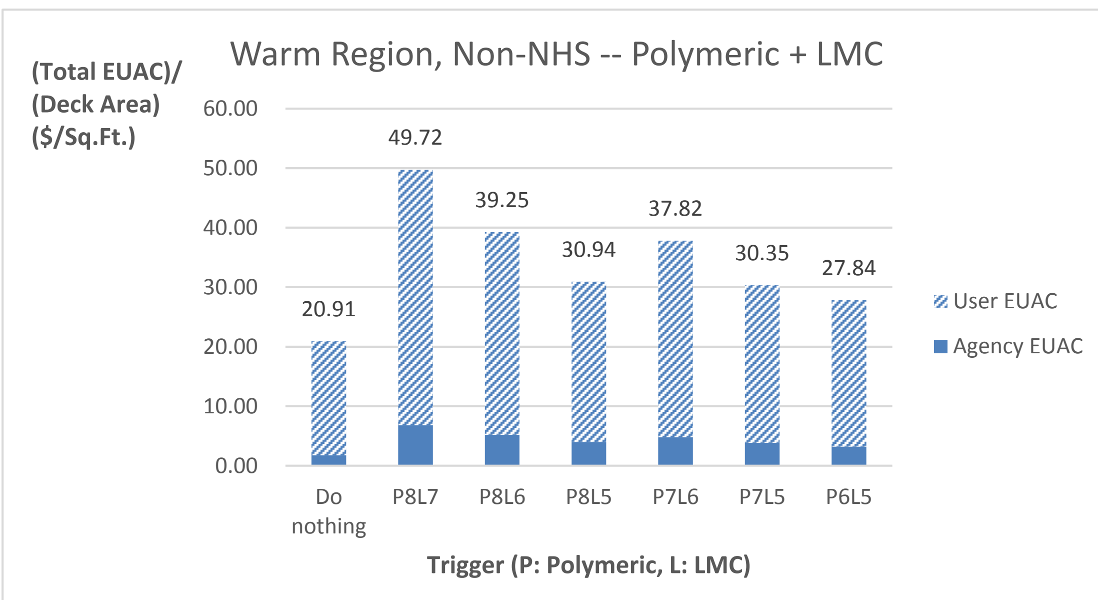


Figure A.15 Life-Cycle Total EUAC Results for Warm Region, Non-NHS, Polymeric and LMC Overlays

Appendix B Additional Proposed Bridge Deck Life-Cycle M&R Strategies (AC:UC=1:1)

Appendix B presents the proposed strategies for the other climate regions and functional classes, including moderate region non-NHS, cold region NHS and non-NHS, and warm region NHS and non-NHS. The results presented herein are based on the weight of AC:UC=1:1. The summarized findings can be found in Sections 4.3 and 4.6.

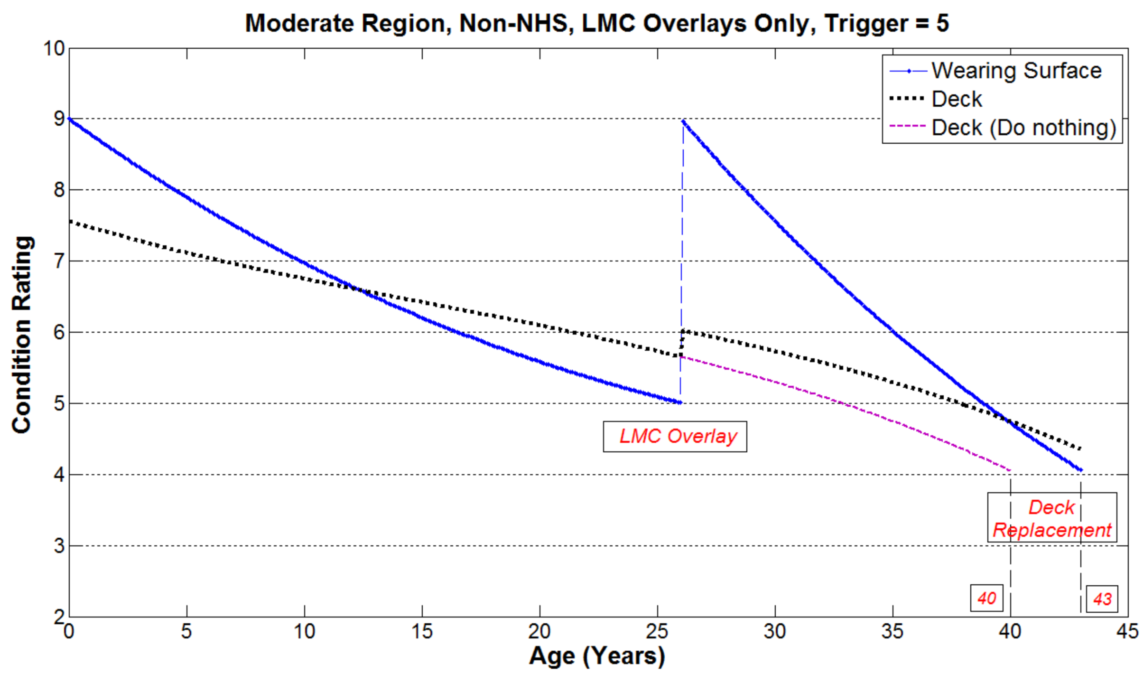


Figure B.1 Proposed Condition-Based Bridge Deck M&R Strategy for Moderate Region, Non-NHS, LMC Overlays Only

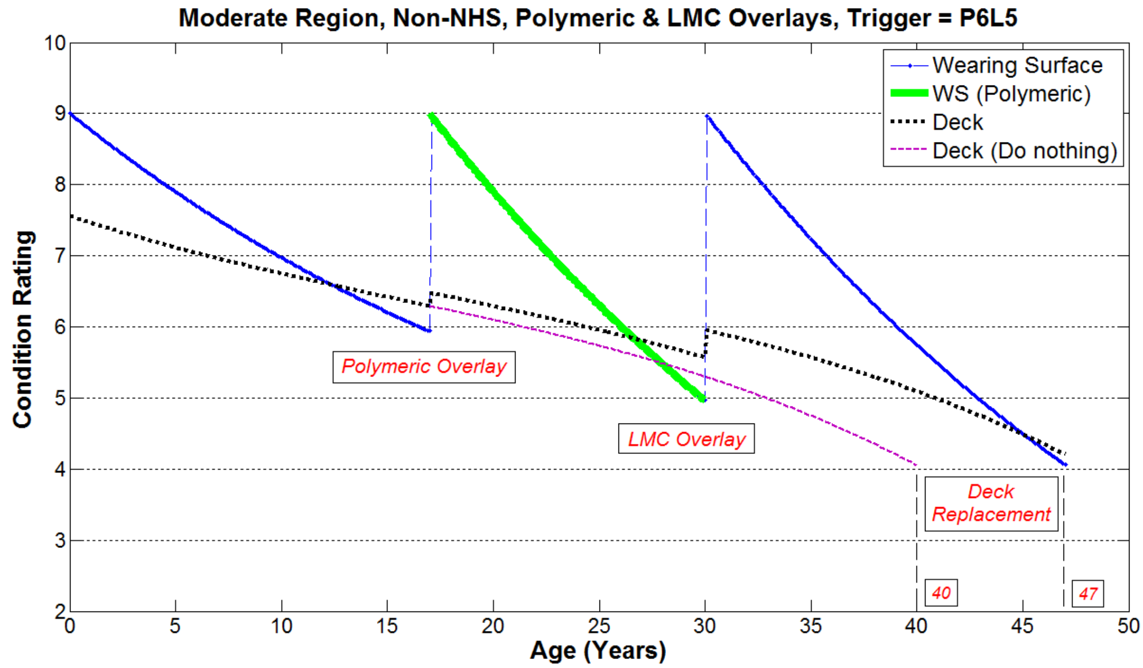


Figure B.2 Proposed Condition-Based Bridge Deck M&R Strategy for Moderate Region, Non-NHS, Polymeric and LMC Overlays

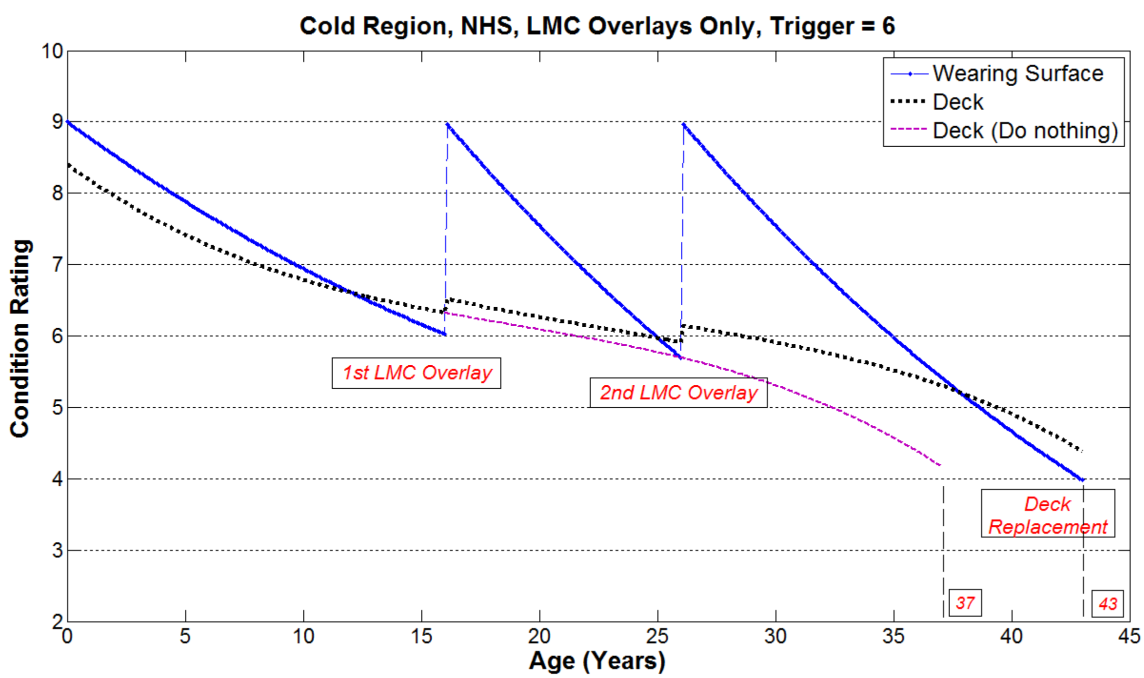


Figure B.3 Proposed Condition-Based Bridge Deck M&R Strategy for Cold Region, NHS, LMC Overlays Only

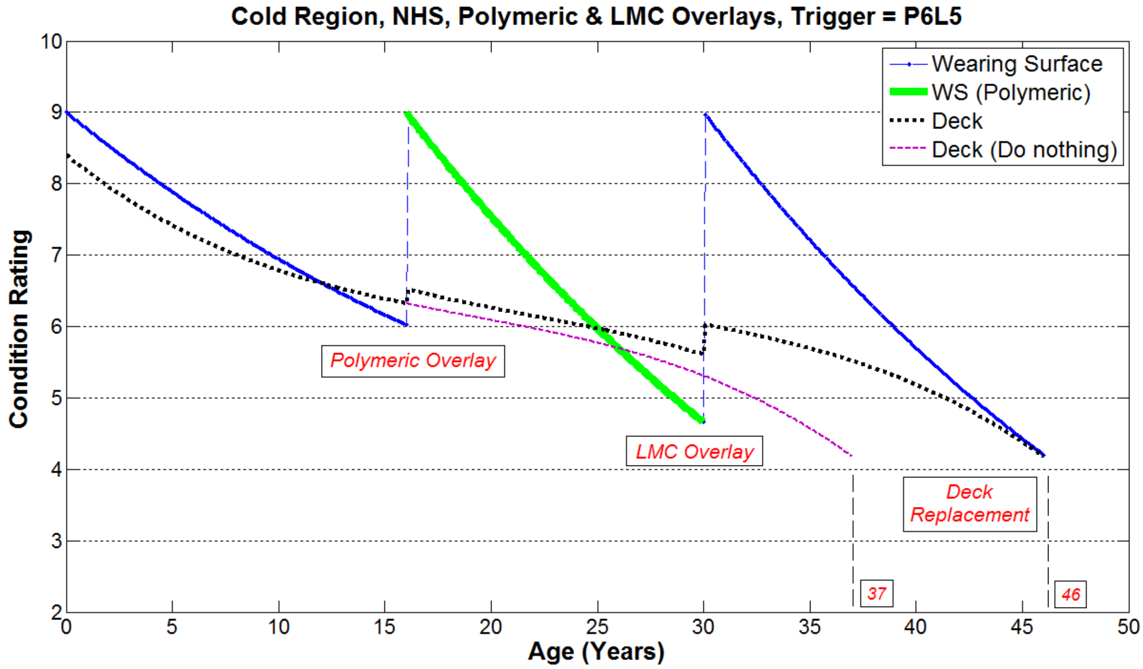


Figure B.4 Proposed Condition-Based Bridge Deck M&R Strategy for Cold Region, NHS, Polymeric and LMC Overlays

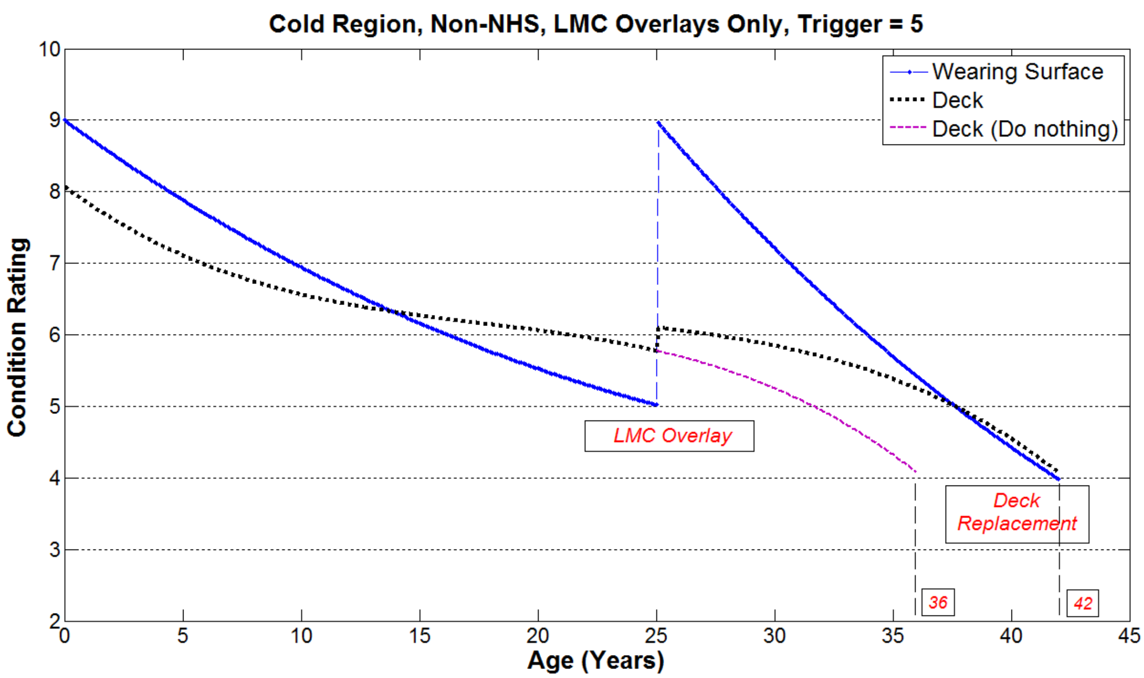


Figure B.5 Proposed Condition-Based Bridge Deck M&R Strategy for Cold Region, Non-NHS, LMC Overlays Only

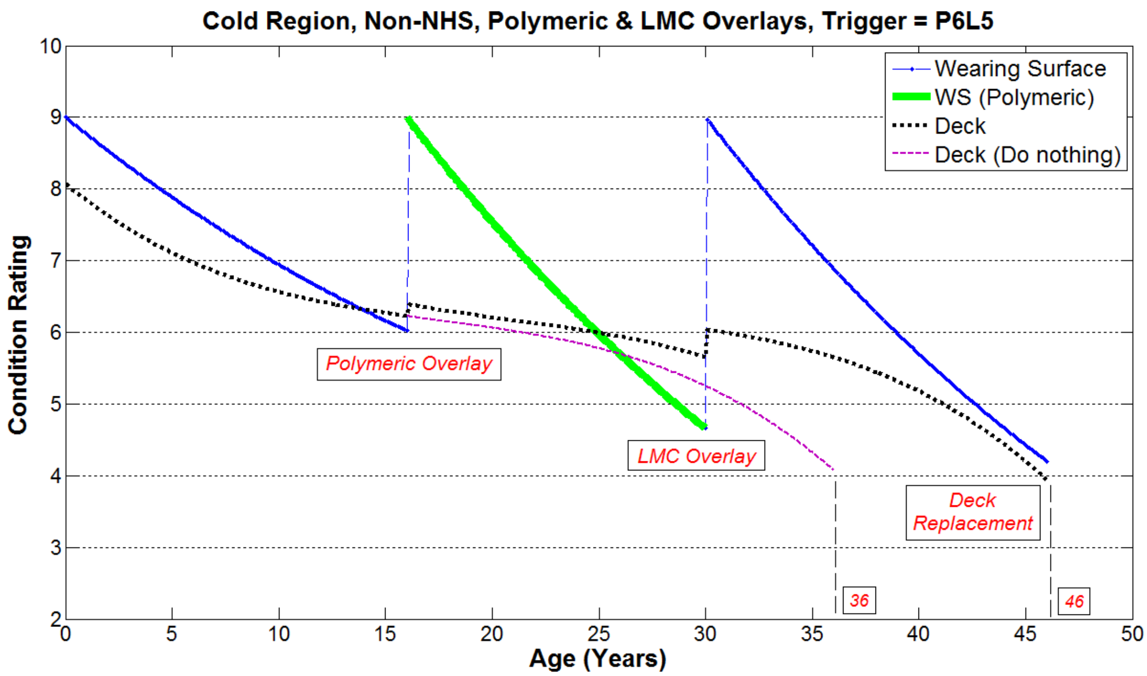


Figure B.6 Proposed Condition-Based Bridge Deck M&R Strategy for Cold Region, Non-NHS, Polymeric and LMC Overlays

