BRIDGE DECK PRESERVATION PORTAL – PHASE 1

Sponsored by:
The Federal Highway Administration
and
The Iowa Department of Transportation

Final Report
February 25, 2020

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16. Abstract

Bridge preservation planning has gained significant interest in recent years due to its high potential to provide better asset management programs. The use of bridge preservation improves the life-cycle cost of the asset as preservation actions should increase the service life at a reduced cost compared to repair or rehabilitation. This project aims to develop a framework for bridge deck preservation tool that can help engineers at state and local departments of transportation choose the optimum preservation action for a given bridge deck. The proposed tool consist of five modules: user inputs, selection of maintenance actions, analytical algorithms, optimization, and output. A comprehensive literature search of available maintenance actions for concrete, steel and timber bridge decks was completed including service life and cost information for each of the maintenance actions. WJE also developed an innovative probabilistic algorithm to provide estimate for service life extension associated with the different maintenance actions based on the pre-existing condition of the bridge deck, traffic loading, and environmental exposure, among other factors, with the estimated uncertainty. A technique to incorporate the estimated service life in available bridge deck deterioration model was also proposed. At the end of the analysis, life-cycle cost analysis is conducted. An optimization technique for automated selection of the best maintenance actions is used to present the ranked options to the user along with other data viewing options that present information is terms of minimum initial cost or expected life extension. This is intended to aid in the decision-making process of the user. Example bridges were analyzed using a preliminary MATLAB tool that was developed to test the logic proposed in this effort. Next steps to complete the effort as well as areas where additional research is needed were also identified.

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Bridge deck preservation, deck maintenance actions, life-cycle cost analysis, service life extension, deterioration models	No restrictions. This document is available to the public from the sponsoring agency.

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EXECUTIVE SUMMARY

Transportation agencies must employ cost-effective asset management strategies to extend the service lives of existing bridge decks as funds and the time needed for replacement or major rehabilitation are limited. The use of bridge deck preservation methods varies widely throughout the United States, and a concise, cost-effective, universal set of guidelines and decision making matrices would aid transportation engineers with bridge deck rehabilitation decisions. While each state will likely view the need for deck preservation and preventive maintenance differently, an easy to use, PC- or web-based set of interactive guidelines suitable for reference by engineers throughout the country is useful in promoting more consistent and universal procedures for decision making, backed by research and experience.

The purpose of this project is to develop a framework for bridge deck preservation portal (referred to simply as the portal or the BDPP) that will be used as a refinement tool for the current bridge management decision-making programs. Compared to current software, this bridge deck preservation portal has a defined scope that focuses only on one bridge element: the deck. Rather than optimizing the maintenance for a network of bridges, it will provide a ranked list of alternative maintenance strategies for the deck of one bridge. The deck is significant because bridges are considered to be in poor condition if their deck, their superstructure, and/or their substructure receives a low condition rating. In addition, bridge decks are the most-used bridge element by the public and, therefore, have significant impact on the quality of service and the public's perception of the bridge condition. Preservation strategies are emphasized both because they are expected to be more cost-effective for bridges in good condition and because the appropriate time and extent of maintenance projects is not as easily identified as the appropriate time and extent of rehabilitation and replacement projects. The portal will be able to consider more deck maintenance options and provide approximate cost, service life, and risk information for individual bridges, which is not currently available in such detail in the network-level programs. In this way, output from current BMS and network-level software that identify bridges for maintenance may be refined to determine the specific maintenance activities that would provide the best benefit at the lowest cost and risk for the individual bridges identified.

The proposed framework includes five modules: user inputs, selection of maintenance actions, analytical algorithms, optimization, and output. These analyses are completed in a probabilistic fashion to include some measure of risk and uncertainty related to service life extension and associated life cycle cost. The user will be prompted to input information related to the bridge deck before the beginning of the analysis. This information includes current condition of the bridge deck (general NBI rating and element-level rating, if available), exposure conditions, physical description and other information that is typically included in the inspection reports. The portal will then recommend maintenance options for further analyses from a comprehensive list of maintenance actions that was collected as part of this project. The maintenance actions will be filtered based on the user input, particularly bridge deck condition and physical description. Note that the user will have the freedom to select additional maintenance actions or remove portal recommended actions from further analysis. The next step is BDPP algorithms which includes three main algorithms as follows: Service Life Extension Estimate (SLEE), Deterioration Model (DM), and Life-Cycle Cost Analysis (LCCA). An extensive literature review was completed to compile information related to maximum and minimum expected service life for the different maintenance actions. In this module, the service life for each action is modified based on the combination of different reduction factors that may affect that particular maintenance action including the deck pre-existing condition, environmental exposure and so on. This new approach provides an innovative technique to include project specific data while estimating the service life of maintenance actions. Note that a probabilistic approach is followed to estimate the reduction factors, which causes all the analyses to be probabilistic. Once determined, the service life

extension can be used with existing deterioration models to determine the overall increase in the service life of the bridge deck. A theoretical approach for including multiple maintenance actions through the life of the deck is proposed and discussed. At the end of the analysis, the portal calculate the life-cycle cost for each maintenance action or plan based on a specified analysis time frame. Note that default cost information for the majority of the maintenance actions were collected during the literature search. However, it is highly recommended that the user input costs for the maintenance actions based on the historical bids in their agency for more accurate analysis. After all the analyses are complete for all the maintenance actions or plans, the BDPP uses an optimization technique to rank all the options considered for the bridge deck preservation. This ranking relies mainly on weighted average of the optimized remaining service life and the life cycle cost of the considered options. Finally the portal outputs the ranked options along with additional data that present information is terms of minimum initial cost or expected life extension for the first maintenance action only to aid the user in the decision-making process.

To test the logic proposed in this framework, a preliminary MATLAB-based tool was developed to conduct limited analysis on three bridges from different states. The tool demonstrated the ability of the framework to complete the probabilistic analyses and rank different maintenance options as proposed by the framework. The examples also confirmed the extreme importance of using accurate cost information. Next steps to complete the effort were identified. The tasks needed to fully develop the tool, either as web-based or PC-based version, were described. Areas of additional research were also presented for future consideration.

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1 INTRODUCTION

1.1 Background

The collapse of the Silver Bridge over the Ohio River in 1967 instigated national interest in improved bridge asset management (Reimann, 2017). The National Bridge Inspection Standards (NBIS, 23 CFR Part 650) were signed one year later in 1968 and require states to inspect the bridges under their jurisdiction nominally every two years and provide a general condition report to the federal government after each inspection. Since then, the NBIS have been revised and further federal legislation, such as Moving Ahead for Progress in the 21st Century (MAP-21), has been implemented. The general goal of this legislation is to improve bridge asset management such that the transportation network provides good serviceability while minimizing cost. MAP-21 specifically requires states to develop risk- and performance-based asset management plans for bridges on the National Highway System (NHS) and specify their own target performance metrics. If more than 10 percent of the bridges on the NHS (weighted by deck area) are considered structurally deficient, then the state is required to spend a minimum amount of federal funding on bridges.

However, the transportation networks are extensive and funds for their maintenance are limited. This requires transportation agencies to find cost-effective asset management strategies that keep as many existing bridges in good service as possible. Traditionally, a "worst first" methodology for maintenance and repair was undertaken wherein bridges in the worst condition were addressed first, but this strategy permits newer bridges to fall into states of disrepair and experience end-of-life earlier than if preemptive action had been taken. Management strategies incorporating preservation of bridges in good condition have been more cost-effective because they postpone deterioration, thereby extending the service life and decreasing the life cycle cost of the bridge. Preservation is defined as the following by the Federal Highway Administration (FHWA):

> "[A]ctions or strategies that prevent, delay, or reduce deterioration of bridges or bridge elements; restore the function of existing bridges; keep bridges in good or fair condition; and extend their service life." (Bridge Preservation Guide, 2018)

The introduction of preventive maintenance substantially increases the number of management options states can consider, and this is beneficial when searching for more cost-effective strategies. However, effective preventive maintenance requires more detailed information and robust decision-making algorithms. To help themselves make informed and optimal decisions, the majority of the states use some form of bridge management software. Bridge management software typically functions as a data repository of detailed inspection reports and condition assessments. Some software packages have modules that model bridge deterioration, conduct life cycle cost analysis, and/or perform cost-benefit analysis. The results from these models help states determine the cost-effectiveness of different management strategies and identify the best strategy for their transportation network.

1.2 Objectives and Portal Outline

The overall objective of this study is to develop a web-based bridge deck preservation portal (BDPP) that can be used by bridge owners to maintain and preserve their bridge decks and promote consistency among states and local agencies. The proposed project tool will be designed to accept inspection data and exposure conditions, select appropriate maintenance strategies according to construction preferences, incorporate estimated service life and cost comparisons, recommend an optimal maintenance strategy, provide an estimate of the risk and uncertainty, and provide the anticipated improvement in service and general NBI rating associated with carrying out the user-chosen maintenance strategy. In order to achieve the overall goal, three sub-objectives are identified for the study:

- Synthesize different bridge deck preservation and rehabilitation guidelines and recommendations available in the literature and used by state DOTs to develop a set of universally-applicable guidelines for bridge deck preservation.
- Develop bridge deck maintenance service life extension estimates and their effect on the overall life of the bridge deck including concrete, steel and timber bridge decks.
- Propose a framework for a web-based bridge deck preservation portal and identify the minimum requirements needed to successfully implement the developed analytical algorithms in the portal.

The bridge deck portal is a project level tool that focuses only on the deck of a given bridge. The tool will have five primary modules as described below.

1. **User Inputs.**
   In the first module, the user will fill out an input form providing description of the structure and its condition (including federally-required, element-level, and non-destructive evaluation data), historic condition data, exposure conditions, and any desired constraints on maintenance activities, such as duration or local contractor experience. Limited information, such as condition and exposure data, may be transferred automatically by interfacing with federal- or state-managed data repositories.

2. **Selection of Maintenance Actions.**
   In the second module, the portal will reference a list of feasible maintenance and rehabilitation actions including preventive maintenance and rehabilitation. This list will be filtered based on threshold criteria; for example, if the bridge deck is in good or fair condition, then certain maintenance/rehabilitation actions will be omitted for the remainder of the analysis. Default threshold criteria will be used by the portal but the user will have the ability to override the thresholds if desired.

3. **Analytical Algorithms.**
   In the third module, the remaining action options will be analyzed. The service life extension, life cycle cost analysis (LCCA), and uncertainty associated with the potential action will be calculated for each action still being considered.

4. **Optimization.**
   In the fourth stage, the potential actions will be ranked according to an optimization of the analytical results from the previous stage.

5. **Portal Output.**
   Finally, in the fifth stage, the action options, ranking, and supporting values calculated in the third stage will be presented to the user.

1.3 Report Organization

This report consists of five chapters. This chapter presents the purpose of the BDPP and how it is envisioned to fit into existing software tools for bridge management, and provides a brief outline of the structure of the BDPP.

Chapter 2 presents the results of a literature review that was conducted to support the development of the portal. The information is organized according to the proposed modules of the BDPP and describes current practices of the states and data and tools that are available to the states. The review discusses both practices and tools that are widespread across the states and those that are used almost exclusively in academia or proprietary software. Common practices and tools are deemed feasible for use now. The rarer practices and tools are incorporated as well so that their development may be tracked and feasibility may be reassessed if the portal is updated in the future.

Chapter 3 presents the proposed framework for the BDPP. The portal inputs are defined and the logic used to identify maintenance activity plans, calculate service life estimates, life cycle costs, and uncertainties, and rank the maintenance plans is explained. The user's ability to tailor the portal logic according to their preferences, objectives, and knowledge is emphasized but the majority of the chapter is dedicated to the assumptions and defaults the portal will assume in the absence of user guidance.

Chapter 4 presents examples of the BDPP at work to demonstrate the validity of the proposed framework. Three bridges from different states are input into the portal and the final results output by the portal are presented, based on the assumptions that the authors made for the different maintenance actions.

Chapter 5 presents the next steps required to develop the portal in Phase II and identifies additional work to validate, improve, and extend the framework and portal capabilities. An RFP for a web-based portal and a list of tasks with associated budget for a MATLAB tool are included.

The authors refer the readers to section 3.1 and Chapter 4 to gain an overview of the proposed tool. Additional information regarding the assumptions and logic included in the tool can be obtained from the remaining sections of the report.

2 LITERATURE REVIEW

A literature review was conducted to identify and compile existing recommendations and decision trees related to the current state of practice for preservation and maintenance of bridge decks. The following information was compiled to support the first four of the proposed portal modules:

1. User input:
    - Types of data collected by bridge inspectors in each region, and
    - How the data is recorded.
2. Maintenance options and selection criteria:
    - Types of preservation activities and specific repairs used by different states,
    - The deterioration level and/or distress type that each activity/repair is typically meant to address, and
    - Threshold criteria used to make decisions between options.
3. Analytical algorithms:
    - Algorithms for service life analysis
        - Experience-based service life estimates of different preservation strategies,
        - Analytic strategies behind deterioration models used by the states, and
        - Estimates of improved service associated with different repairs.
    - Life cycle cost analysis
        - Experience-based cost estimates of different maintenance and preservation strategies, and
        - Types of cost estimation (e.g., initial estimates or life cycle costs).
    - Uncertainty and risk management
        - Existing risk assessment strategies used by the states.
4. Optimization strategies:
    - Available optimization functions, and
    - Current state practices to optimize results from Module 3.

The discussion in this section focuses exclusively on information, practices, and tools currently available to and/or used by the states. Additional data, enhanced models, and other tools that are not typically used by the states may be considered during the development of the portal framework but will not be addressed in this chapter.

2.1 User Inputs

The user input module will include all the information pertinent to the bridge deck where maintenance or rehabilitation is required. In this module, the user will input information regarding the bridge deck features, exposure and traffic conditions, desired construction parameters, cost and service life data, etc. This information will be used by the portal in later modules to determine the most cost-effective deck preservation strategy. Currently, most of the available information related to the condition of the bridge deck is collected during mandatory bridge inspections. The states are federally required to report bridge inspection data to the federal government. For ease of reporting and data review, the FHWA provides an information datasheet that must be filled out and submitted by each state for each bridge after every inspection. The following discussion describes the parameters listed on the datasheet that are relevant to bridge decks. These are ideal inputs for the bridge deck portal since they are standardized across the nation.