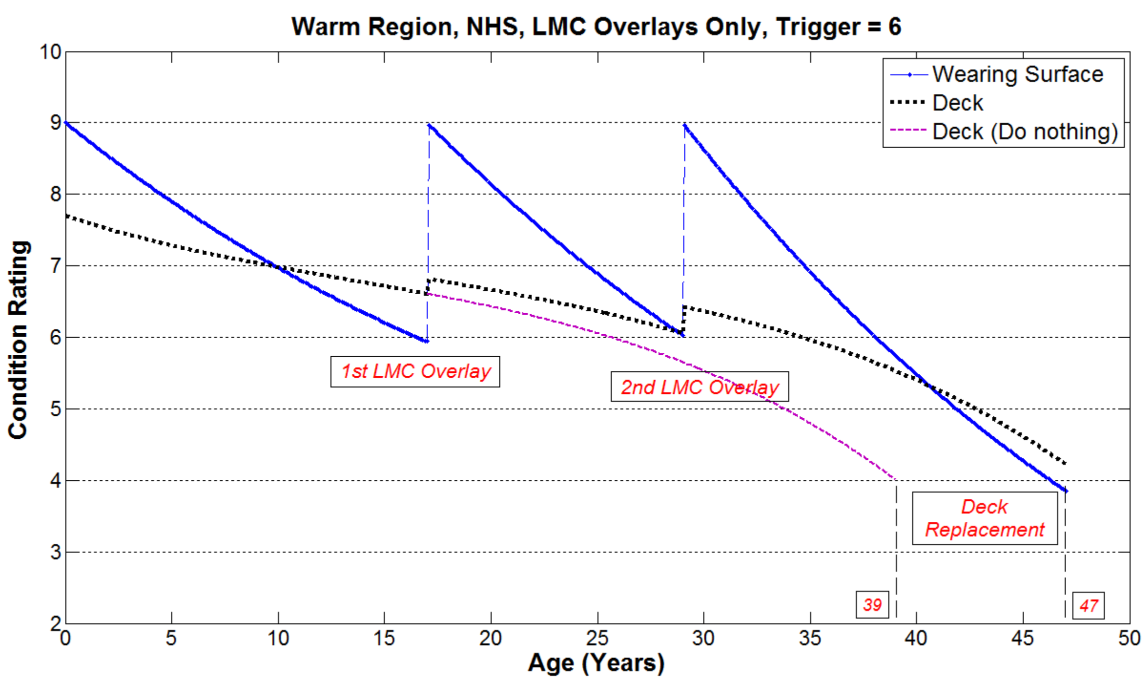


Figure B.7 Proposed Condition-Based Bridge Deck M&R Strategy for Warm Region, NHS, LMC Overlays Only

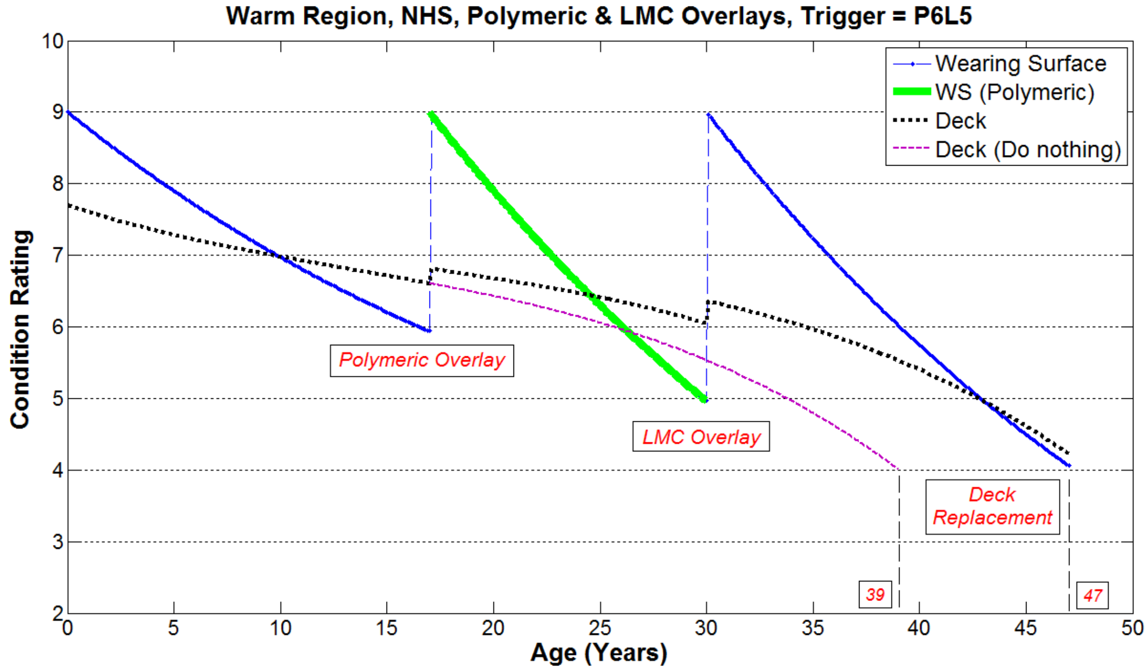


Figure B.8 Proposed Condition-Based Bridge Deck M&R Strategy for Warm Region, NHS, Polymeric and LMC Overlays

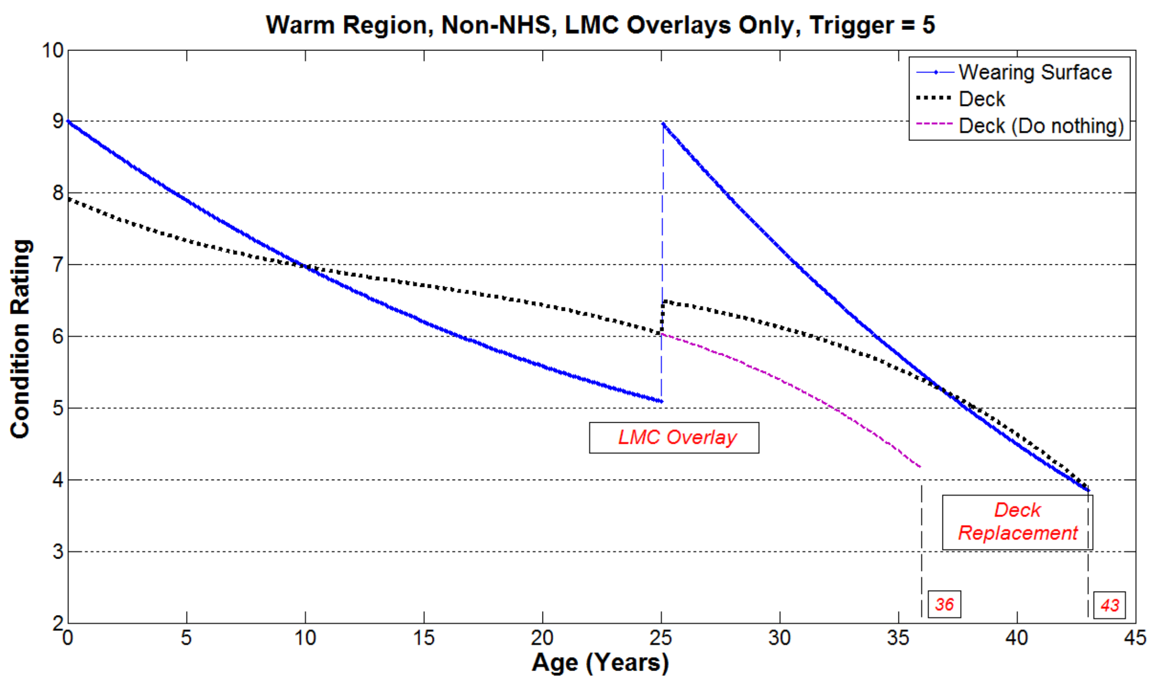


Figure B.9 Proposed Condition-Based Bridge Deck M&R Strategy for Warm Region, Non-NHS, LMC Overlays Only

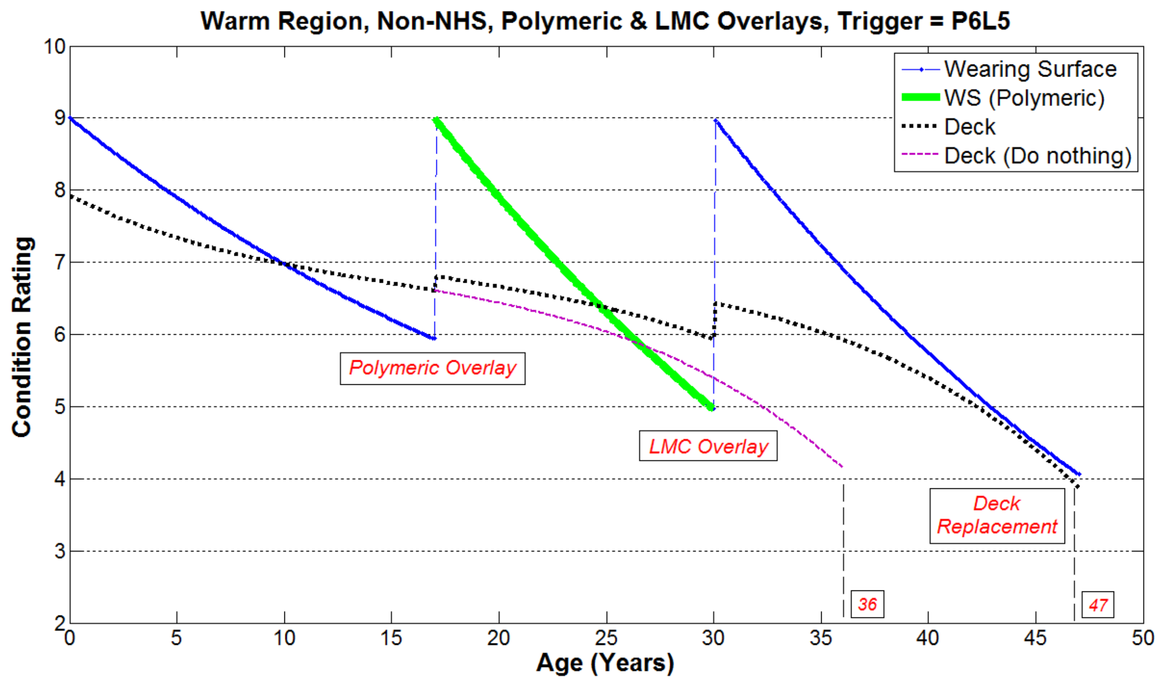


Figure B.10 Proposed Condition-Based Bridge Deck M&R Strategy for Warm Region, Non-NHS, Polymeric and LMC Overlays

Appendix C Additional Examples of Candidate Deck Life-Cycle M&R Strategies (Polymeric + LMC Overlays)

Appendix C presents additional examples of strategies for moderate region NHS that were found to be less cost-effective based on the analysis carried out in this dissertation, 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 could become the new cost-effective strategy.

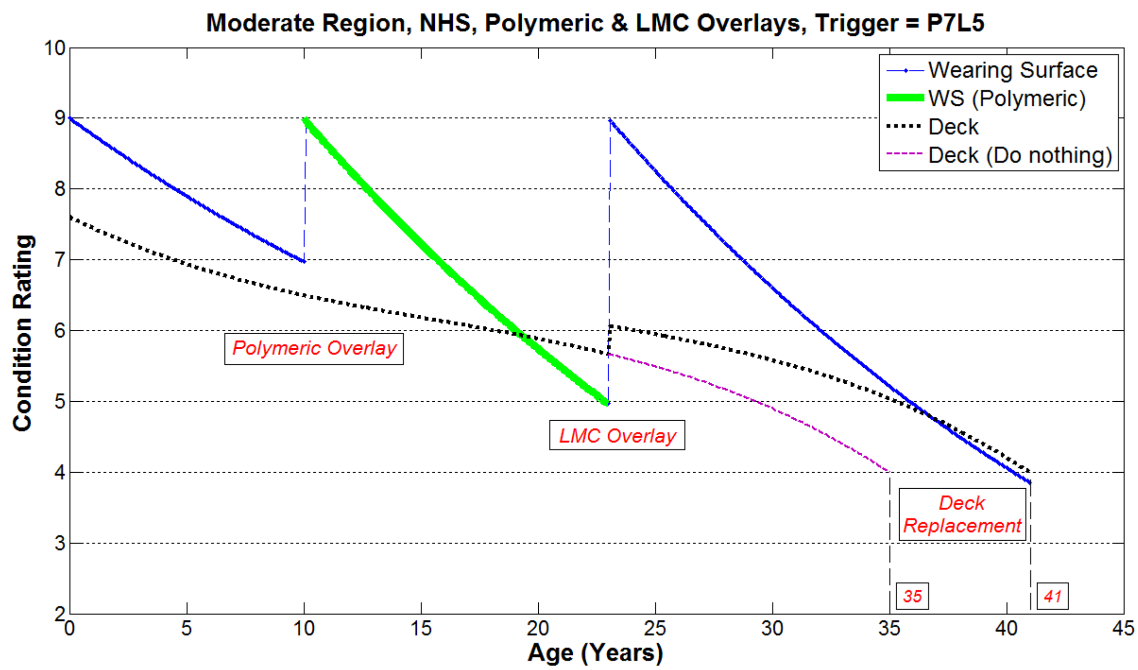


Figure C.1 Profile of Other Candidate Deck M&R Strategies for Moderate Region, NHS, Polymeric and LMC Overlays (Trigger = P7L5)

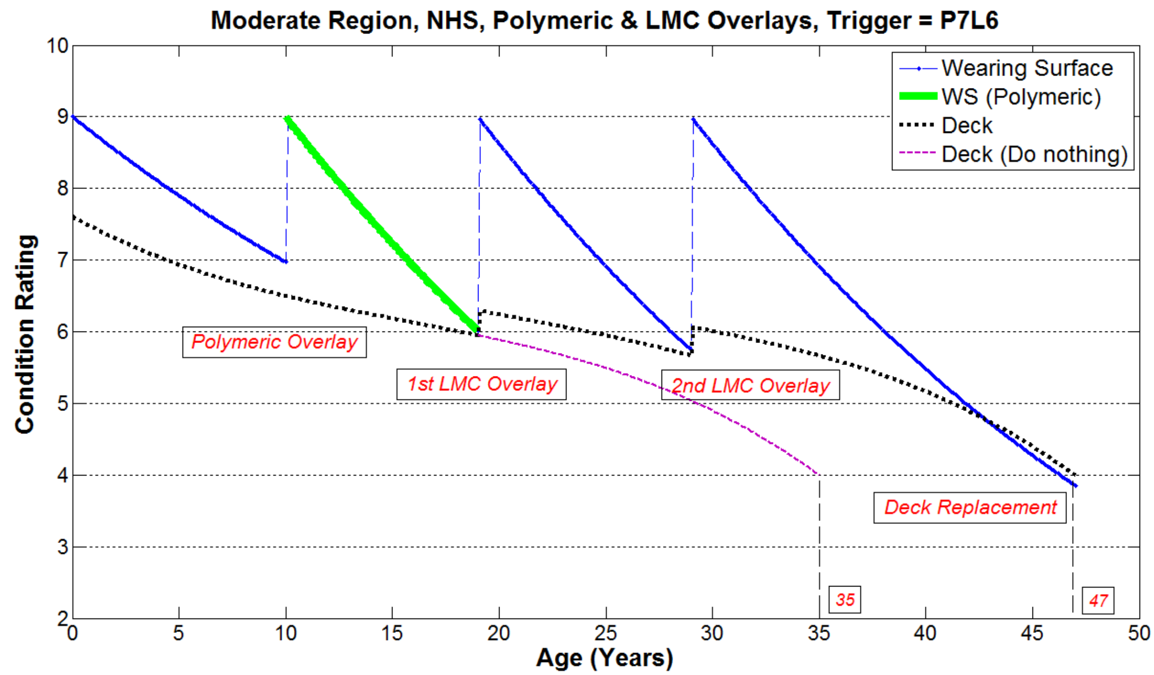


Figure C.2 Profile of Other Candidate Deck M&R Strategies for Moderate Region, NHS, Polymeric and LMC Overlays (Trigger = P7L6)

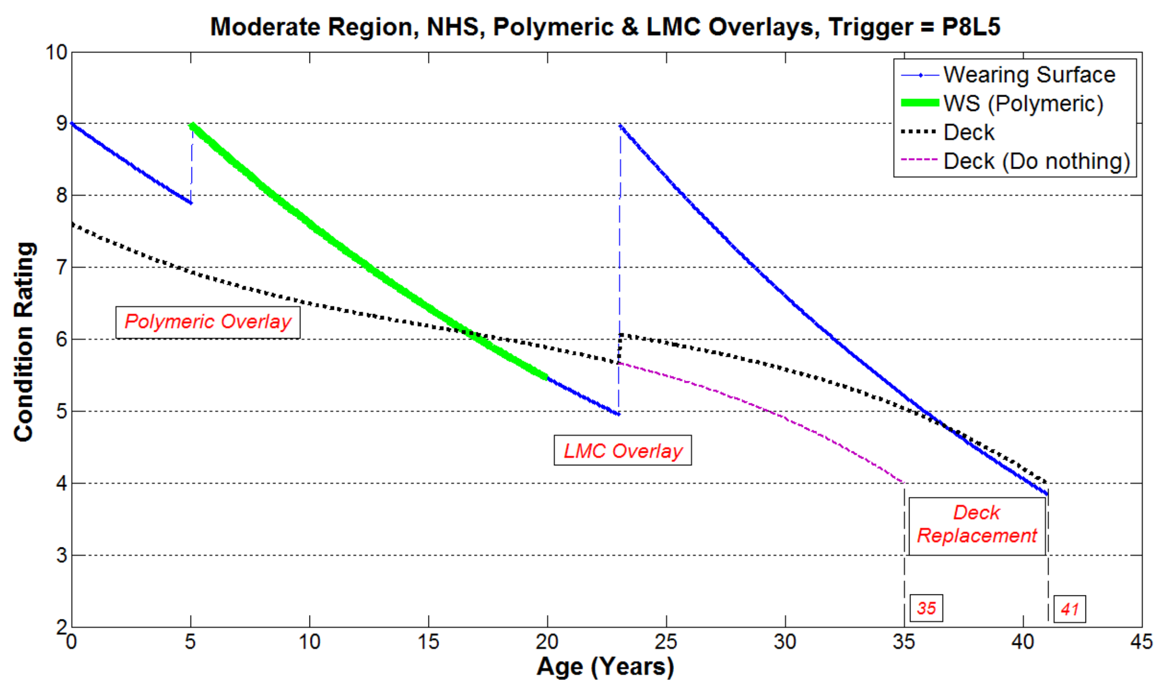


Figure C.3 Profile of Other Candidate Deck M&R Strategies for Moderate Region, NHS, Polymeric and LMC Overlays (Trigger = P8L5)

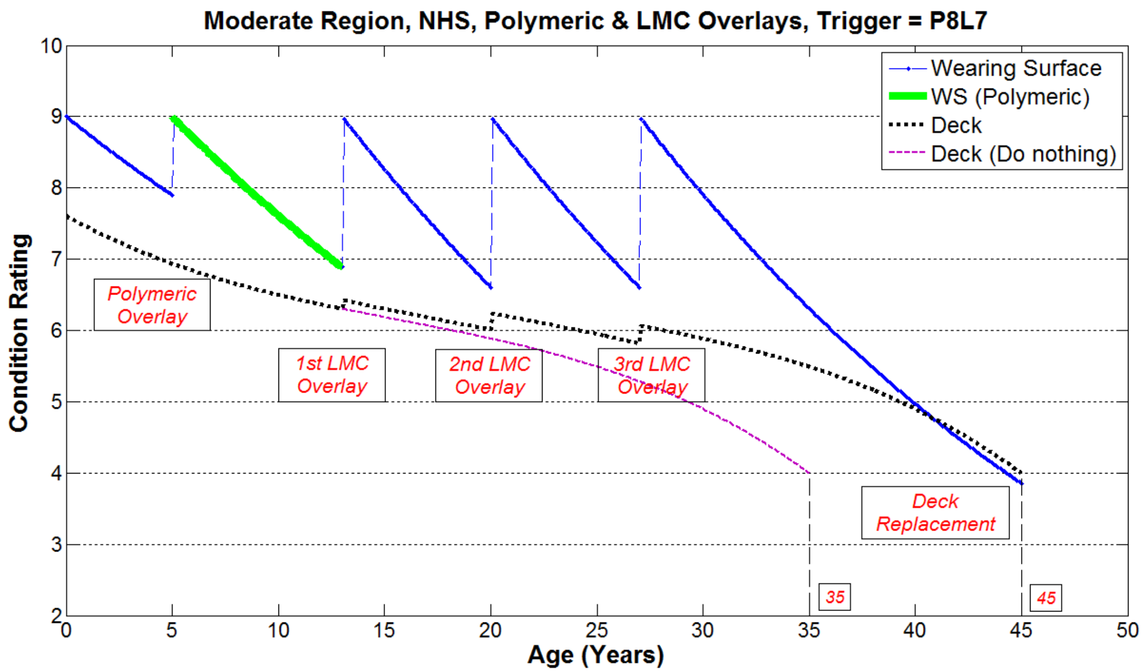


Figure C.4 Profile of Other Candidate Deck M&R Strategies for Moderate Region, NHS, Polymeric and LMC Overlays (Trigger = P8L7)

Appendix D Additional Sensitivity Analysis Results

Appendix D presents the sensitivity analysis conducted for the other climate regions and functional classes, including cold region non-NHS, moderate region NHS and non-NHS, and warm region 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 were discussed in Section 4.5.