The first subsection below describes the data that has been required since the NBIS started. This data describes the bridge holistically and has been recently seen as insufficient for good bridge management practices. As a result, element-level inspection practices have been required for bridges on the NHS since 2014, and these practices are described in the second subsection. The final subsection discusses state practices and how they differ from each other. While all states are held to the federal law, some states began to invest in element-level inspection and data retention systems to improve bridge management prior to the implementation of MAP-21.

2.1.1 Federally-Required Data

The NBIS require that states inspect and report the conditions of bridges within their jurisdiction to the federal government. Inspections are typically to be carried out every two years, although more frequent inspections may be required or less frequent inspections may be adequate depending on the condition of the bridge. Less frequent inspections require FHWA approval. The FHWA Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges (1995) (henceforth referred to as FHWA Recording and Coding Guide) provides bridge inspection organizations with the Structure Inventory and Appraisal Sheet (SI&A sheet), a datasheet that lists the data to be reported to the national bridge inventory after every inspection. The SI&A sheet includes the following entries categorized by topic:

Bridge Deck Characterization and Condition

- ***Year built and year reconstructed.*** Year built tells the overall age of the structure. The "year reconstructed" is reported as well wherein "reconstruction" refers to an activity that was eligible for federal aid, excluding painting of structural steel, replacement or upgrade of any safety features, utility work, emergency repair due to an accident, overlay projects associated with wider highway resurfacing projects, retrofits that do not significantly alter the load-carrying capacity of the bridge, and work intended to extend the bridge life while a replacement plan is being prepared.
- ***Deck structure type.*** Deck structure types are categorized as cast-in-place concrete, precast concrete panels, open steel grating, closed steel grating, steel plates (including orthotropic), corrugated steel, aluminum, and wood or timber. A final miscellaneous category titled "other" is a reportable option for this entry as well. If a bridge has multiple structure types, only the most dominant one is to be reported.
- ***Wearing surface/protection system.*** This reported item is separated into three subitems: the type of wearing surface exposed to abrasive traffic, the type of waterproofing membrane underneath, and any protection strategies used to prevent steel corrosion. Wearing surfaces are categorized as monolithic concrete, integral concrete, latex concrete, low slump concrete, epoxy overlay, bituminous overlay, wood or timber, gravel, or the miscellaneous category "other". If there is no additional material or additional concrete thickness added to the slab beyond what is required structurally, then no wearing surface is present. The membrane under the wearing surface may be categorized as built-up, preformed fabric, or epoxy and options "unknown", "other", and "none" are also available. The deck protection systems are categorized as epoxy-coated reinforcing steel, galvanized reinforcement, other coatings on reinforcement, cathodic protection, polymer impregnated concrete, and internally sealed concrete. As for the membrane, options "unknown," "other," and "none" are also available.
- ***Deck Condition.*** The bridge is divided into its deck, superstructure, and substructure and each component is assigned a condition rating between 0 and 9. This rating system is called the general National Bridge Inventory (NBI) rating. The full definitions of the ratings are:

9 – Excellent condition (condition immediately after construction)
8 – Very good condition (no problems noted)
7 – Good condition (some minor problems)
6 – Satisfactory condition (structural elements show some minor deterioration)
5 – Fair condition (all primary structural elements are sound but may have minor section loss, cracking, spalling or scour)
4 – Poor condition (advanced section loss, deterioration, spalling or scour)
3 – Serious condition (loss of section, deterioration, spalling or scour have seriously affected primary structural components; local failures are possible. Fatigue cracks in steel or shear cracks in concrete may be present.
2 – Critical condition (advanced deterioration of primary structural elements. Fatigue cracks in steel or shear cracks in concrete may be present or scour may have removed substructure support. Unless closely monitored it may be necessary to close the bridge until corrective action is taken.)
1 – "Imminent" failure condition (major deterioration or section loss present in critical structural components or obvious vertical or horizontal movement affecting structure stability. Bridge is closed to traffic but corrective action may put back in light service.)
0 – failed condition (out of service and beyond corrective action)

The Recording and Coding Guide stresses that the general NBI rating scale is intended to be "an overall characterization of the general condition of the entire component" and inspectors must consider both the severity and the extent of all localized damage. While the scale promotes uniformity, this still permits significant variation between ratings since different inspectors' judge the combinations of severity and extent differently. When determining the rating, the bridge's in-place, existing condition is to be compared to its as-built condition. The as-built condition is considered a perfect 9 regardless of how well the as-built condition matches the design documents. Any temporary supports or structures are ignored and the bridge is rated as though they do not exist. Load carrying capacity is not taken into consideration, but the rating is intended to reflect the structural integrity of the bridge. For the deck, this means that the wearing surface, corrosion protection system, joints, and other non-structural components are not considered in the rating. However, the FHWA Recording and Coding Guide states that the conditions should be noted.

The federal government maintains a Long-Term Bridge Performance (LTBP) bridge data web-portal – InfoBridge ™. The portal contains a nation-wide database of the major component general NBI condition ratings and provides a bridge inventory map. This is a fast, convenient method to quickly communicate the overall condition of the bridge network. An image of the general NBI deck condition rating map extracted from the portal for Iowa bridges is shown in Figure 2.1.

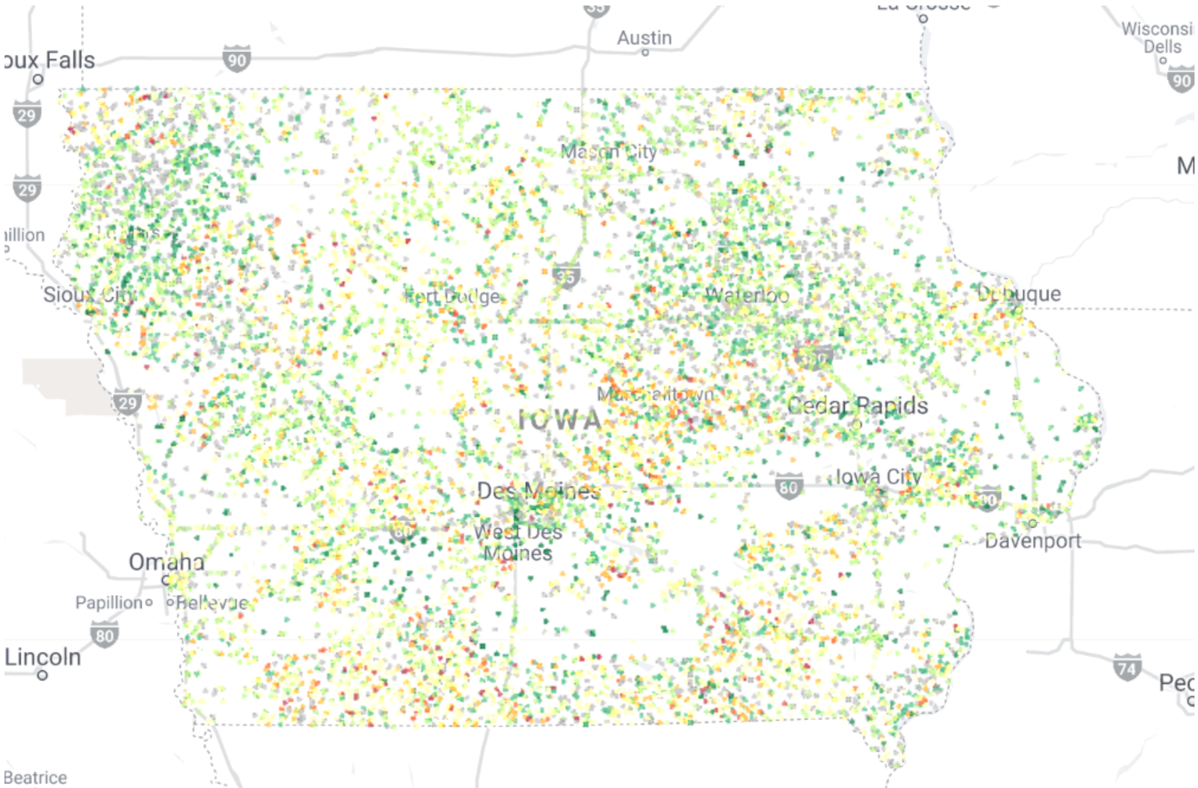


Figure 2.1. Deck condition rating map for Iowa Bridge Inventory extracted from FHWA LTBP InfoBridge.