Table D.1 Sensitivity Analysis for Weights between Agency and User Costs for Cold Region, Non-NHS, LMC Overlays Only

	Weight (AC:UC)	**Trigger**			
		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 Cold Region, Non-NHS, Polymeric and LMC Overlays

	Weight (AC:UC)	**Trigger**						
		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 Cold Region, Non-NHS, LMC Overlays Only

	Traffic (ADT)	**Trigger**			
		Do Nothing	**WS = 5**	**WS = 6**	**WS = 7**
(Total EUAC) / (Deck Area) ($\$/ft^2$)	2,000	5.92	8.06	10.94	14.56
	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 Cold Region, Non-NHS, Polymeric and LMC Overlays

	Traffic (ADT)	Trigger						
		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 Moderate Region, NHS, LMC Overlays Only

	Weight (AC:UC)	Trigger			
		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 Moderate Region, NHS, Polymeric and LMC Overlays

	Weight (AC:UC)	Trigger						
		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 Moderate Region, NHS, LMC Overlays Only

	Traffic (ADT)	Trigger			
		Do Nothing	WS = 5	WS = 6	WS = 7
(Total EUAC) / (Deck Area) ($/ft^2)	2,000	6.53	6.83	7.47	8.52
	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 Moderate Region, NHS, Polymeric and LMC Overlays

	Traffic (ADT)	Trigger						
		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 Moderate Region, Non-NHS, LMC Overlays Only

	Weight (AC:UC)	Trigger			
		Do Nothing	WS = 5	WS = 6	WS = 7
(Total EUAC) / (Deck Area) ($/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 Moderate Region, Non-NHS, Polymeric and LMC Overlays

	Weight (AC:UC)	Trigger						
		Do Nothing	P8L7	P8L6	P8L5	P7L6	P7L5	P6L5
(Total EUAC) / (Deck Area) ($/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 Moderate Region, Non-NHS, LMC Overlays Only

	Traffic (ADT)	Trigger			
		Do Nothing	WS = 5	WS = 6	WS = 7
(Total EUAC) / (Deck Area) ($/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 Moderate Region, Non-NHS, Polymeric and LMC Overlays

	Traffic (ADT)	Trigger						
		Do Nothing	P8L7	P8L6	P8L5	P7L6	P7L5	P6L5
(Total EUAC) / (Deck Area) ($\$/ft^2$)	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 Warm Region, NHS, LMC Overlays Only

	Weight (AC:UC)	Trigger			
		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 Warm Region, NHS, Polymeric and LMC Overlays

	Weight (AC:UC)	Trigger						
		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 Warm Region, NHS, LMC Overlays Only

	Traffic (ADT)	Trigger			
		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 Warm Region, NHS, Polymeric and LMC Overlays

	Traffic (ADT)	Trigger						
		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 Warm Region, Non-NHS, LMC Overlays Only

	Weight (AC:UC)	Trigger			
		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 Warm Region, Non-NHS, Polymeric and LMC Overlays

	Weight (AC:UC)	Trigger						
		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 Warm Region, Non-NHS, LMC Overlays Only

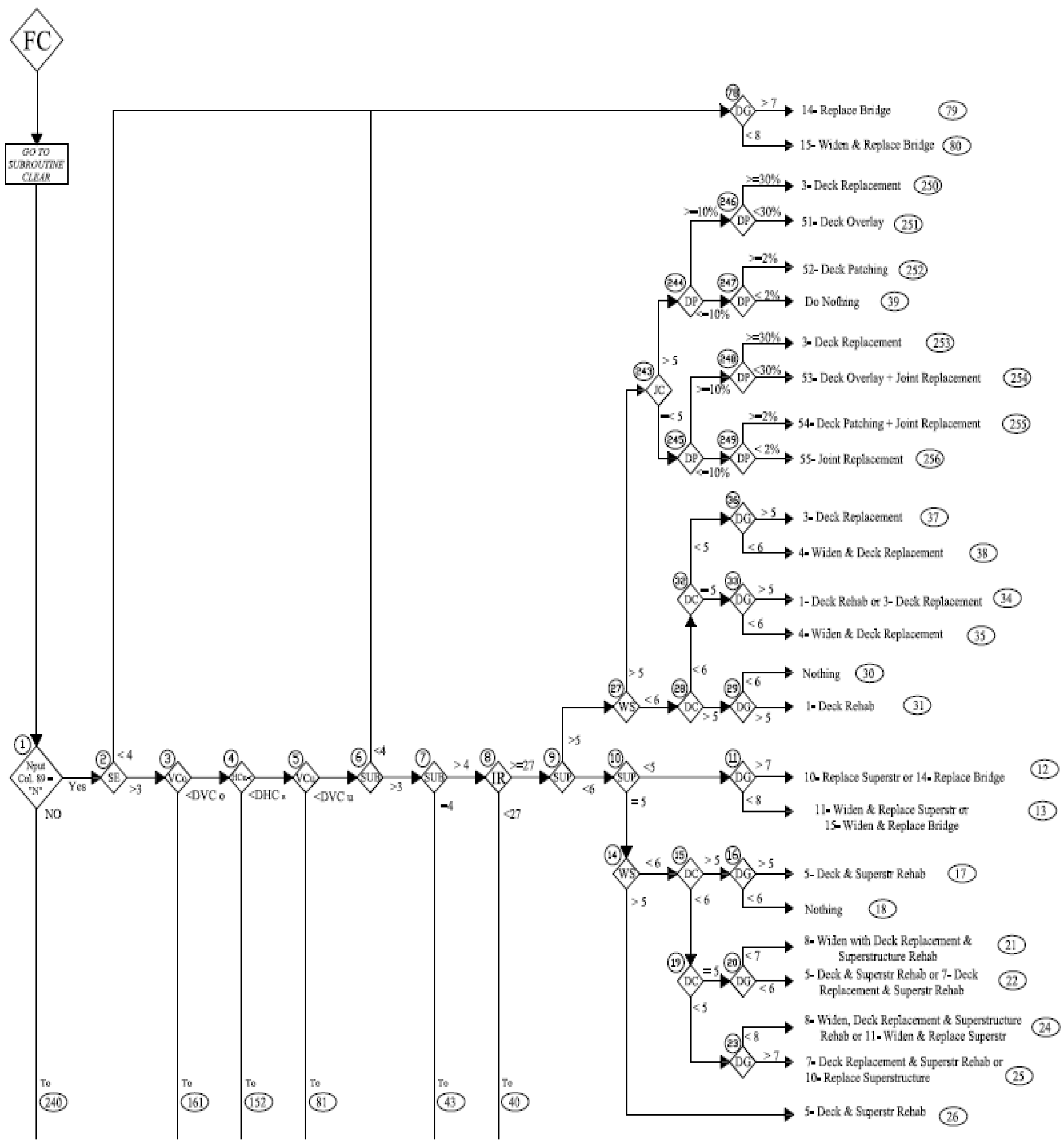
	Traffic (ADT)	Trigger			
		Do Nothing	WS = 5	WS = 6	WS = 7
(Total EUAC) / (Deck Area) ($/ft^2)	2,000	7.90	11.02	14.47	18.34
	5,000	17.12	23.38	30.12	37.68
	10,000	32.49	43.97	56.20	69.91
	20,000	63.23	85.14	108.37	134.37

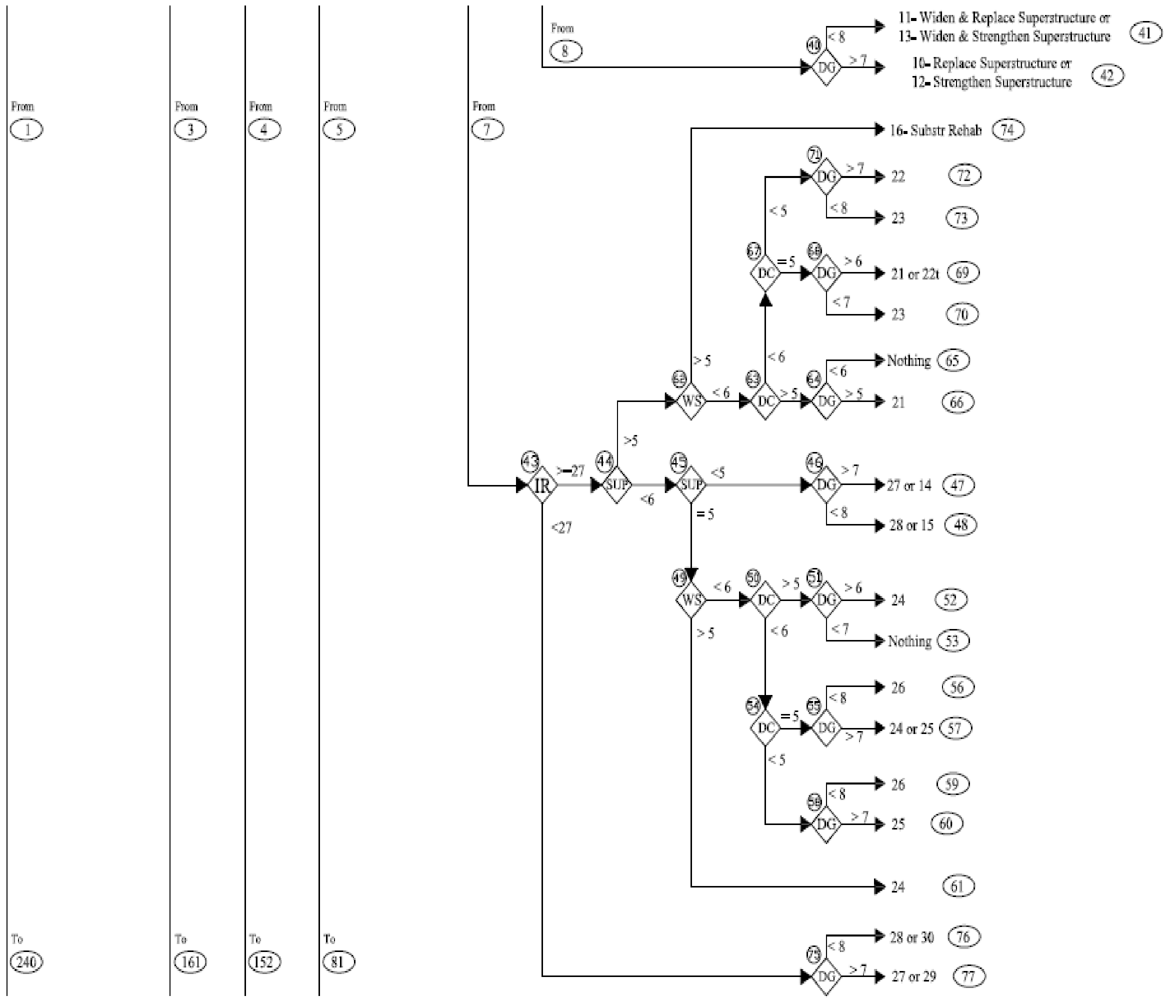
Table D.20 Sensitivity Analysis for Traffic Volume for Warm Region, Non-NHS, Polymeric and LMC Overlays

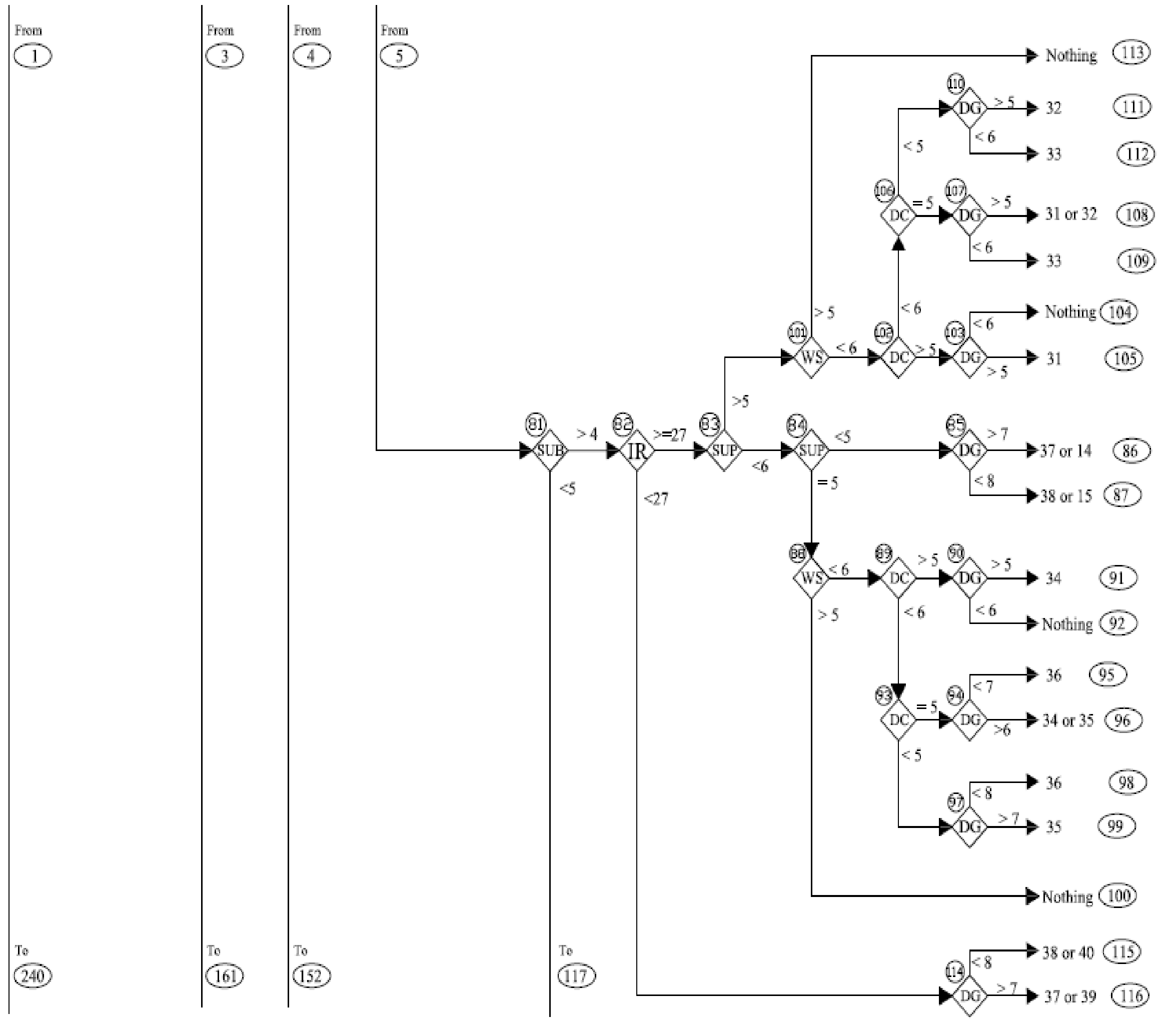
	Traffic (ADT)	**Trigger**						
		Do Nothing	**P8L7**	**P8L6**	**P8L5**	**P7L6**	**P7L5**	**P6L5**
(Total EUAC) / (Deck Area) ($/ft^2)	2,000	7.90	20.56	16.11	12.64	15.38	12.35	11.11
	5,000	17.12	41.21	32.50	25.60	31.27	25.10	22.96
	10,000	32.49	75.62	59.81	47.21	57.76	46.34	42.71
	20,000	63.23	144.4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

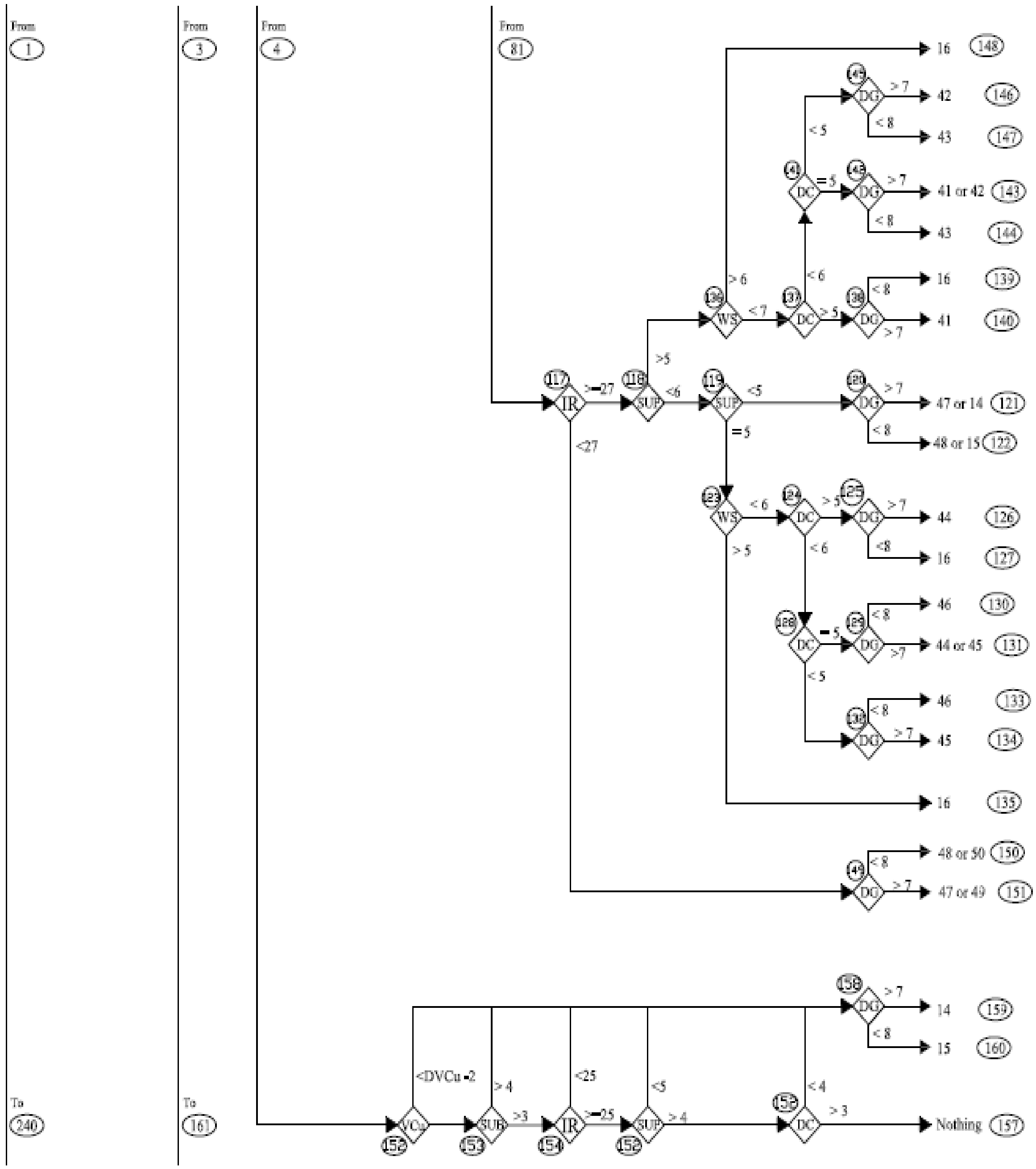
Appendix E IBMS DTREE for NHS and Non-NHS Bridges

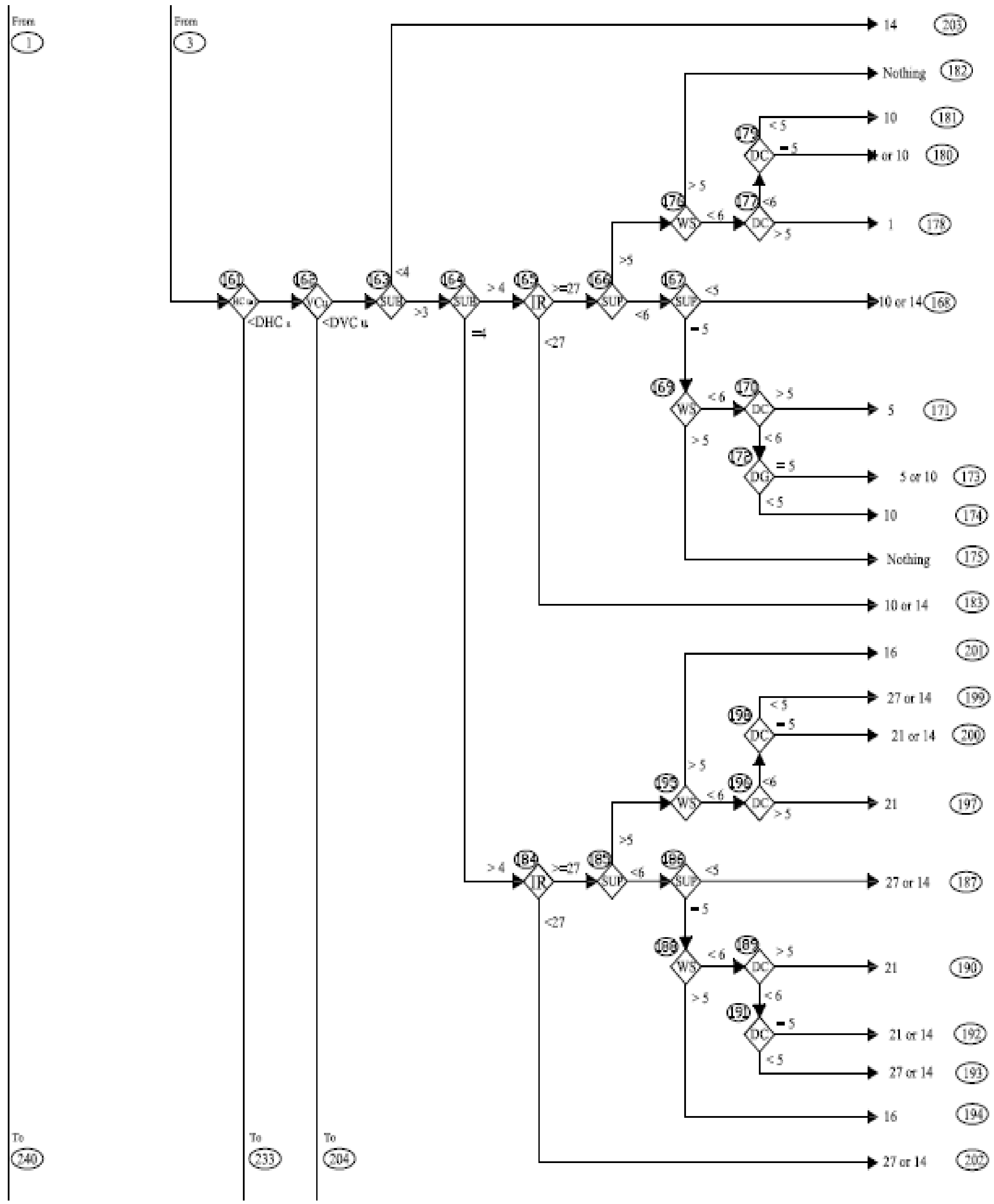
DTREE for NHS Bridges:



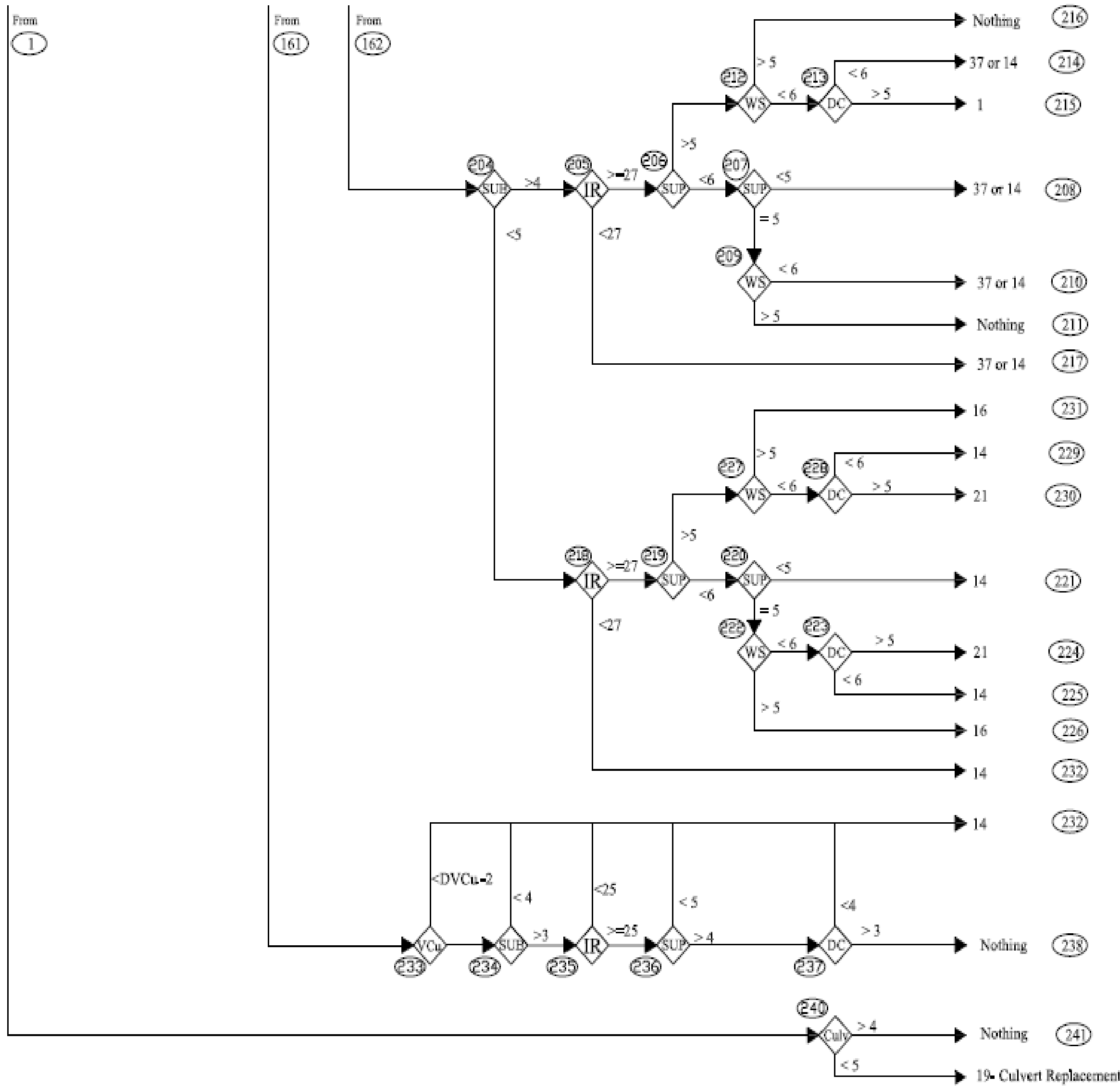

From
8
11- Widen & Replace Superstructure or
13- Widen & Strengthen Superstructure
41
10- Replace Superstructure or
12- Strengthen Superstructure
42
From 1
From 3
From 4
From 5
From 7
16- Substr Rehab
74
IR
SUP
WS
DC
DG
22
72
23
73
21 or 22t
69
70
Nothing
65
21
66
27 or 14
47
28 or 15
48
24
52
Nothing
53
26
56
24 or 25
57
59
25
60
61
28 or 30
76
27 or 29
77
To 240
To 161
To 152
To 81


From
1
From
3
From
4
From
5
SUB
IR
SUP
SUP
WS
DC
DG
WS
DC
DG
> 4
<5
>=27
<27
>5
<6
<5
= 5
> 5
< 6
Nothing
113
32
111
33
112
31 or 32
108
33
109
Nothing
104
31
105
37 or 14
86
38 or 15
87
34
91
Nothing
92
36
95
34 or 35
96
36
98
35
99
Nothing
100
38 or 40
115
37 or 39
116
To
240
To
161
To
152
To
117

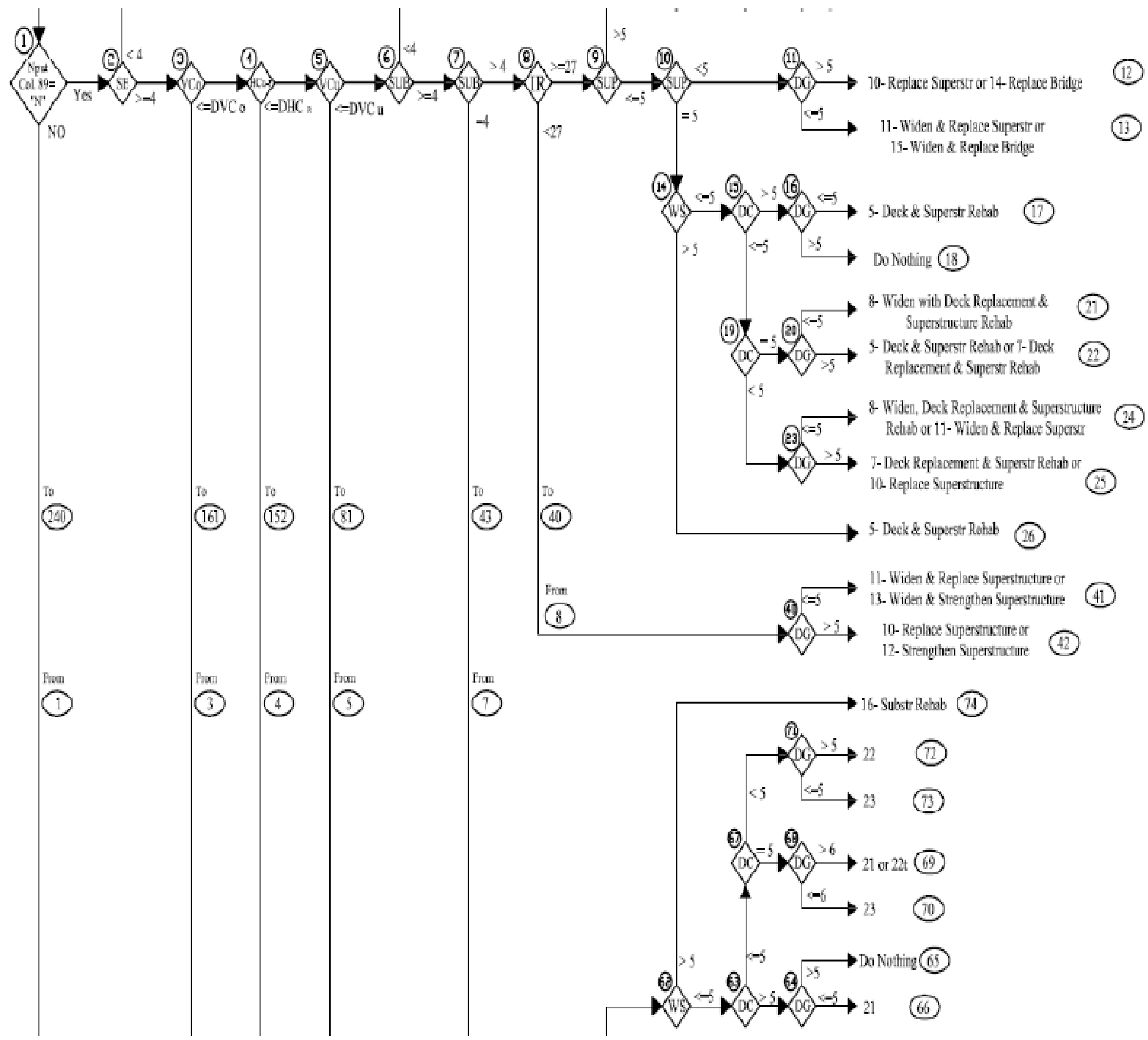

From 1
From 3
From 4
From 81
To 240
To 161
IR
SUP
WS
DC
DG
SUB
VCu
Nothing



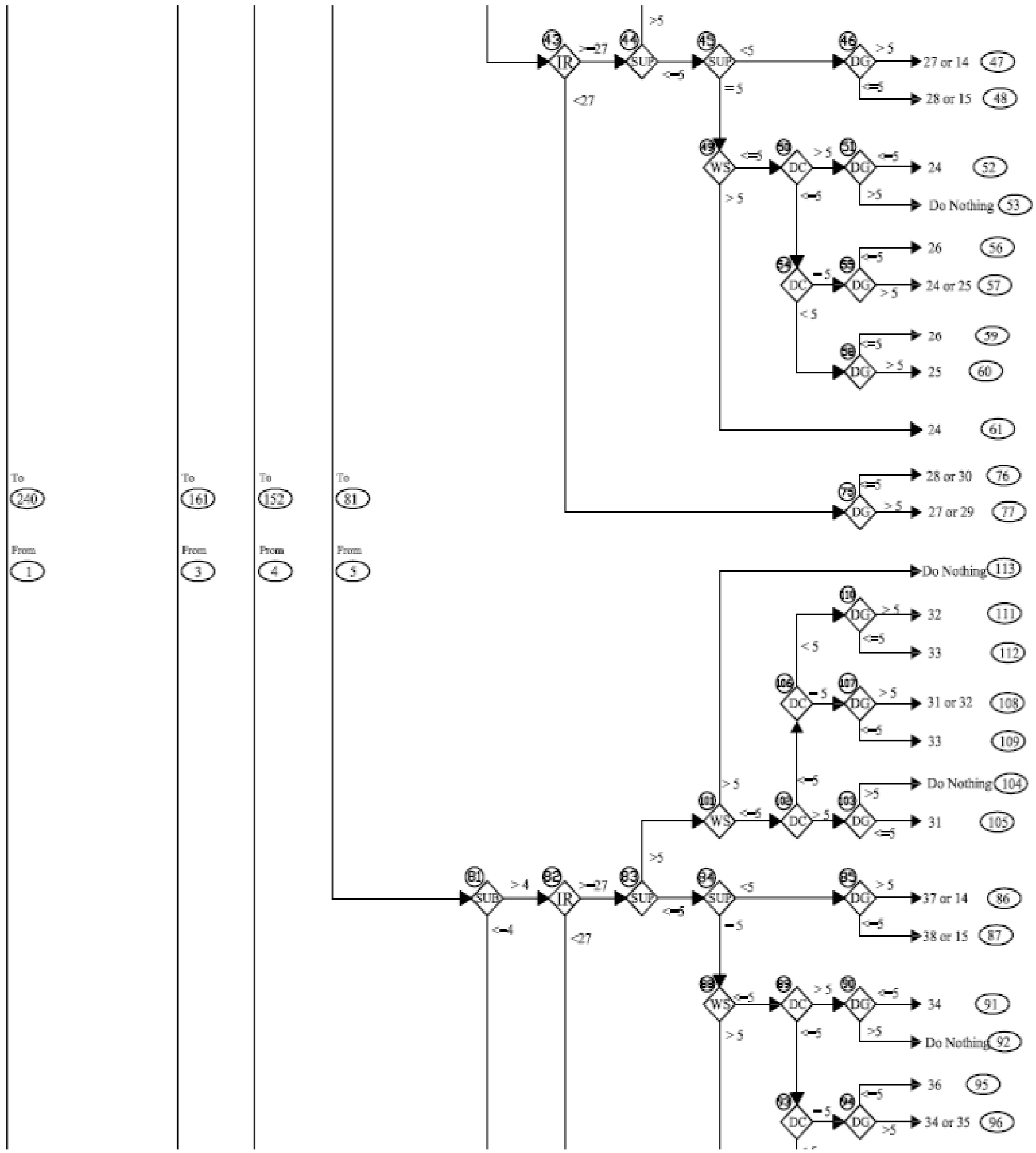
From
1
From
3
14
203
Nothing
182
10
181
or 10
180
1
178
10 or 14
168
5
171
5 or 10
173
10
174
Nothing
175
10 or 14
183
16
201
27 or 14
199
21 or 14
200
21
197
27 or 14
187
21
190
21 or 14
192
27 or 14
193
16
194
27 or 14
202
To
240
To
233
To
204
<DHC
<DVC
SUB
SUP
JR
WS
DC
>=27
<27