Exposure Conditions

- ***Location.*** Location determines the environmental exposure of the bridge, which in turn controls the degradation experienced by the bridge. Primary environmental factors that affect degradation include ambient moisture due to humidity and precipitation, and chlorides from deicing salts or marine features. Degradation mechanisms and modeling are discussed in more detail in Section 2.3, *Algorithms for Service Life Analysis*. For this section, entries in the SI&A datasheet that characterize the location of the bridge and help describe its exposure to moisture and/or chlorides include:
    - ***State name and code.*** The state the bridge is in and the state's three-digit code are reported. The code is determined by the Federal Information Processing Standards (FIPS) and the FHWA region the state is located in.
    - ***County code.*** The county code is also identified using the FIPS and provided.
    - ***Place code.*** "Place" refers to the city, town, township, village, or other census-designated place the bridge is located in. If a code exists, it is determined using the FIPS like the others, but not all places have codes.
    - ***Features Intersected.*** The name of the road, river, bay, or other feature intersected is recorded here. It provides indirect information regarding humidity, splash, and seawater exposure experienced by the deck.
    - ***Location.*** This is a narrative description of the location of the bridge. As an example, the nearest city or highway may be identified.

  - ***Latitude and Longitude.*** These values are included on the sheet, but are not required if the bridge is not located on the NHS. They are intended to facilitate mapping in ARCGIS and GPS positioning, but can be useful in determining environmental exposure as well.
- ***Average daily traffic (ADT) and Average Daily Truck Traffic (ADTT).*** The most recent count of ADT and the year in which it was counted is to be reported. The percentage of the ADT that is truck traffic is required as well.
- ***Future ADT.*** An estimate of the future ADT is reported at the end of the document, as well as the number of years until the future ADT is expected. The forecast must be between 17 and 22 years.

Proposed Work

- ***Type of work (for proposed improvements).*** Only the major projects in the following list are reported here. Records of minor repairs and preventive maintenance work, which are of primary interest in the proposed portal, cannot be extracted from the SI&A sheet and will have to be considered by state engineers using the portal.
  - Replacement of bridge because of substandard load carrying capacity or bridge roadway geometry,
  - Replacement of bridge because of relocation of road,
  - Widening of existing bridge without deck rehabilitation or replacement,
  - Widening of existing bridge with deck rehabilitation or replacement,
  - Bridge rehabilitation because of general structure deterioration or inadequate strength,
  - Bridge deck rehabilitation with only incidental widening,
  - Bridge deck replacement with only incidental widening, and
  - Other structural work.
- ***Project costs.*** The total project cost for improvements is to be provided as well as the year in which the estimate was made. Estimates are not permitted to be more than 8 years old.
- ***Bypass, detour length.*** This value indicates the inconvenience to the motorists due to construction. If a bypass is available, then a special code is used. Otherwise the total additional travel distance required of each motorist due to the closed bridge is reported in kilometers.

While the above describes everything that is reported in the SI&A sheet regarding bridge decks and repair, states are supposed to record much more detailed notes in their inspections. The FHWA Bridge Inspector's Reference Manual (BIRM) states that "[a]lthough component condition rating and reporting…provides a consistent method for evaluation and reporting, the data is not comprehensive enough to support bridge preservation performance-based decision support" (Ryan, Mann, Chill, & Ott, Bridge Inspector's Reference Manual, 2012). In response to this shortcoming, MAP-21 requires that element-level data be reported for all highway bridges on the NHS starting in 2014 (Lwin, 2013). Agencies are not required but strongly encouraged to record element-level data for bridges off of the NHS as well.

2.1.2 Federally-Required Element-Level Data

The FHWA BIRM divides a bridge deck into the following elements: the top and bottom of the bridge deck; expansion joints; sidewalks and railings; drainage; signage; electrical lighting; and barriers, gates, and other traffic control devices. Signage, electrical lighting, and traffic control devices are not related to the structural or material performance of the bridge and are relatively easy to replace; subsequently, they are omitted in this literature review. Additionally, the FHWA Specification for NBI Bridge Elements only requires that the condition of the deck, the expansion joints, and the wearing surfaces and protective coatings be reported

(FHWA, 2014). Because the performance of the drainage system affects the service life of the deck, some limited review of policy regarding drainage is included in this report as well.

Element-level reports are both standardized and customizable. Elements are classified as National Bridge Elements (NBEs), Bridge Management Elements (BMEs), or Agency Developed Elements (ADEs). The NBEs are nationally standardized such that they are consistent across the country; only the deck/slab used to transfer vehicular loads to the superstructure is considered an NBE of the deck elements. BMEs include the joints, wearing surfaces, and protective systems. The ADEs permit an agency to define customized elements that may be sub-elements of NBEs or BMEs or completely separate, non-related elements.

Previously, the deck was assigned a condition rating between 0 and 9. At the element level, there are four condition states CS1 (good), CS2 (fair), CS3 (poor), and CS4 (severe). The quantity of the feature corresponding to each condition state within each element is estimated and reported in terms of area, length, or count, as appropriate. Detailed definitions for each condition state are provided for each type of deck material and distress. A table from the Manual of Bridge Element Inspection, Edition 2, listing defects and describing the corresponding condition states for reinforced concrete is shown in Figure 2.2 (AASHTO Committee on Bridges and Structures, 2019). More detailed tables with pictures to accompany the definitions are also available in the manual. For NBEs, these definitions are strictly set and standardized, but for BMEs and ADEs, they are considered somewhat flexible. Unlike the traditional general NBI condition ratings, this system can accommodate multiple types of distress. The condition state for each type is added to get the total quantity that falls under CS1, CS2, CS3, and CS4. However, a list of distress types is optional.