From
1
From
161
From
162
Nothing
216
37 or 14
214
1
215
37 or 14
208
37 or 14
210
Nothing
211
37 or 14
217
16
231
14
229
21
230
14
221
21
224
14
225
16
226
14
232
14
232
Nothing
238
Nothing
241
19- Culvert Replacement
SUB
IR
SUP
WS
DC
VCu
Culv
<DVCu-2

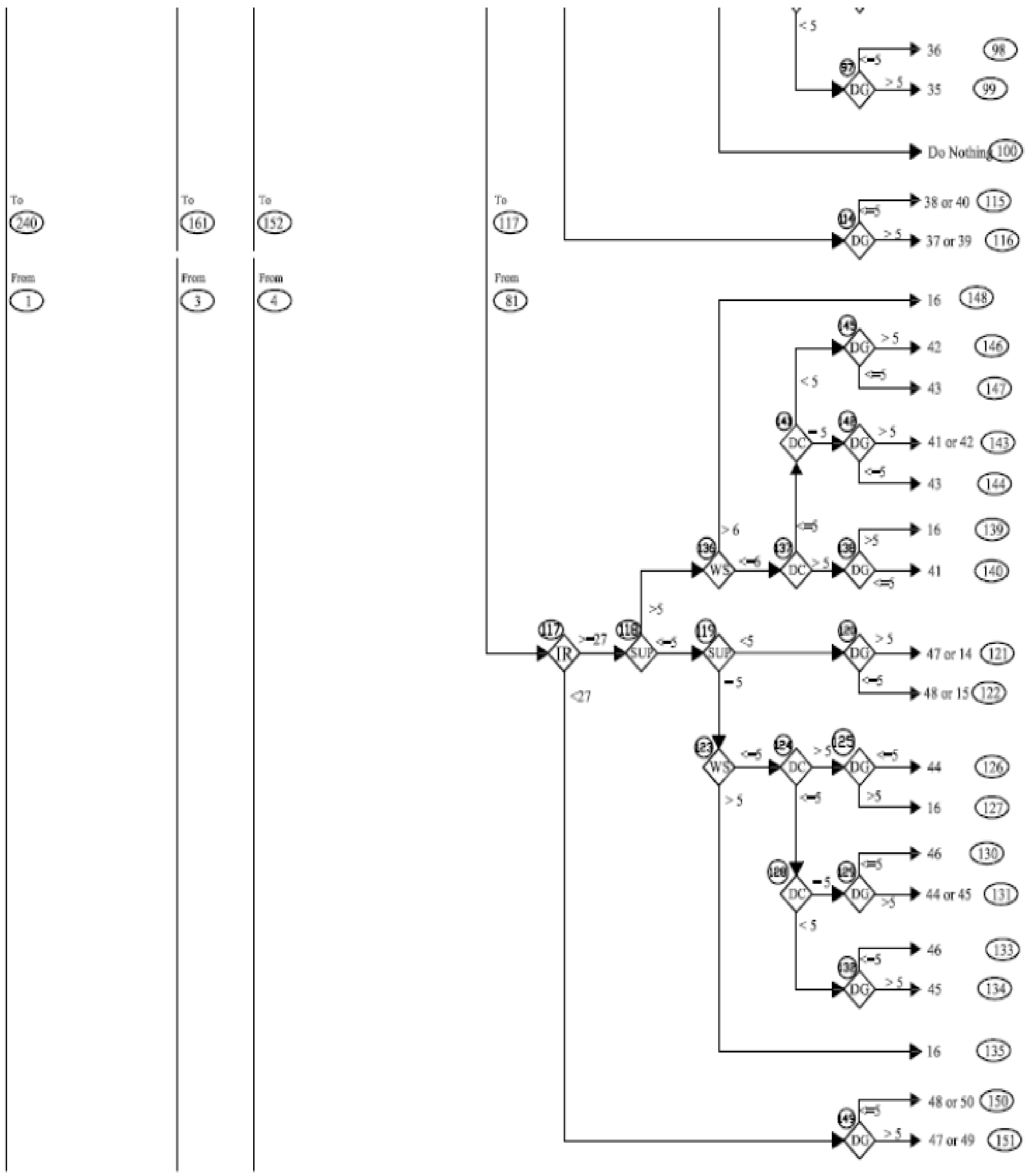
DTREE for Non-NHS Bridges:



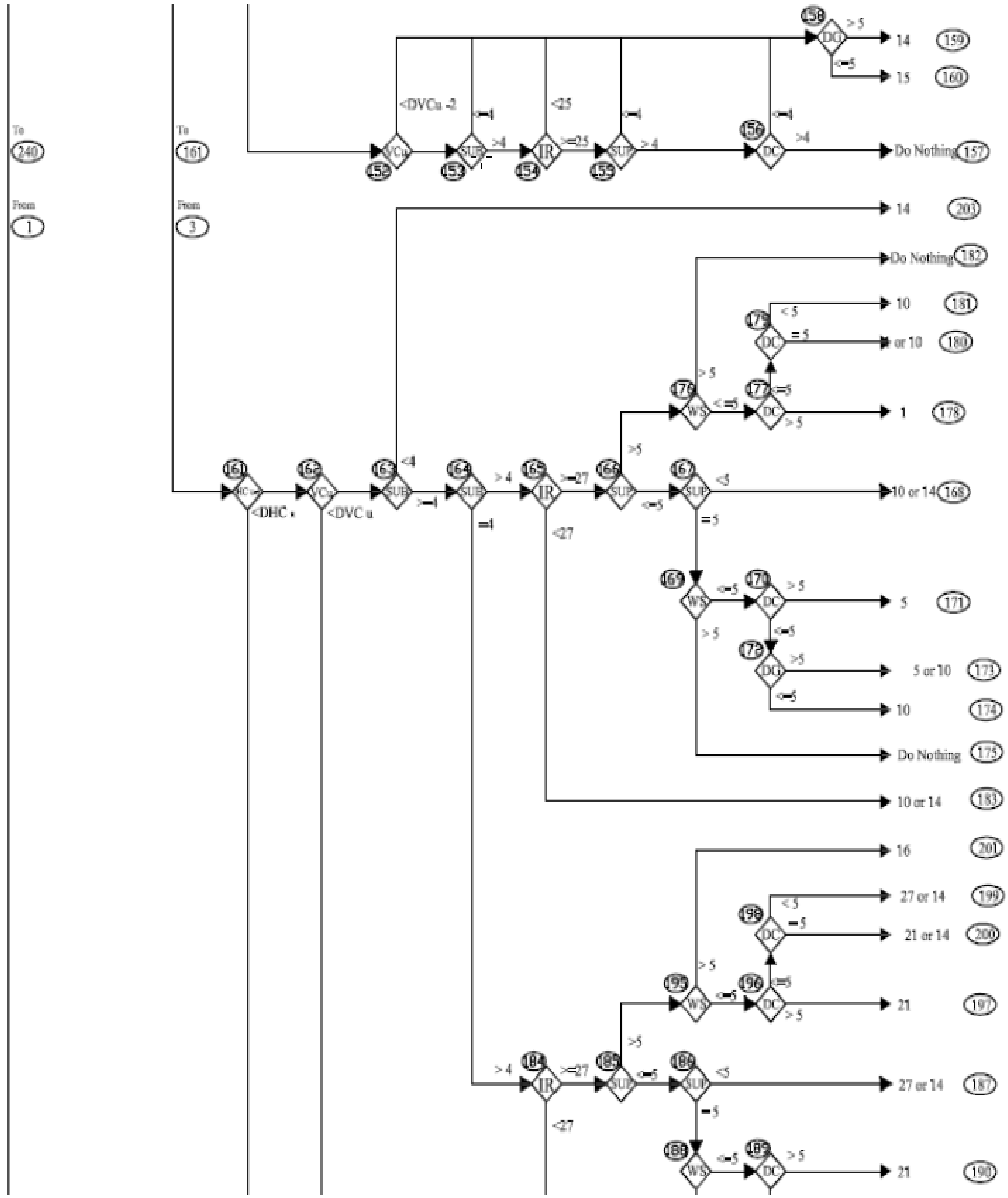
Nput Col. 89= "N"
Yes
NO
SE
VCo
VCu
SUB
IR
SUP
DG
WS
DC
10- Replace Superstr or 14- Replace Bridge
11- Widen & Replace Superstr or 15- Widen & Replace Bridge
5- Deck & Superstr Rehab
Do Nothing
8- Widen with Deck Replacement & Superstructure Rehab
5- Deck & Superstr Rehab or 7- Deck Replacement & Superstr Rehab
8- Widen, Deck Replacement & Superstructure Rehab or 11- Widen & Replace Superstr
7- Deck Replacement & Superstr Rehab or 10- Replace Superstructure
5- Deck & Superstr Rehab
11- Widen & Replace Superstructure or 13- Widen & Strengthen Superstructure
10- Replace Superstructure or 12- Strengthen Superstructure
16- Substr Rehab
22
23
21 or 22t
23
Do Nothing
21
To
From



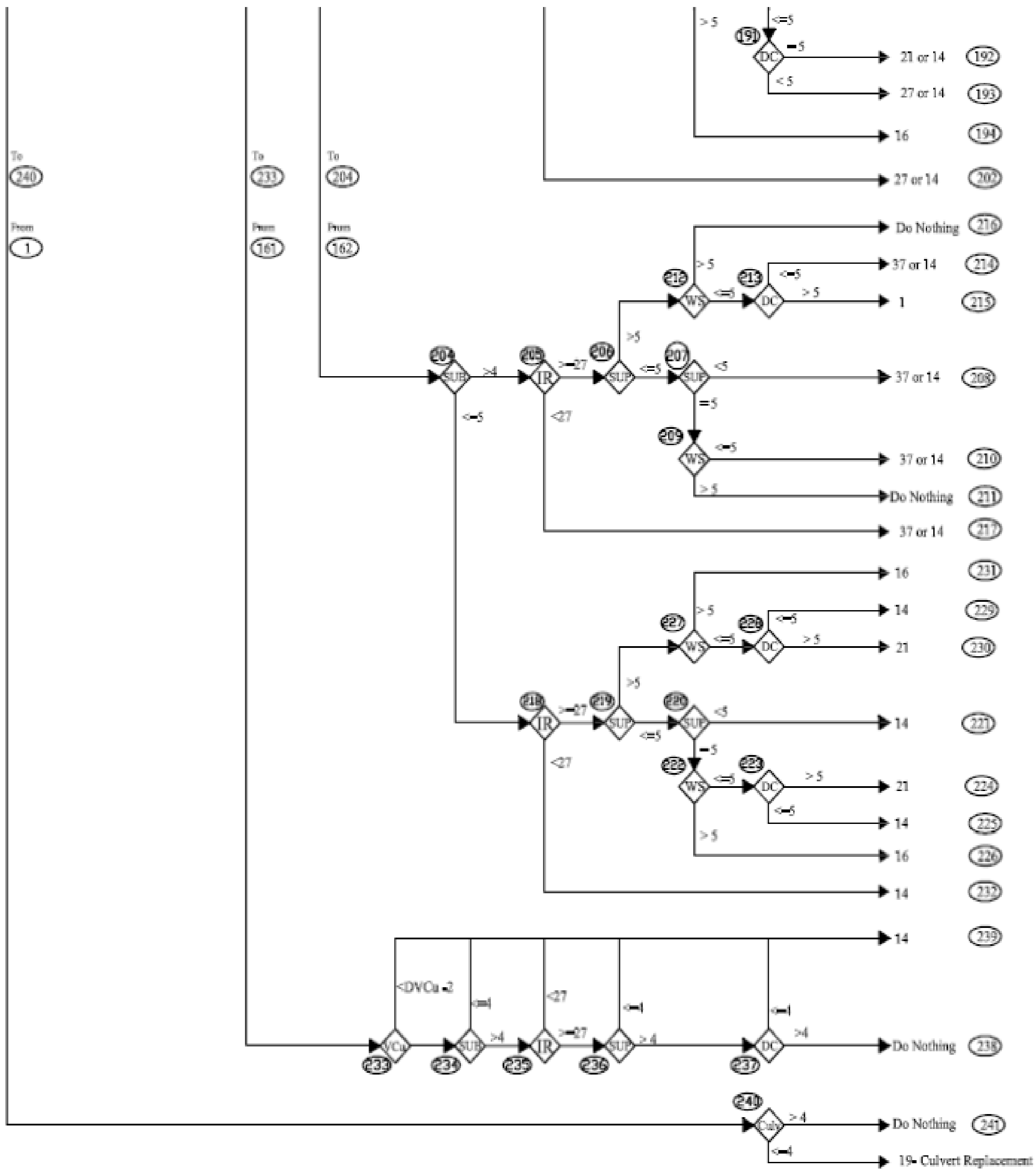
To 240
To 161
To 152
To 81
From 1
From 3
From 4
From 5
IR
SUP
WS
DC
DG
SUB
27 or 14
28 or 15
24
Do Nothing
26
24 or 25
25
28 or 30
27 or 29
32
33
31 or 32
31
37 or 14
38 or 15
34
36
34 or 35



To
240
To
161
To
152
To
117
From
1
From
3
From
4
From
81
IR
SUP
WS
DC
DG
Do Nothing
38 or 40
37 or 39
41 or 42
47 or 14
48 or 15
44 or 45
48 or 50
47 or 49



To
240
From
1
To
161
From
3
DG
> 5
14
159
<=5
15
160
<DVCu -2
<=4
<25
<=4
<=4
VCu
SUP
>4
IR
>=25
SUP
> 4
DC
>4
Do Nothing
157
152
153
154
155
156
158
14
203
Do Nothing
182
10
181
< 5
DC
= 5
or 10
180
179
> 5
176
WS
<=5
177
DC
<=5
1
178
> 5
>5
161
162
163
164
165
166
167
<4
> 4
>=27
<5
DHC
VCu
SUB
SUB
IR
SUP
SUP
10 or 14
168
<DHC
<DVC u
>=4
=4
<27
<=5
=5
169
WS
<=5
170
DC
> 5
5
171
> 5
<=5
172
DG
>5
5 or 10
173
<=5
10
174
Do Nothing
175
10 or 14
183
16
201
27 or 14
199
< 5
198
DC
= 5
21 or 14
200
> 5
195
WS
<=5
196
DC
<=5
> 5
21
197
>5
> 4
184
IR
>=27
185
SUP
<=5
186
SUP
<5
27 or 14
187
= 5
<27
188
WS
<=5
189
DC
> 5
21
190


To
240
From
1
To
233
From
161
To
204
From
162
21 or 14
192
27 or 14
193
16
194
27 or 14
202
Do Nothing
216
37 or 14
214
1
215
37 or 14
208
37 or 14
210
Do Nothing
211
37 or 14
217
16
231
14
229
21
230
14
227
21
224
14
225
16
226
14
232
14
239
Do Nothing
238
Do Nothing
241
19- Culvert Replacement

Appendix F Additional Duration Model Estimation Results and Plots

Appendix F supplements the estimation results of the duration models discussed in Section 5.1 but not presented in that section, including estimated parameters and graphical illustrations of the survival functions and hazard functions for the models for D7WS, D6WS, D5WS, D8LMC, D7LMC, D6LMC, D5LMC, D8ASP, D7ASP, D6ASP, and D5ASP.