Defects	CS 1 GOOD	CS 2 FAIR	CS 3 POOR	CS 4 SEVERE
Delamination/Spall/ Patched Area (1080)	None.	Delaminated. Spall 1 in. or less deep or 6 in. or less in diameter. Patched area that is sound.	Spall greater than 1 in. deep or greater than 6 in. diameter. Patched area that is unsound or showing distress. Does not warrant structural review.	The condition warrants a structural review to determine the effect on strength or serviceability of the element or bridge; OR a structural review has been completed and the defects impact strength or serviceability of the element or bridge.
Exposed Rebar (1090)	None.	Present without measurable section loss.	Present with measurable section loss but does not warrant structural review.	
Efflorescence/Rust Staining (1120)	None.	Surface white without build-up or leaching without rust staining.	Heavy build-up with rust staining.	
Cracking (RC) (1130)	Insignificant cracks or moderate-width cracks that have been sealed.	Unsealed moderate-width cracks, or unsealed moderate pattern (map) cracking.	Wide cracks or heavy pattern (map) cracking.	
Abrasion/Wear (PSC/RC) (1190)	No abrasion or wearing.	Abrasion or wearing has exposed coarse aggregate but the aggregate remains secure in the concrete.	Coarse aggregate is loose or has popped out of the concrete matrix due to abrasion or wear.	
Settlement (4000)	None.	Exists within tolerable limits or arrested with no observed structural distress.	Exceeds tolerable limits but does not warrant structural review.	
Scour (6000)	None.	Exists within tolerable limits or has been arrested with effective countermeasures.	Exceeds tolerable limits but is less than the critical limits determined by scour evaluation and does not warrant structural review.	
Damage (7000)	Not applicable.	The element has impact damage. The specific damage caused by the impact has been captured in CS 2 under the appropriate material defect entry.	The element has impact damage. The specific damage caused by the impact has been captured in CS 3 under the appropriate material defect entry.	The element has impact damage. The specific damage caused by the impact has been captured in CS 4 under the appropriate material defect entry.

Figure 2.2. Table of defects that may be recorded for reinforced concrete elements and descriptions of each condition state (AASHTO Committee on Bridges and Structures, 2019).

The Manual for Bridge Element Inspection, Edition 2 (referred to as the MBEI) additionally provides guidance on reporting exposure conditions, as shown in Figure 2.3. The dominant environmental factor that could shorten the element's service life is predicted. However, this information is not required to be reported federally.

Environment	Description
1—Benign	Neither environmental factors nor operating practices are likely to significantly change the condition of the element over time, or their effects have been mitigated by the presence of highly effective protective systems.
2—Low	Environmental factors, operating practices, or both either do not adversely influence the condition of the element, or their effects are substantially lessened by the application of effective protective systems.
3—Moderate	Any change in the condition of the element is likely to be quite normal as measured against the environmental factors, operating practices, or both that are considered typical by the agency.
4—Severe	Environmental factors, operating practices, or both contribute to the rapid decline in the condition of the element. Protective systems are not in place or are ineffective.

Figure 2.3. Table of the exposure condition categories for bridges, as defined by the Manual for Bridge Element Inspection, Edition 2 (AASHTO Committee on Bridges and Structures, 2019).

2.1.3 State Inspection Records and Bridge-Specific Data

While element-level data are only required of bridges on the NHS by the federal government, many states now require the same forms and information to be provided for bridges off the NHS. State inspection manuals may provide additional types of decks, membranes, deck protection systems, or overlays or more refined options to choose from. For example, the Washington State Bridge Inspection Manual (WSBIM) considers decks made of fiber-reinforced polymer and those made of concrete with lightweight aggregate as separate options. But in general, the report information and ratings are consistent with the federally-required inspections.

Most states maintain this information in a BMS. Typically, AASHTOWare BrM is used for this purpose, a BMS that was originally developed as part of a FHWA-sponsored NCHRP project but that was quickly handed to AASHTO for further development (AASHTO, 2019). AASHTOWare BrM is still being developed today with Version 5.3 published on September 19, 2017. Some states such as Maine and Maryland use InspectTech, developed by Bentley. Iowa uses the Structure Inventory and Inspection Management System (SIIMS). These systems help maintain a historic repository of condition information. Because AASHTOWare was developed in the 1990s, many states have historic records of general NBI data, which is useful in deterioration modeling and life cycle planning as discussed in later sections. However, because element-level data was not required until 2014, some states only have two or three historic datapoints for conditions of NBEs and BMEs. Element-level data collected prior to 2013 was based on the AASHTO Guide for Commonly Recognized (CoRe) Structural Elements (AASHTO CoRe Guide). However, there is lack of translation/correlations between old and new method, which are also approximate at best if found. While the idea of element-level data and condition states is the same, the specific elements and defects considered are different and any element-level data collected based on the AASHTO CoRe Guide needs to be translated to current element-level condition ratings as defined by the MBEI. Some states such as Maryland also keep detailed digital records of maintenance activities, including preservation and minor rehabilitation projects.

Another major practice that differs between states is the test methods used in bridge deck inspections. All of the inspection data required by the federal government may be determined through visual inspection and sounding surveys of the deck. Few states consider additional test methods to be feasible for routine inspections due to the special equipment, additional time, and advanced analysis associated with them.

However, these additional tests can provide valuable indications of underlying distress or corrosive conditions not visible to the user. For example, Maryland is working towards including ground penetrating radar (GPR) data in its data inventory and using the results to identify delaminations and rebar depths quickly (Cutts, Wynn, Hollens, & Gagarin, 2016). Maine and Alaska both include chloride concentration in the deck when discussing appropriate rehabilitation or repair activities (Guertin Elkerton & Associates, 2003; Alaska Department of Transportation and Public Facilities, 2017). Maine also acknowledges that destructive strength testing data may be necessary and discusses taking cores from decks. Colorado requires chloride testing for any project considering new overlays, deck widening, or deck rehabilitation or repair, with the exception of decks that are too young to have seen much exposure, or have been protected from chloride contamination throughout their lives (Colorado Department of Transportation, 2018). Other states also use chloride content profiling and ground penetrating radar (GPR) cover surveys to determine the depth of concrete cover to be removed during overlay installation projects. In some cases, concrete cores are collected to determine concrete diffusion coefficient using Rapid Chloride Permeability Test or NT Build Test, which aid in service life modeling. While these test methods are more typically suggested and conducted by consulting agencies, and are generally used when defining the scope of repair work rather than identifying the type of project, the more common test methods such as chloride content profiling and GPR could be useful user inputs in addition to the condition ratings, if the information is already available.

It is noted that while states often collect information related to crack width and frequency on concrete decks, there is generally a lack of correlation between the observed cracks and the service life. Conceptually, it is expected that wide cracks will facilitate ingress of chlorides and moisture through the deck and corrode reinforcing steel. As such, deck sealers and crack sealing are often used on bridges with “significant” cracking. Available literature discusses the width of cracks at which moisture or chloride ingress is expected, but do not discuss this effect on the remaining service life. For example, a study by Krauss and Rogalla (1996) indicated that cracks with surface widths of 0.002 inch to 0.008 inch can result in water leakage through the deck. While challenging, the effect of cracks can be investigated using mechanistic service life modeling approaches, which are described in a following section. However, there is a lack of industry standards in terms of relations between crack densities and expected service life and also recommendations related to crack widths and frequency at which a deck/crack sealer must be applied.

2.2 Selection of Maintenance Actions

This section includes a list of established maintenance and rehabilitation options that have a proven track record and are typically used in maintenance of bridge decks. Several experimental overlays judged to be potentially viable according to feasibility and case studies are included as well for completion. A brief overview of these options is presented in this section. In addition, the different filters and thresholds currently used by state DOTs to perform threshold-based selection of maintenance options is discussed.

2.2.1 Maintenance Options

The FHWA Bridge Preservation Guide 2018 classifies activities that are completed to improve the current condition of bridge elements as either maintenance, rehabilitation, or replacement. Maintenance is considered routine or preventive, and preventive maintenance may be further categorized as cyclical or condition-based. The definitions for these different types of activities according to the FHWA guide are provided below (Bridge Preservation Guide, 2018):

- **Maintenance.** Work "performed to maintain the condition of the transportation system or respond to specific conditions or events that restore the highway system to a functional state of operations." Subcategories include:
  - **Routine maintenance.** Work "performed in reaction to an event, season, or activities that are done for short-term operational need that do not have preservation value."
  - **Preventive maintenance.** "[C]ost-effective means of extending the service life of highway bridges."
    - **Cyclical maintenance.** Maintenance "performed on pre-determined intervals that aim to preserve and delay deterioration of bridge elements or component conditions."
    - **Condition-based maintenance.** Maintenance performed "in response to known defects… [that] improves the condition of that portion of the element but may or may not result in an increase in the component condition rating."
- **Rehabilitation. "[**M]ajor work required to restore the structural integrity of a bridge, as well as work necessary to correct major safety defects."
- **Replacement.** In the context of this project, "[t]otal replacement" of an existing deck with a new deck constructed on the same bridge.

Table 2.1 through Table 2.3 provide lists of feasible activities, which are categorized as cyclical maintenance, condition-based maintenance, or rehabilitation. Descriptions of the maintenance actions considered in the BDPP are provided in Appendix B. Required or suggested time intervals for cyclical maintenance are provided as well if they were found in literature. The activities are further separated by the type of deck material. The types of decks considered are concrete, steel, and timber since these are the most common. Because asphalt and concrete overlays are commonly used on steel and timber decks, many of the activities applicable to concrete decks are applicable to the other types as well. There is little information of FRP decks in literature due to their limited use. While FRP can be relatively desirable due to its lack of susceptibility to corrosion, most groups are unfamiliar with their maintenance and repair, and durability of repairs is not well-documented. Repair of FRP materials is subsequently omitted from this review. However, FRP decks often require overlays and other wearing surfaces and as for steel and timber decks, the activities listed for "all decks" and concrete decks may be applied to the maintenance of these wearing surfaces.

Routine maintenance activities are generally completed to improve the bridge performance in the short-term and examples include trash litter and dead animal removal, snow removal and application of deicing salts and chemicals, and storm damage. These activities generally target the quality of the ride over the deck rather than the long-term structural and material integrity. Therefore, such activities are not included in the scope of this report. Maintenance activities that are to be conducted routinely are classified as cyclical preventive maintenance if they help prolong the service life of the structure. For bridge decks, cyclical maintenance is mostly related to cleaning and removal of dirt, debris, and deicing chemicals from bridge deck components. One such activity is joint cleaning and sealing which primarily affects the service life of the underlying super- and sub-structures, not the bridge deck although good joint maintenance prevents the deck edges at the joint from deteriorating. Drainage work is considered preventive maintenance as well since clogged drains can cause ponding on decks, which negatively affects service life of the deck.

Many of the activities may be considered both cyclical and condition-based maintenance, and even components of a rehabilitation project as well. For example, an epoxy or polyester concrete overlay may be placed after 5 years of service regardless of the deck condition. This overlay is intended to extend the service life of the bridge deck by providing a new wear surface and preventing moisture and chloride ingress prior to severe damage, making it preventive maintenance. Since it was placed at a pre-determined time regardless of the condition of the bridge, it is considered a cyclical maintenance activity despite the fact that it may not be replaced periodically. Alternatively, the overlay may be a condition-based maintenance activity if it is to be placed once the original wearing surface loses its traction. Or an epoxy or polyester concrete overlay may be placed as part of a rehabilitation project after chloride-contaminated concrete has been removed and replaced.

Table 2.1. Summary of maintenance and rehabilitation activities applicable to all types of decks.

DECK TYPE	Activities	Preventive Maintenance			Rehabilitation[c]
		Cyclical Maintenance	Recommended Frequency[a, b]	Condition-Based Maintenance	
ALL DECKS	Deck cleaning/washing	X	0.5 to 2 yrs.		
	Drain cleaning	X	1 to 2 yrs.		
	Replace wearing surface	X	12 yrs.	X	
	Roughen surface		n/a	X	
	Deck overlay (general)	X	12 yrs.	X	X
	Asphalt overlay w/membrane	X	10 to 15 yrs.	X	X
	Asphalt overlay w/o membrane	X	5 to 15 yrs.	X	
	Rigid overlay (PCC, HPC)		20 to 30 yrs.	X	X
	Microsilica concrete overlay		20 to 25 yrs.	X	X
	UHPC overlay		n/a	X	X
	Rosphalt overlay		n/a	X	
	Epoxy/polyester concrete overlay	X	15 to 20 yrs.	X	X
	Latex-modified overlay		20 to 25 yrs.	X	X
	Joint cleaning	X	1 to 5 yrs.	X	
	Joint seal installation/repair	X	6 to 10 yrs.	X	X
	Joint structural repair	X		X	X

[a] If frequency is not mentioned in literature, "--" is shown.
[b] Sources for recommended frequencies are Zhang, Labi, Fricker, & Sinha, 2017; Sprinkel, Brown, & Thompson, 2004; Bowman & Moran, 2015; and Gupta et al., 2016.
[c] Actions that can be used as part of a rehabilitation program.

Table 2.2. Summary of activities applicable to concrete decks and some overlays.

DECK TYPE	Activities	Preventive Maintenance			Rehabilitation[b]
		Cyclical Maintenance	Recommended Frequency[a]	Condition-Based Maintenance	
CONCRETE DECKS/SLABS	Crack repair/sealing	X	4 to 5 yrs[d, e]	X	
	Epoxy injection	X	--	X	
	Deck sealing	X	3 to 6 yrs[c, d, e]		
	Deck patching with asphalt or concrete	X	1 to 12 yrs[d, e]	X	
	Deck patching with concrete	X	1 to 12 yrs[d, e]	X	X
	Repair potholes	X	--[f]	X	
	Removal of loose concrete	X	2 yrs[g]		
	Cathodic protection	X	--	X	X
	Electrochemical chloride extraction	X	1 to 2 yrs[e]	X	X

[a] If frequency is not mentioned in literature, "--" is shown.
[b] Actions that can be used as part of a rehabilitation program.
[c] Source: (Zhang, Labi, Fricker, & Sinha, 2017).
[d] Source: (Bowman & Moran, 2015).
[e] Source: (Gupta, et al., 2016).
[f] While values were not found in literature, coldpatches used for potholes generally only last one season. Frequency may be assumed to be 1 year.
[g] Loose concrete typically removed during routine inspection.

Table 2.3. Summary of activities applicable to steel and timber decks.