Table F.1 Model Estimation Results for D7WS (Weibull)

Variable	**Estimated Parameter**	**t-Statistic**	**p-Value**
Constant	2.475	30.19	0.0000
Age	-0.0151	-5.43	0.0000
NNHS	0.225	3.28	0.0010
South	-0.122	-2.94	0.0033
ADT	-0.103e-04	-2.88	0.0040
P	1.678	35.21	
λ	0.0968	46.76	
No. of observations	1077		
Log likelihood at convergence	-1167.78		

Table F.2 Model Estimation Results for D6WS (Weibull)

Variable	**Estimated Parameter**	**t-Statistic**	**p-Value**
Constant	2.366	23.79	0.0000
Age	-0.0102	-2.81	0.0050
ADT	-0.158e-04	-3.08	0.0021
P	1.545	22.96	
λ	0.124	31.59	
No. of observations	471		
Log likelihood at convergence	-537.61		

Table F.3 Model Estimation Results for D5WS (Weibull)

Variable	**Estimated Parameter**	**t-Statistic**	**p-Value**
Constant	2.682	12.72	0.0000
South	-0.251	-1.89	0.0593
Truck	-0.0756	-2.42	0.0155
Concrete	-0.215	-1.64	0.1018
P	1.412	12.93	
λ	0.126	18.49	
No. of observations	194		
Log likelihood at convergence	-235.69		

Table F.4 Model Estimation Results for D8LMC (Log-logistic)

Variable	**Estimated Parameter**	**t-Statistic**	**p-Value**
Constant	1.899	24.35	0.0000
Age	-0.0347	-2.08	0.0373
South	0.352	2.57	0.0101
P	5.722	6.78	
λ	0.165	22.98	
No. of observations	51		
Log likelihood at convergence	-12.57		

Table F.5 Model Estimation Results for D7LMC (Weibull)

Variable	**Estimated Parameter**	**t-Statistic**	**p-Value**
Constant	2.343	78.86	0.0000
North	-0.132	-2.68	0.0073
Concrete	-0.0787	-2.01	0.0440
P	3.354	21.23	
λ	0.102	49.29	
No. of observations	247		
Log likelihood at convergence	-93.42		

Table F.6 Model Estimation Results for D6LMC (Log-logistic)

Variable	**Estimated Parameter**	**t-Statistic**	**p-Value**
Constant	1.907	29.50	0.0000
INT	-0.329	-3.48	0.0005
South	0.199	1.76	0.0780
P	2.626	14.70	
λ	0.160	21.45	
No. of observations	239		
Log likelihood at convergence	-210.82		

Table F.7 Model Estimation Results for D5LMC (Weibull)

Variable	**Estimated Parameter**	**t-Statistic**	**p-Value**
Constant	0.856	7.89	0.0000
INT	0.198	1.51	0.1305
NNHS	0.206	1.79	0.0733
Concrete	0.151	1.69	0.0909
P	1.658	11.41	
λ	0.334	21.69	
No. of observations	218		
Log likelihood at convergence	-221.60		

Table F.8 Model Estimation Results for D8ASP (Log-logistic)

Variable	**Estimated Parameter**	**t-Statistic**	**p-Value**
Constant	2.187	55.51	0.0000
South	0.343	5.89	0.0000
ADT	-0.201e-04	-1.21	0.2267
P	3.447	15.05	
λ	0.101	34.54	
No. of observations	314		
Log likelihood at convergence	-233.62		

Table F.9 Model Estimation Results for D7ASP (Log-logistic)

Variable	**Estimated Parameter**	**t-Statistic**	**p-Value**
Constant	2.207	40.36	0.0000
Age	-0.00499	-2.98	0.0052
South	-0.0621	-1.79	0.0743
Concrete	0.0982	2.14	0.0325
P	3.021	38.62	
λ	0.114	56.79	
No. of observations	1197		
Log likelihood at convergence	-1067.8		

Table F.10 Model Estimation Results for D6ASP (Weibull with Gamma Heterogeneity)

Variable	**Estimated Parameter**	**t-Statistic**	**p-Value**
Constant	2.098	29.77	0.0000
Age	-0.00392	-1.78	0.0751
South	0.161	3.70	0.0002
ADT	-0.179e-04	-2.43	0.0151
P	1.844	16.53	
λ	0.133	24.73	
θ	0.187	1.62	
No. of observations	945		
Log likelihood at convergence	-984.70		

Table F.11 Model Estimation Results for D5ASP (Weibull with Gamma Heterogeneity)

Variable	**Estimated Parameter**	**t-Statistic**	**p-Value**
Constant	1.067	2.88	0.0040
Age	0.0116	6.35	0.0000
NNHS	0.507	2.35	0.0189
North	0.177	2.08	0.0379
South	0.147	1.85	0.0644
Truck	-0.0241	-2.22	0.0266
Water	-0.636	-1.99	0.0466
P	2.616	10.25	
λ	0.265	14.76	
θ	2.351	5.48	
No. of observations	762		
Log likelihood at convergence	-848.67		

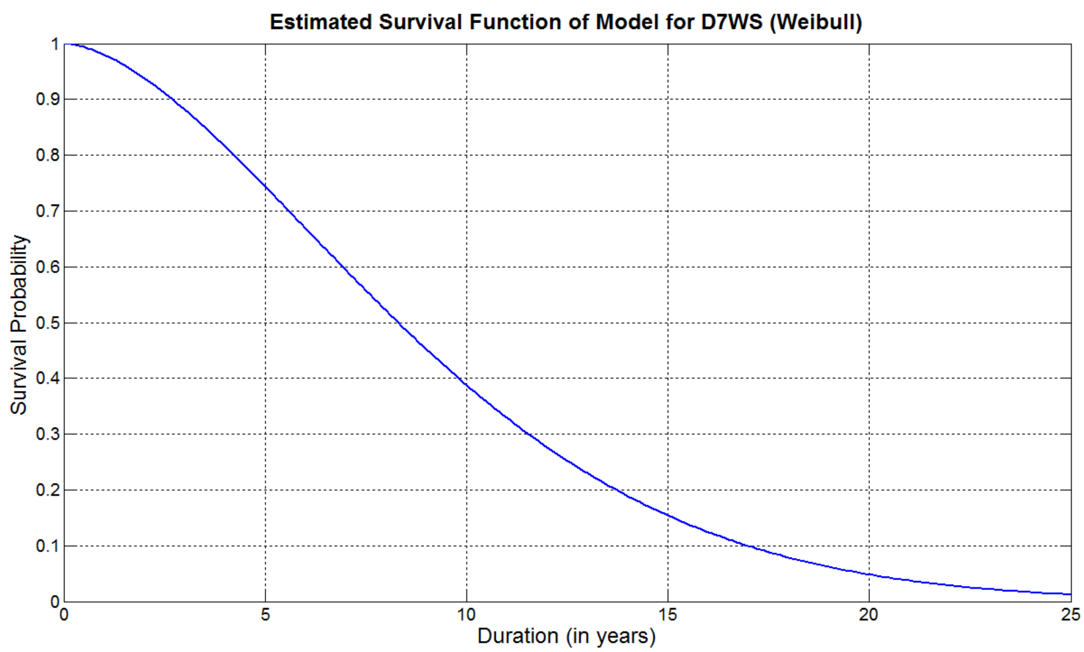


Figure F.1 Estimated Survival Function of Model for D7WS (Weibull)

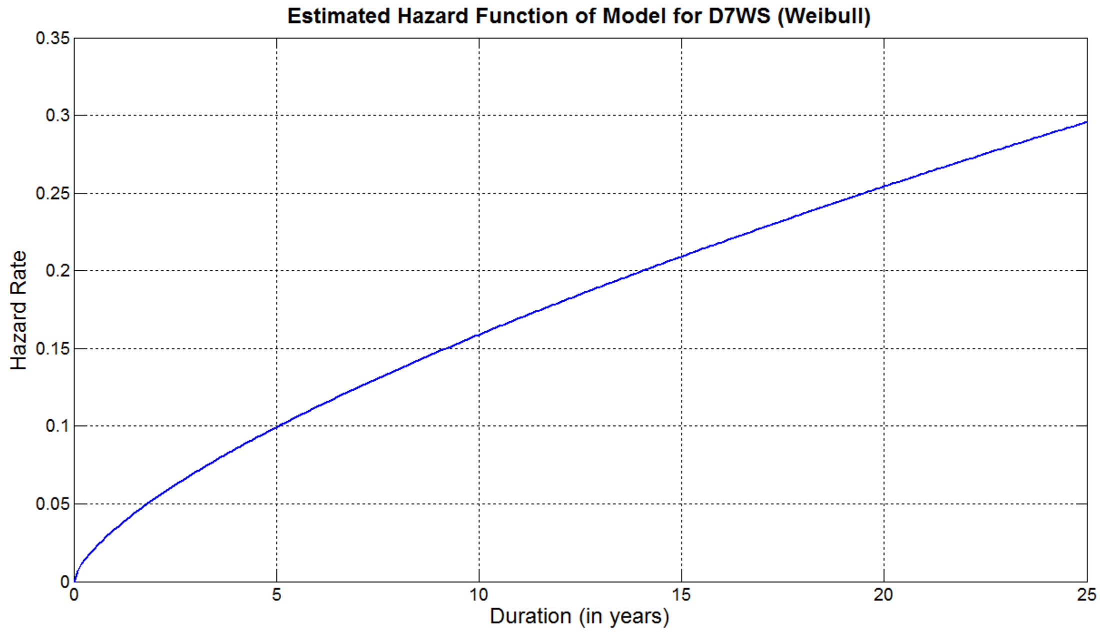


Figure F.2 Estimated Hazard Function of Model for D7WS (Weibull)

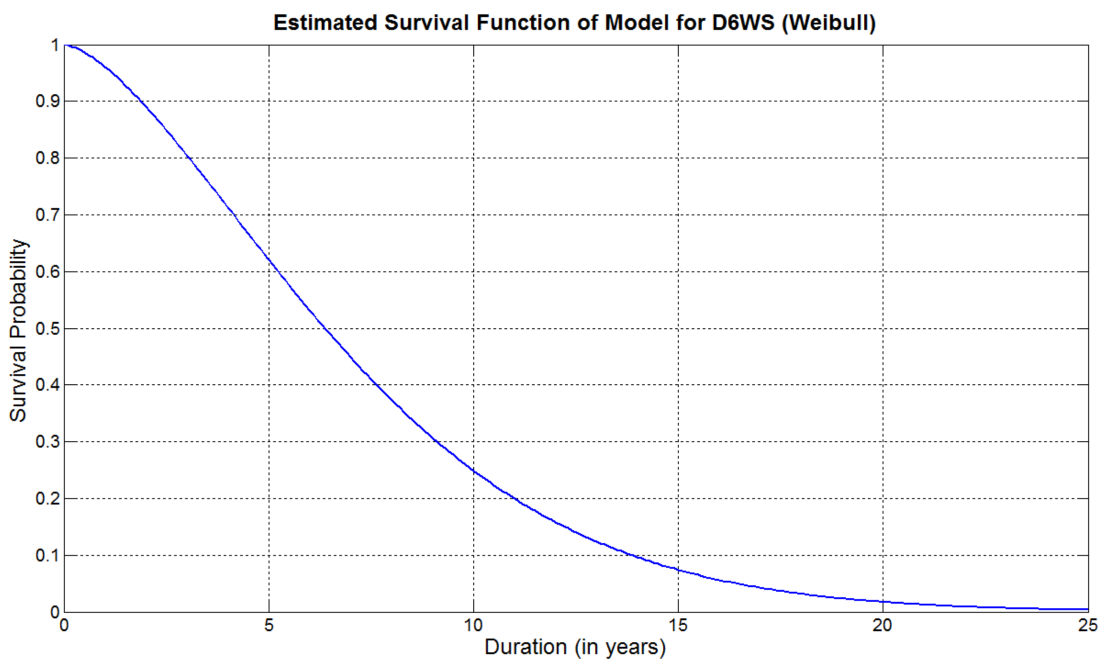


Figure F.3 Estimated Survival Function of Model for D6WS (Weibull)

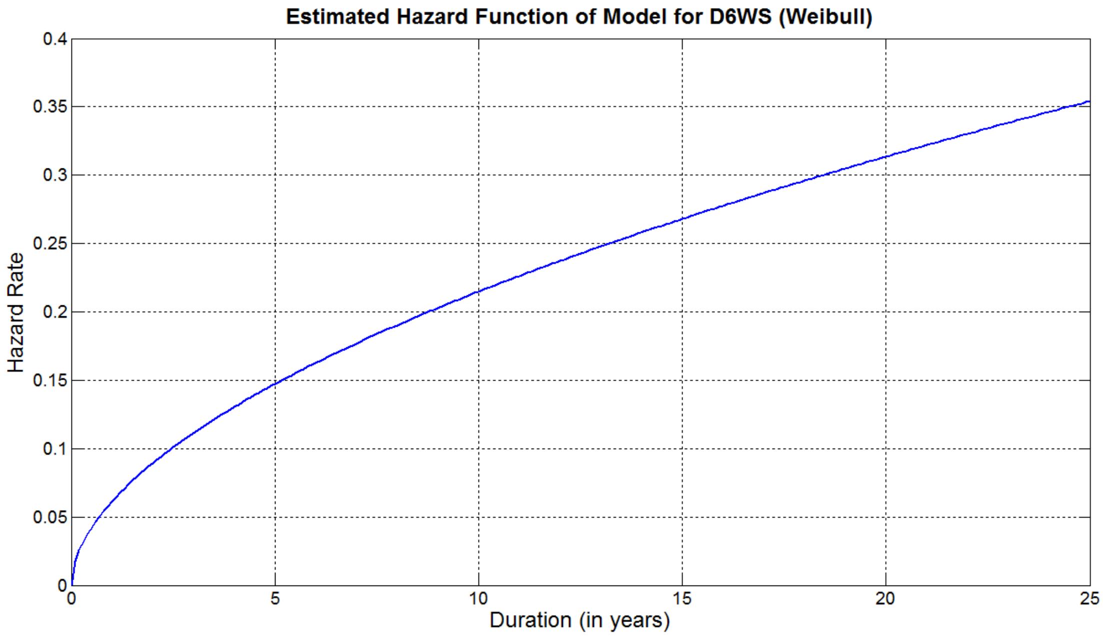


Figure F.4 Estimated Hazard Function of Model for D6WS (Weibull)

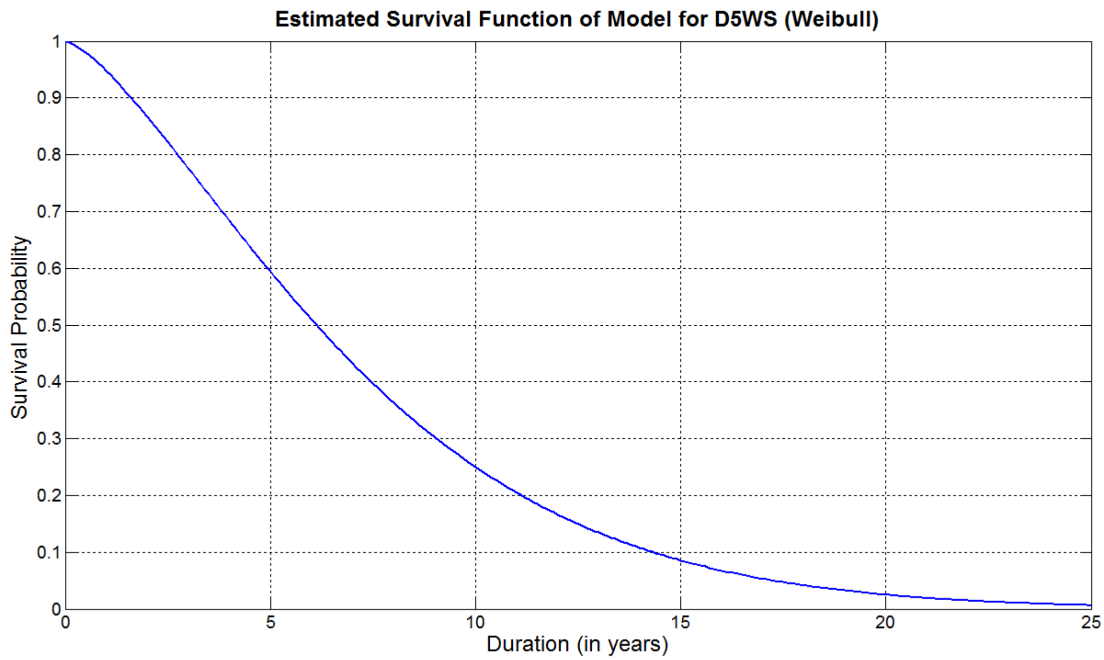


Figure F.5 Estimated Survival Function of Model for D5WS (Weibull)

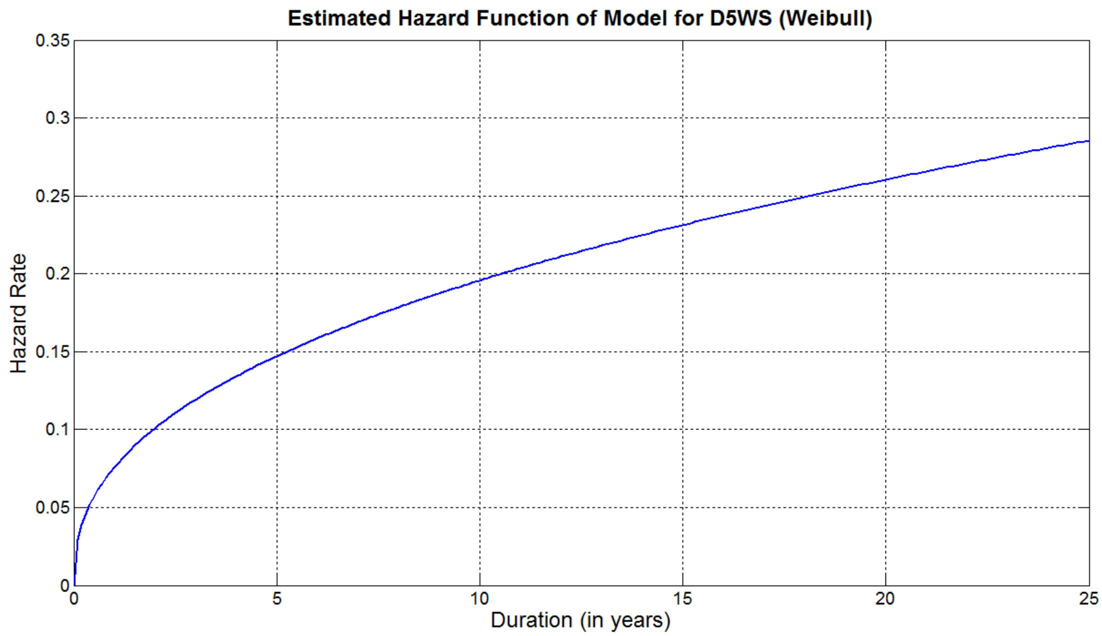


Figure F.6 Estimated Hazard Function of Model for D5WS (Weibull)

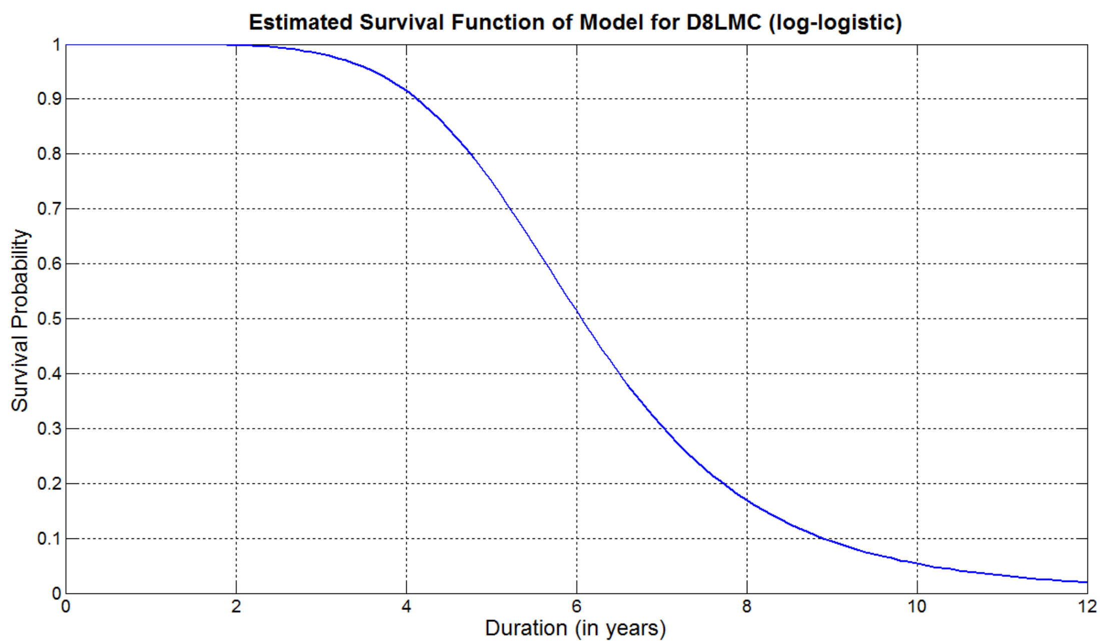


Figure F.7 Estimated Survival Function of Model for D8LMC (Log-logistic)