DECK TYPE	Activities	Preventive Maintenance			Rehabilitation[b]
		Cyclical Maintenance	Recommended Frequency[a]	Condition-Based Maintenance	
STEEL DECKS/ SLABS	Deck patching with asphalt	X	1 to 12 yrs[d]	X	
	Deck patching with concrete	X	1 to 12 yrs[d]	X	X
	Repair potholes	X	--	X	
	Deck sealing of overlay	X	3 to 6 yrs[d]		
	Spot painting structural steel	X	5 to 12 yrs[d]	X	
	Painting structural steel	X	12 yrs[d]	X	X
	Metallizing structural steel		n/a	X	X
	Cathodic protection	X	--	X	X
	Filling the deck with concrete		n/a	X	X
	Repair broken connections			X	X
	Apply studs for traction			X	
TIMBER DECKS	Replacing timber deck planks	X	--	X	
	Replacing timber deck runners		n/a	X	
	Applying water repellant	X	--		
	Controlling moisture sources		n/a	X	
	In-place preservative treatment	X	3 to 5 yrs[c]	X	
	Fumigating		n/a	X	
	Fire retardant	X	--		
	Applying paint	X	--	X	
	Stress laminating nail-laminated decks		n/a	X	X

[a] If frequency is not mentioned in literature, "--" is shown.
[b] Actions that can be used as part of a rehabilitation program.
[c] Source: (FHWA, 2018).
[d] Source: (Bowman & Moran, 2015)

2.2.2 Filters and Thresholds

As shown by the lists in Tables 2.1 through 2.3, there is a multitude of activities to choose from. There are two primary ways that states use to sort activities into a list of feasible options and a final decision. The first relies on the general NBI rating of the deck, or the element-level rating. This method is more common since this information is federally required and easily available at low cost. In the second method, the applicable activities are determined by the type of distress observed on the structure and the underlying cause of distress. While effective, this method often requires more detailed data, some of which cannot be obtained in a visual inspection and sounding survey alone. Common non-destructive tests include ground-penetrating radar to identify concrete cover and deep delaminations and half-cell potential to identify probable corroding areas. Chloride profiling to identify the extent and levels of chloride contamination at the depth of the steel may also be completed. Multiple states, including Maine, Alaska, and Colorado, require or strongly recommend conducting additional tests prior to certain types of maintenance activities, such as measuring the chloride contamination of the concrete prior to overlay application and rehabilitation work (Alaska Department of Transportation and Public Facilities, 2017; Guertin Elkerton & Associates, 2003; Colorado Department of Transportation, 2018). State DOTs often hire external consultants to conduct in-depth inspections and provide professional recommendations based on the results, making this method more costly. If state forces are used, then the increased labor still makes this method more expensive than relying on qualitative, general NBI ratings and element-level data.

Table 2.4 shows the threshold-based criteria adopted by Kentucky DOT to decide the type of activity to apply to a bridge deck based on the general NBI and element-level ratings (Kentucky Transportation Cabinet, 2018). The translation between general NBI rating and element-level ratings used by the Maine DOT is provided in Table 2.5.

Table 2.4. Determination of type of activity based on condition ratings (Kentucky DOT).

General NBI Rating	Element-Level Rating	Type of Activity
7 to 9 (good)	1 (good)	Cyclical preventive maintenance
5 or 6 (fair)	2 or 3 (fair to poor)	Condition-based preventive maintenance or rehabilitation
4 or less (poor)	4 (severe)	Major rehabilitation or replacement

Table 2.5. Determination of type of activity based on condition ratings (Maine DOT).

General NBI Rating	Element-Level Rating	Type of Activity
7 to 9	1 (good)	Cyclical preventive maintenance
5 or 6	2 (fair)	Condition-based preventive maintenance or rehabilitation
3 to 4	3 (poor)	Rehabilitate or replace
2 or less	4 (severe)	Replace or close

The tables above indicate that the type of maintenance is determined by a general rating but as discussed in Section 2.1 *User Inputs*, element-level data is reported as the quantity of the element belonging to CS1, CS2, CS3, and CS4. As a result, these tables are a good starting point but should be improved prior to determining the type of activity to select based on element-level data. Cut-offs in terms of the percentage of the deck area belonging to each element-level rating are required instead.

States use percent of damage in more detailed decision matrices, wherein suggestions are provided based on the deck deficiency, defined as the percentage of the deck surface area with delaminations, spalls, and patches, and the soffit deficiency, defined as the percentage of the deck underside with the same. While not a direct expression of the quantity in CS2, CS3, and CS4, this is a good characterization of damage. Many states narrow down the potential activities further using the following parameters:

- Concrete cover and rebar type,
- Presence of exposed rebar,
- Bridge age and scheduled replacement,
- Condition of superstructure and substructure;
- Load rating, ADT, and redundancy of the bridge[1], and
- Chloride contamination and half-cell potential (HCP) results.

Two examples of decision matrices that determine the most appropriate activity based on these variables are shown in Appendix A. The first was developed by Michigan (Michigan Department of Transportation, 2017) and the second is from Minnesota (Bridge Office, 2015).

Alternatively, states such as North Dakota, Colorado, and Florida provide discussion on appropriate conditions for each activity (Colorado Department of Transportation, 2018; FHWA, 2018; Nebraska Department of Roads Bridge Division, 2014). For example, Florida uses the FHWA-NHI Course No. 130108 Bridge Maintenance Reference Manual (BMRM), which provides a list of treatments used in response to each type of deck distress. Unsuitable options are eliminated based on deck deficiency, concrete cover, crack maps, chloride contamination, HCP, and concrete pH. The concrete cover and test information are used to identify the likelihood of deterioration due to chloride-induced corrosion qualitatively and then the deck deficiency and crack widths are used to identify the type of activity that should be completed. Activity types include "do nothing," "seal deck," "overlay," "repair," "rehabilitate," and "replace." The manual additionally provides a decision table for responding to distress caused by alkali-silica reaction based on petrographic analysis and compressive strength of concrete cores.

These decision matrices are not absolute, and this is generally acknowledged by the states. Missouri requires additional deck testing if the bridge is rated 6 or 7 in order to determine what the scope of the repair project needs to be, and subsequently minimize costs (MO-DOT, n.d.). Minnesota states that the suggested scope may change if the soffit deficiency is high, despite the fact that soffit deficiency is not an input for the state's matrix (Bridge Office, 2015). Furthermore, Minnesota requires a different deck deficiency before deciding on replacement if the deck is composed of the top flange of the superstructure instead of a structurally separate component; the cut-off for an independent deck system is 25% whereas the cut-off is 60% for a deck that is part of the superstructure. Exceptions are typically described in footnotes for the matrices.

[1] Redundancy refers to the criticality of the bridge in the transportation system. For example, bridges that cross the same feature are considered redundant while a bridge that has a very large detour length is considered non-redundant or critical.

2.3 Algorithms for Service Life Analysis

Two different approaches of analyzing the service life of bridge elements are commonly used. The first approach, which is called deterioration modeling, consists of using historic data from a set of bridges that share common characteristics and exposure (such as concrete bridges located in the same state) to develop statistical models that predict the remaining service life of the bridge of interest. These methods rely on historical data (such as general NBI or element-level NBE data) and provide a macro-level understanding of the bridge performance on the basis of the observed past performance. They output a deterioration curve that describes the transition from a good state (e.g., CS1 if element-level data, 9 if general ratings) to subsequent, poorer states (e.g., CS2 through CS4, general ratings of 7 to 3) over time as shown in Figure 2.4. End-of-service-life is typically considered to be a general NBI rating of 4 or 3 since ratings of 2 and 1 indicate the bridge likely needs to be taken out of service. Element-level values indicating end-of-service-life of elements have yet to be widely established due to the lack of historical data and the complexity of the reported data. Hearn (2019) provides suggested thresholds for triggering replacement that differ based on the type of material and type and severity of the defect in the AASHTO Guide to Bridge Preservation Actions (Project NCHRP 14-36). However, as models using element-level data are developed and applied, these thresholds defining end-of-service-life will likely vary between states due to differences in practice and standards.