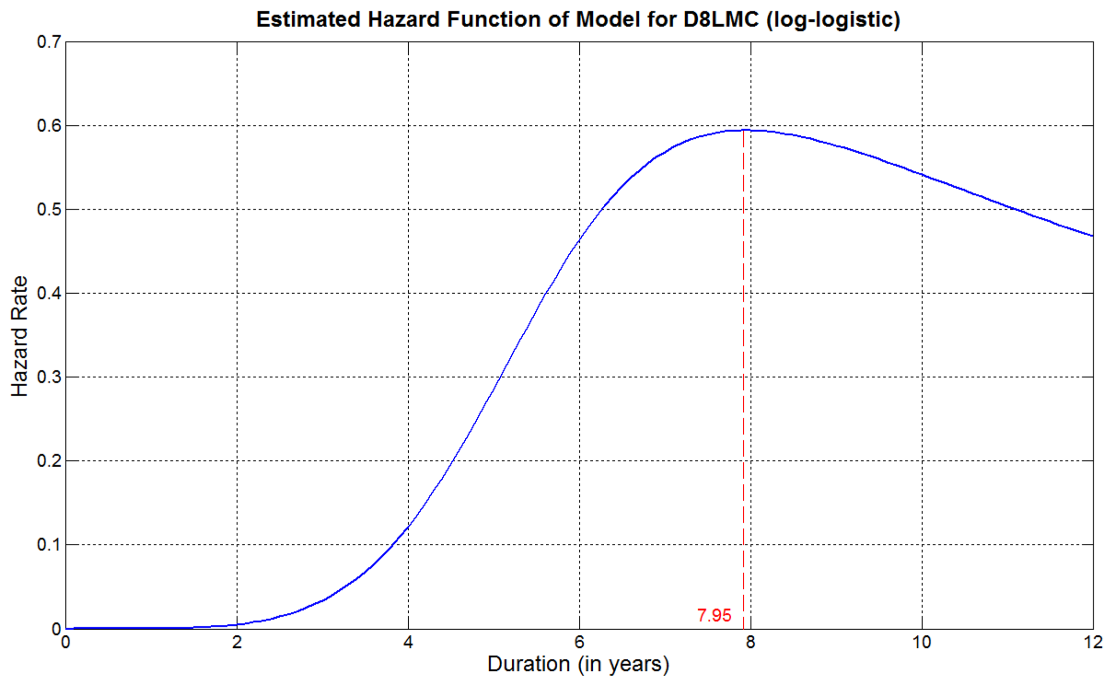


Figure F.8 Estimated Hazard Function of Model for D8LMC (Log-logistic)

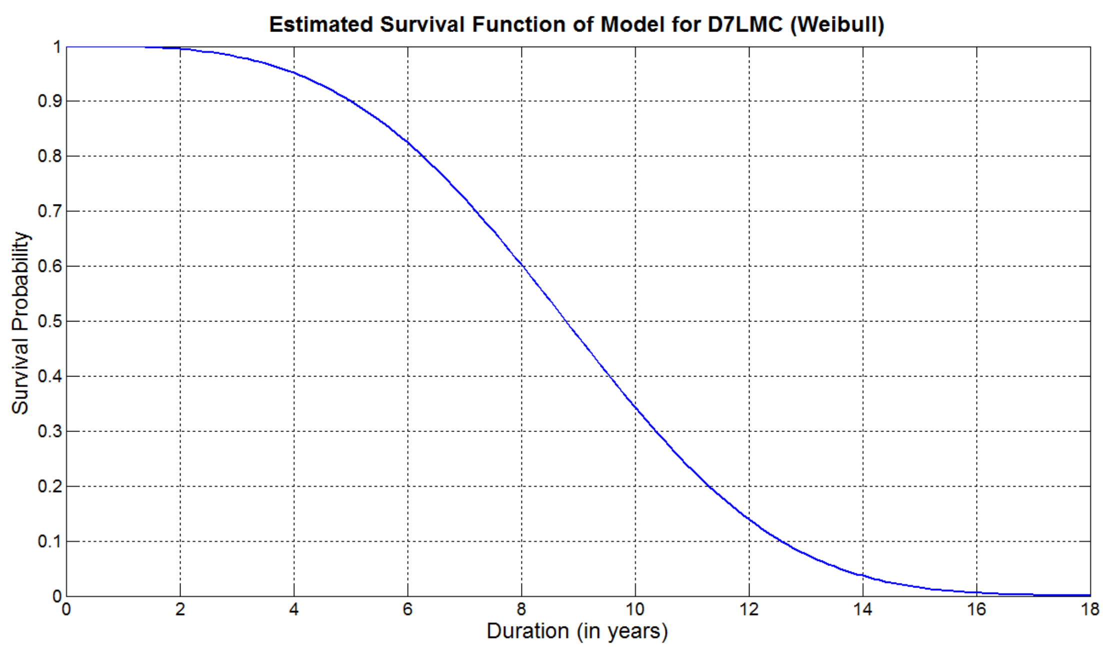


Figure F.9 Estimated Survival Function of Model for D7LMC (Weibull)

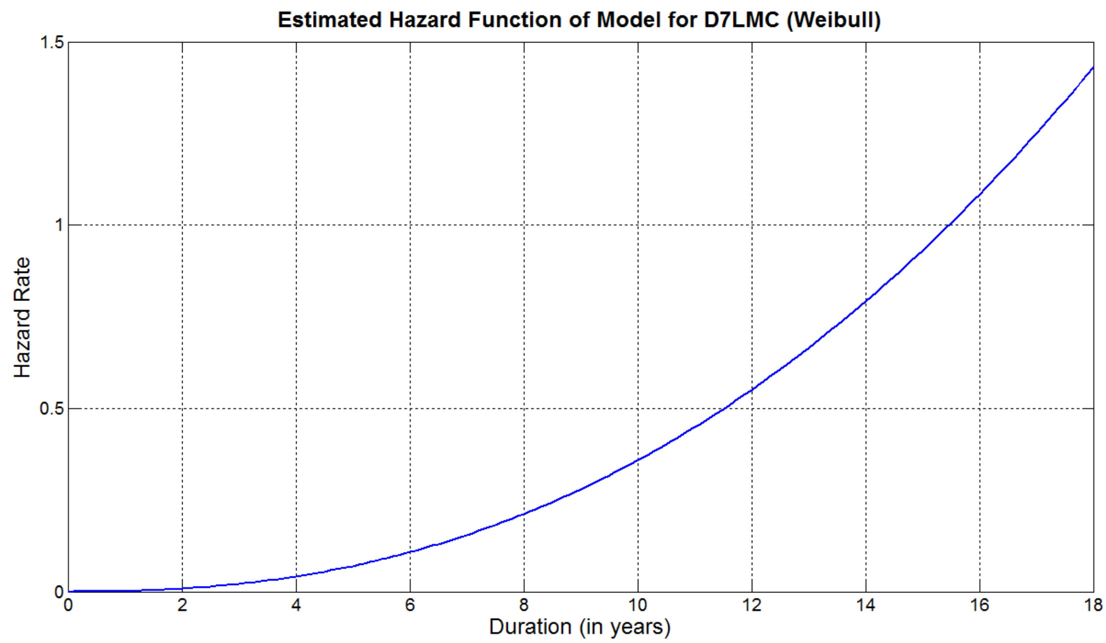


Figure F.10 Estimated Hazard Function of Model for D7LMC (Weibull)

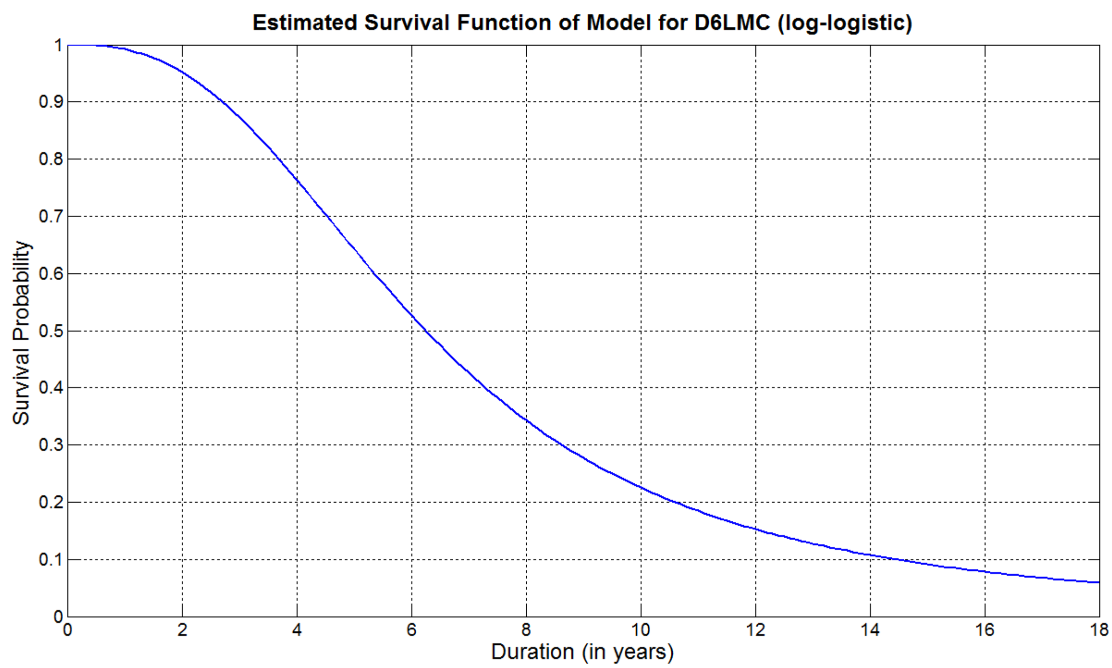


Figure F.11 Estimated Survival Function of Model for D6LMC (Log-logistic)

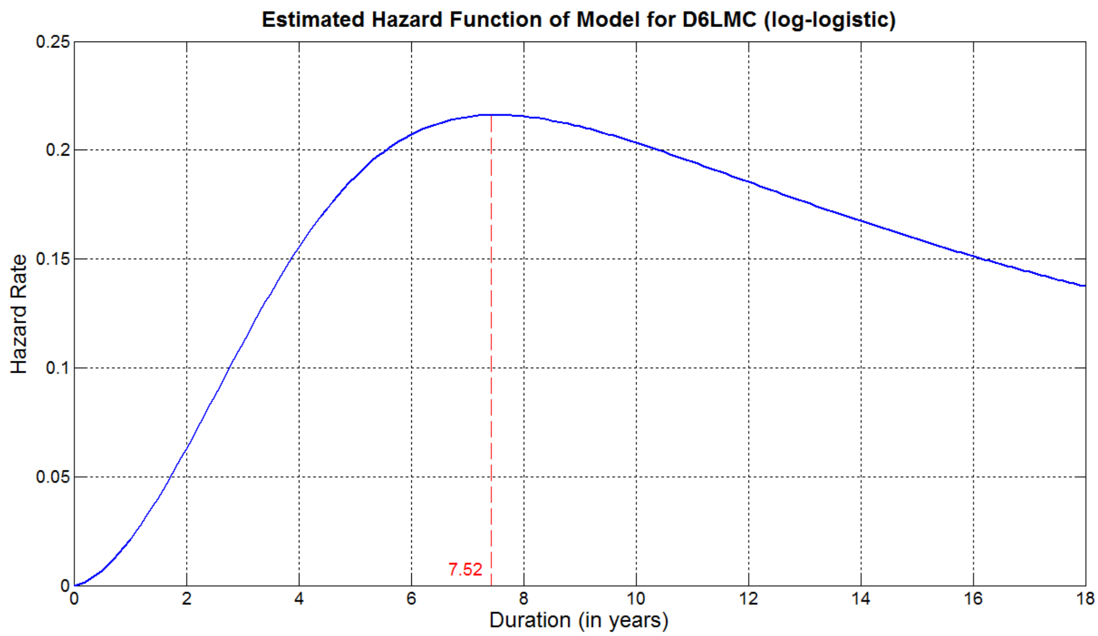


Figure F.12 Estimated Hazard Function of Model for D6LMC (Log-logistic)

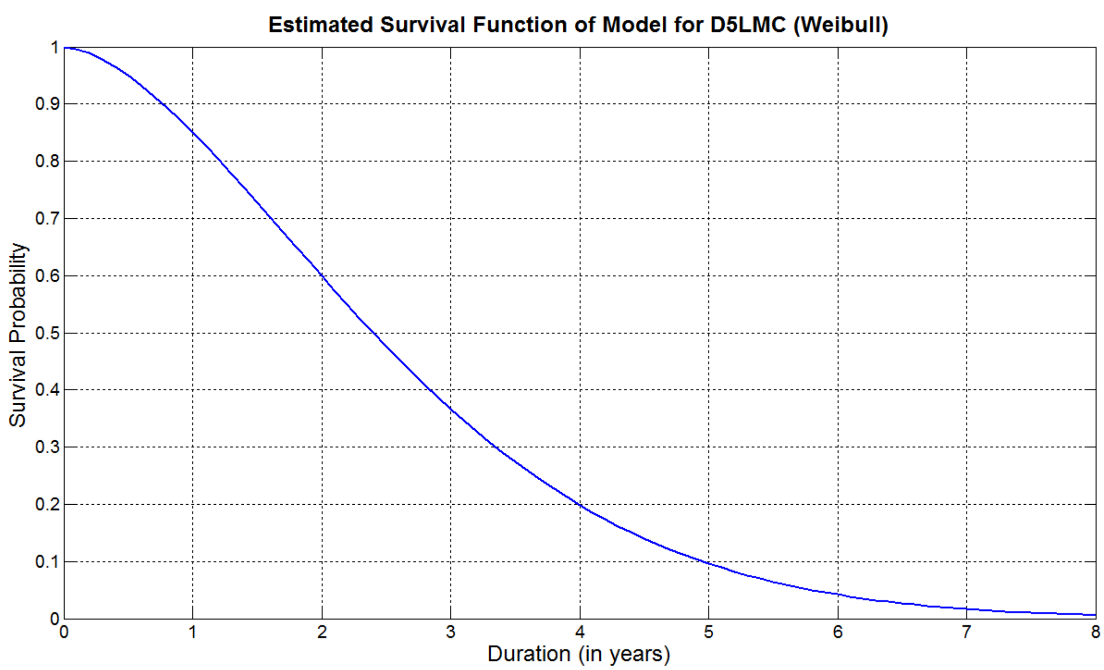


Figure F.13 Estimated Survival Function of Model for D5LMC (Weibull)

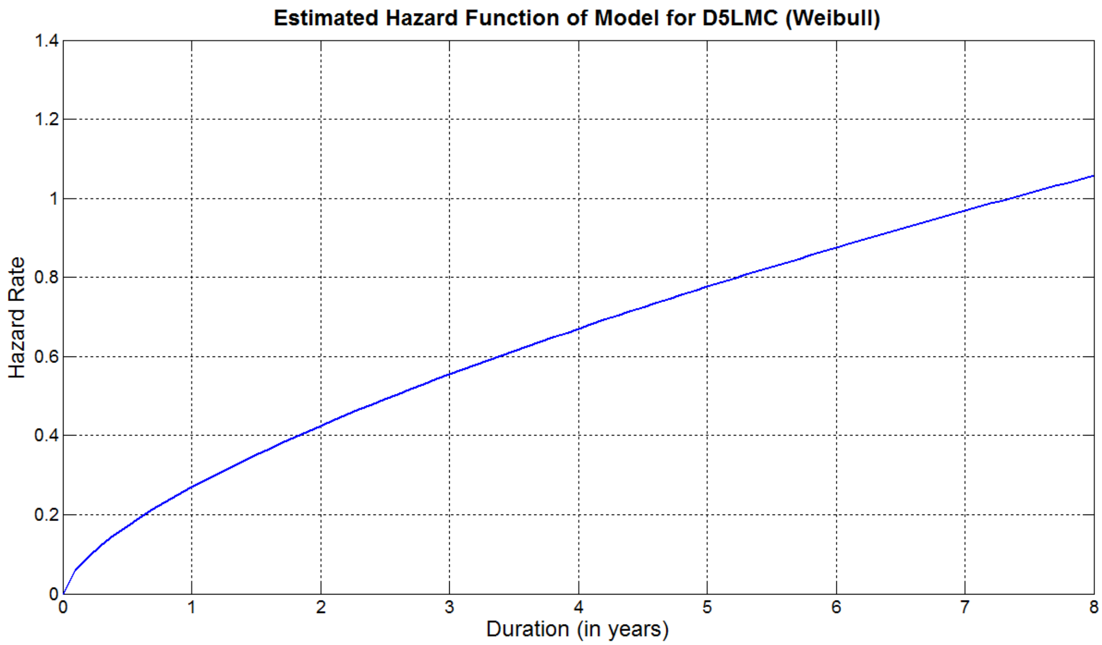


Figure F.14 Estimated Hazard Function of Model for D5LMC (Weibull)

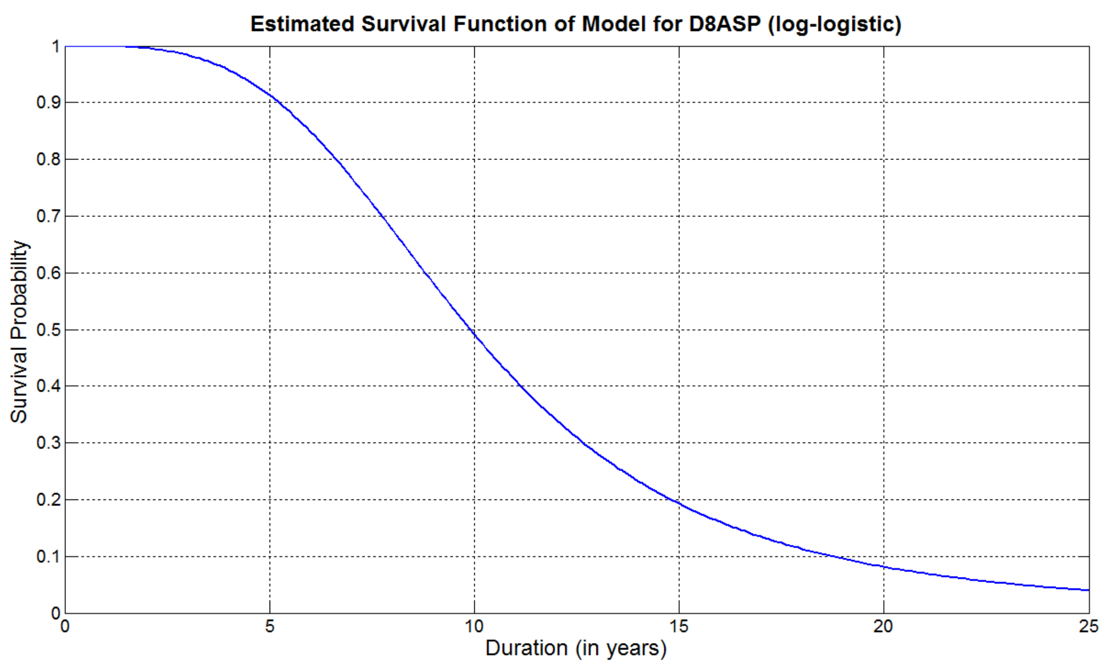


Figure F.15 Estimated Survival Function of Model for D8ASP (Log-logistic)

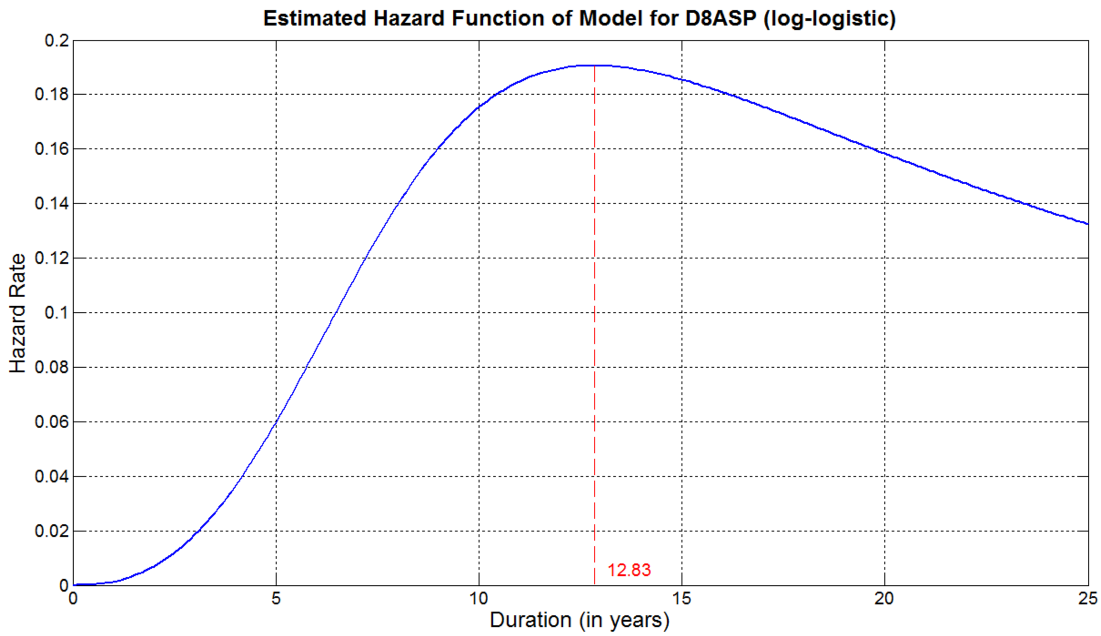


Figure F.16 Estimated Hazard Function of Model for D8ASP (Log-logistic)

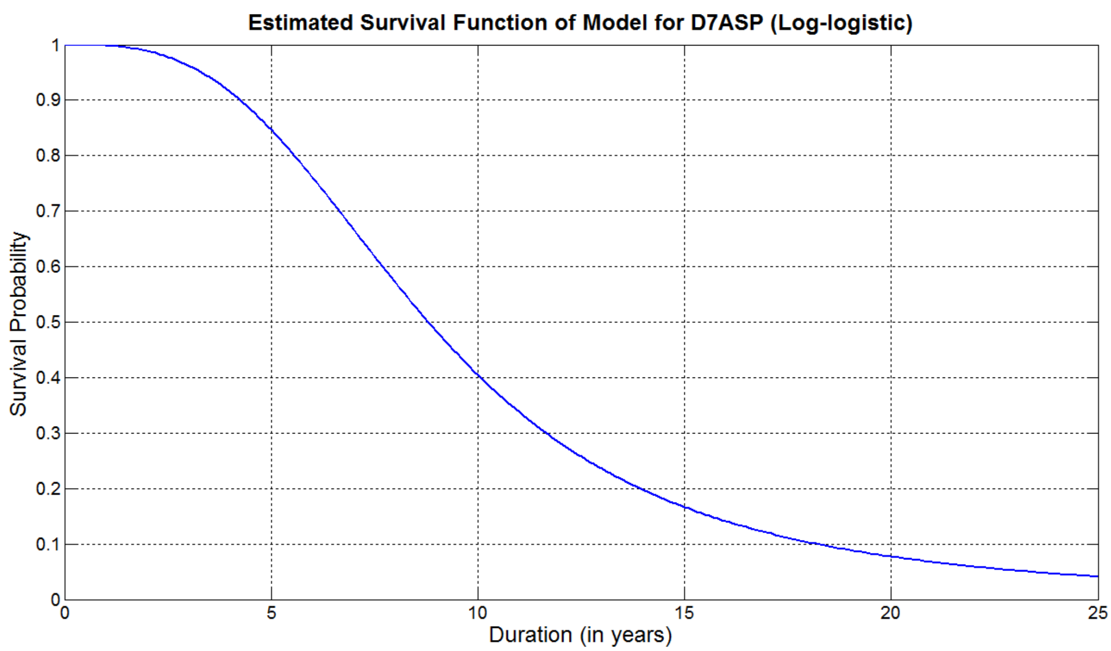


Figure F.17 Estimated Survival Function of Model for D7ASP (Log-logistic)

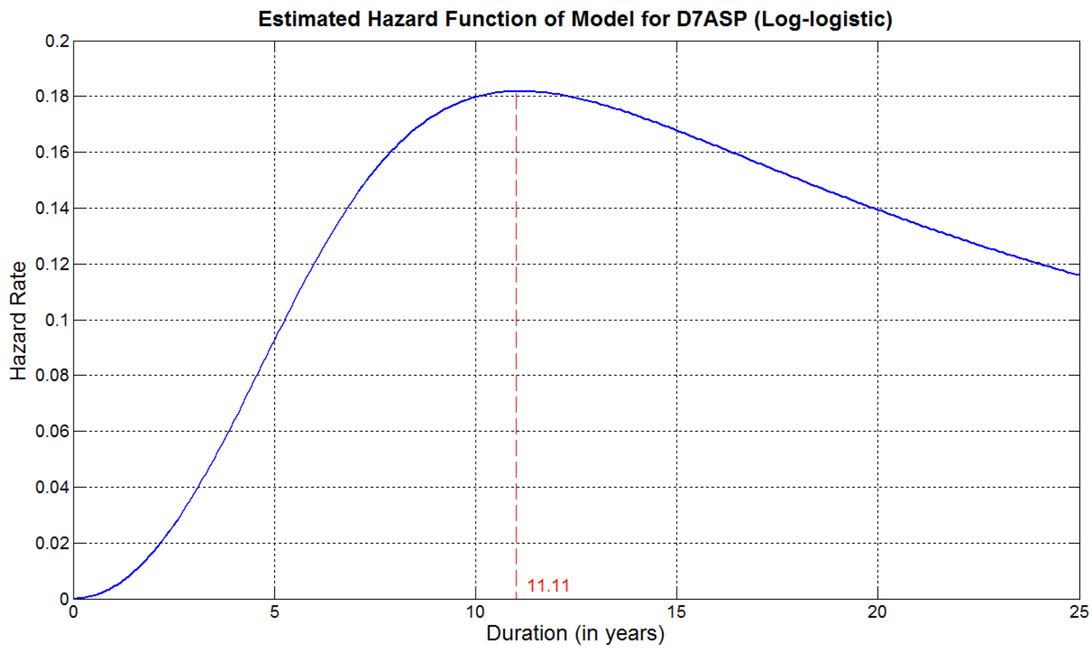


Figure F.18 Estimated Hazard Function of Model for D7ASP (Log-logistic)

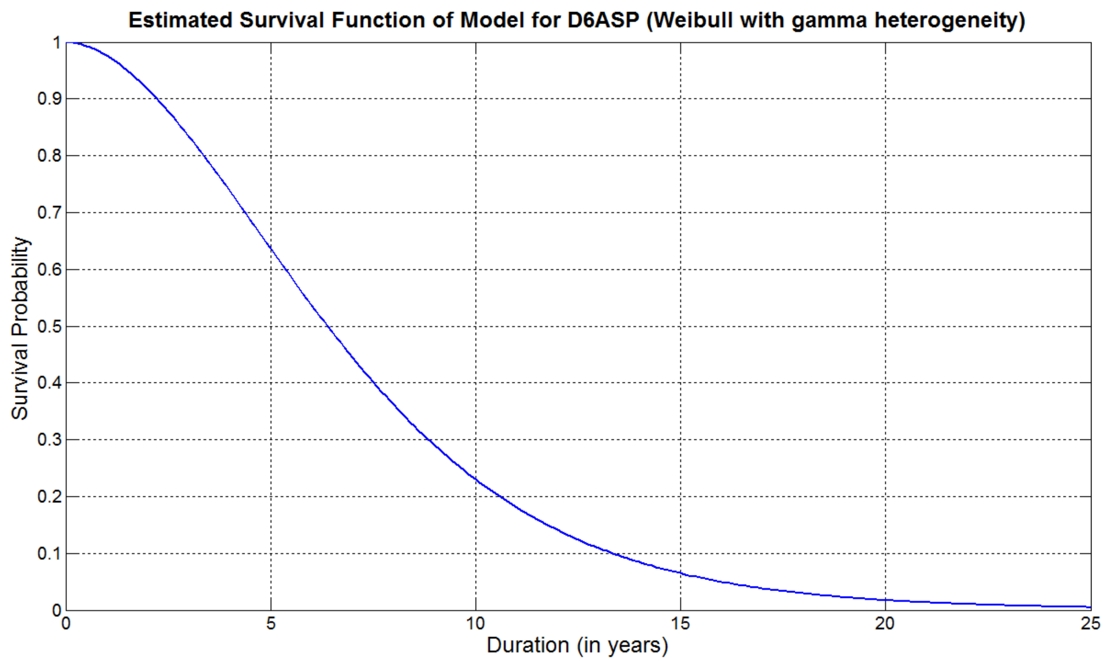


Figure F.19 Estimated Survival Function of Model for D6ASP (Weibull with Gamma Heterogeneity)

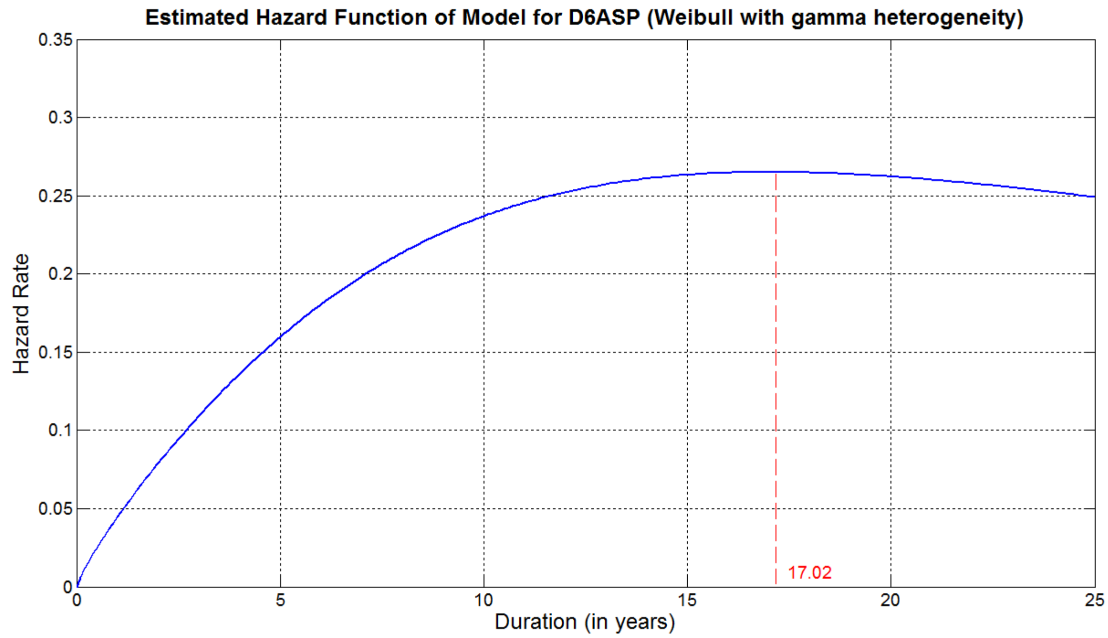


Figure F.20 Estimated Hazard Function of Model for D6ASP (Weibull with Gamma Heterogeneity)

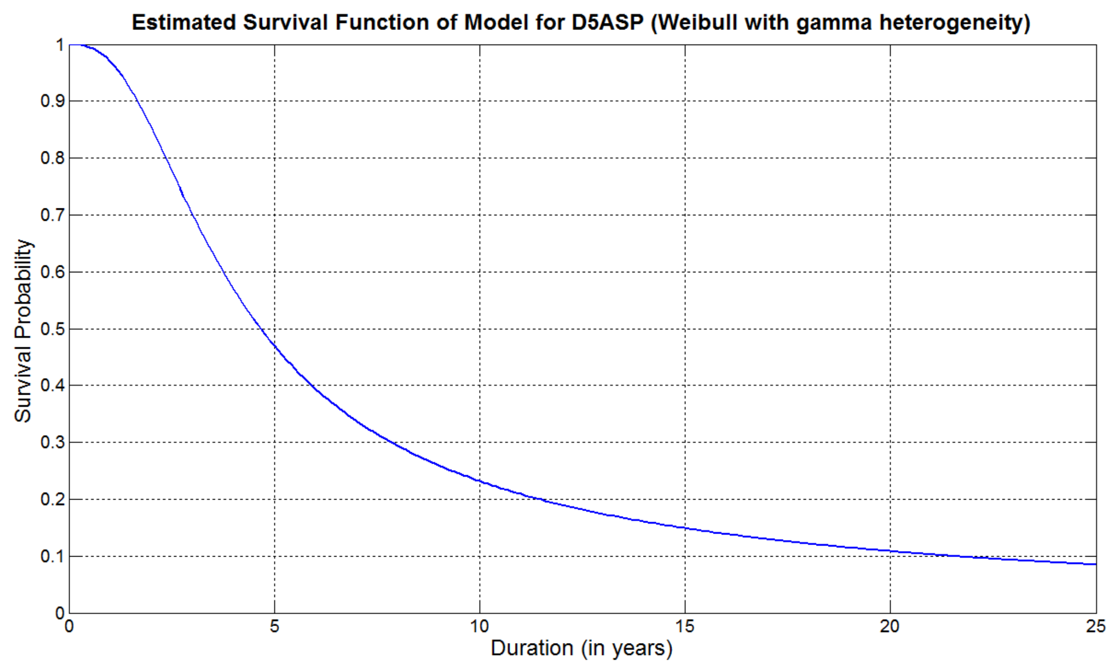


Figure F.21 Estimated Survival Function of Model for D5ASP (Weibull with Gamma Heterogeneity)

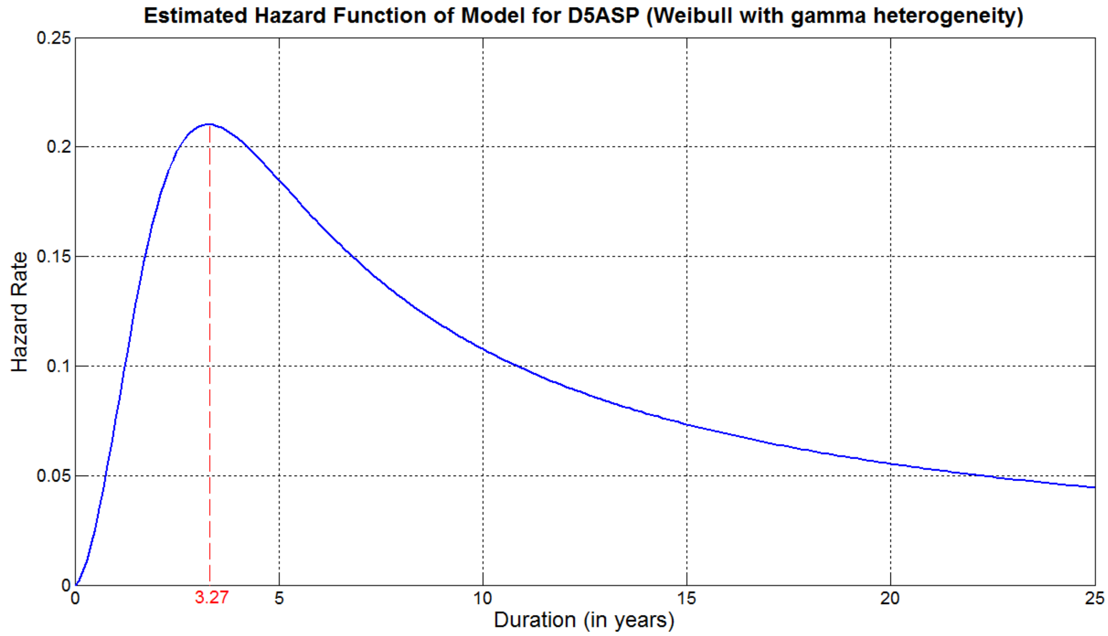


Figure F.22 Estimated Hazard Function of Model for D5ASP (Weibull with Gamma Heterogeneity)

VITA

VITA

Zhibo Zhang was born in Anshan, China, on February 14, 1989. He received the highest score in Anshan City in the high school entrance exam and was admitted to Anshan No. 1 High School. After three years of excellent academic performance, he was admitted to Tsinghua University, Beijing, the top university in China, and received his Bachelor of Science in civil engineering, one of the top-ranked majors in Tsinghua. In August 2011, he traveled to the United States and began his graduate studies in the School of Civil Engineering at Purdue University in West Lafayette, Indiana. During his studies at Purdue, he received a Master of Science in Civil Engineering in May 2013 and a Master of Science in Economics in December 2014. He expects to receive his Doctor of Philosophy in December 2016. While at Purdue he participated in several transportation research projects; and his research interests include, but are not limited to, highway infrastructure management, life-cycle economic evaluation of highway projects, and econometric modeling.