Alternatively, the second approach to estimating service life, called mechanistic modeling, requires knowledge of the specific characteristics of the bridge (such as mixture design, chloride contamination and exposure, permeability, and protective systems) to provide predictions of material-level degradation. These models describe the progression of physical and chemical deterioration mechanisms and are capable of predicting the time at which corrosion of the steel section or reinforcement begins and how quickly surface damage develops. Mechanistic models rely on an in-depth understanding of the physical relationships between material or structural properties and performance, which are typically developed by staged field or laboratory testing. The end-of-service-life is typically expressed as the time at which a certain percentage of the structure is expected to have visible damage, or when the probability of surface damage reaches a pre-set threshold. A threshold of 10% is generally considered best practice but again, this may vary between models according to the practices of the states and requirements of the bridge owners.

It is important to emphasize that while both deterioration models and mechanistic models predict service life, they have distinct applications. Because deterioration models describe the average performance of a set of bridges with similar characteristics and exposure, they may be used to predict the performance of any bridge that has the same set of assumed characteristics and exposure. However, when observed at the greater level of detail required for mechanistic modeling, these bridges are distinct and cannot be grouped together. This is why each individual bridge requires a unique mechanistic model and mechanistic models cannot be shared between similar bridges like deterioration models.

These two approaches are fundamentally complementary in nature. In general, the mechanistic techniques fall under the micro-level quantification of bridge performance and aim to characterize local material properties and/or identify material-level forms of deterioration or damage. Deterioration modeling takes a more global approach and generally focuses on quantifying the bridge performance on a system/component-level of a network of bridges. Although these two approaches complement each other, there are few examples of how this complementary nature can be exploited to improve the accuracy and comprehensiveness of bridge assessment. In the next several sections, each approach will be briefly discussed. The discussion uses concrete-related examples as it is the most common and complex construction material for bridge decks; however, the decision trees are intended to encompass steel and timber decks as well.

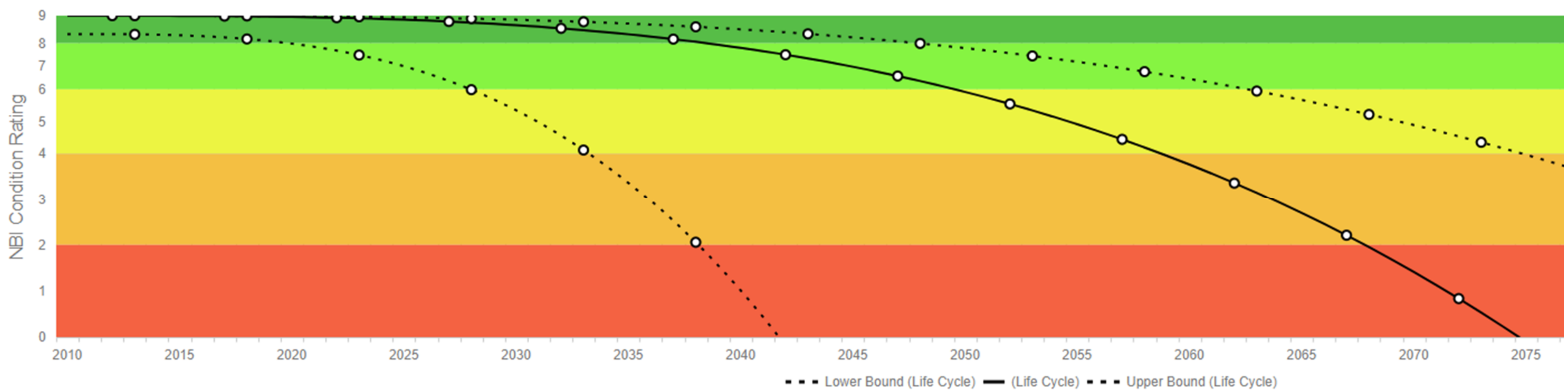


Figure 2.4. Theoretical deterioration model for a bridge deck.

2.3.1 Deterioration Models

The time at which the bridge or bridge deck needs to be replaced or repaired may be estimated using a deterioration model. Deterioration models are built by collecting and categorizing historical condition data and then identifying deterioration rates and trends by statistical approaches. Reviewing the technical literature reveals several types of approaches to deterioration modeling, including deterministic, artificial intelligence (AI), and probabilistic. Deterministic models correlate age or a limited number of other parameters with the component's condition using a simple mathematical formulation, such as a linear combination of the age and other parameters of interest. Despite the ease of model development and interpretation, deterministic models do not account for the variation in the variables and processes of bridge deterioration processes or consider the effects of unobserved explanatory variables.

Alternatively, AI platforms for bridge engineering applications are currently being studied and developed by both scholars and practitioners. AI models such as artificial neural networks (ANN) and machine learning (ML) utilize modern computer techniques to automate intelligent data ‘‘learning’’ processes of bridge deterioration behaviors. These techniques are mostly inspired by natural rules and present the solutions based on experience and development of various discriminators that can sort similar data. AI platforms have the benefit of being able to consider massive amounts of variables to achieve significant life cycle cost savings, but the amount of data required is substantial and, potentially, costly. Since AI has the ability to learn as more data is entered, more variables could be considered to produce refined deterioration models that result in better maintenance program outcomes. The AI software would be able to modify the algorithms based on local historic data, which would allow the decision making to take into account variables that have previously been too difficult to capture, including: highly localized weather information, impacts of available construction materials, and local procedures for snow and ice removal. Despite their power, AI models are disliked because their logic is not transparent to users. The models act as black boxes and do not explicitly provide a function correlating the output to the given inputs. The computations must be conducted a-priori requiring significant trial-and-error operations.

In contrast with both deterministic and AI-based models, probabilistic deterioration models view bridge deterioration as a stochastic process affected by various parameters. A stochastic deterioration model can consider correlated explanatory variables and describe a continuous deterioration between the discrete states used in the general NBI ratings and element-level condition records (Mishalani & Madanat, 2002). The probabilistic/stochastic models rely on transition probabilities, which represent the likelihood that an element will decrease in condition rating between two adjacent inspections. The stochastic models can be classified either as state-based (such as Markovian) or time-based (such as Weibull) models. State-based models predict deterioration based on the current state of the element while time-based models predict deterioration based on the amount of time the element has been in its current state. Among these two conventional methods, the current practice conventionally employs the Markovian approach due to its simplicity. The next part of this section provide a summary of this methodology. A more detailed explanation of Markovian and Markov/Weibull models is presented elsewhere (Mishalani & Madanat, 2002).

Model Inputs.
Variables that affect the service life of the structure are called explanatory variables. They may be categorized as asset, site, or loading characteristics and repair history (Ford, et al., 2012). Explanatory variables that have been identified for concrete and steel structures are listed in Table 2.6. Different models can incorporate different combinations of the inputs listed and some incorporate multiple variables while others only accept age. If the deterioration model only accepts a limited subset of the variables listed in

Table 2.6, then it is important to understand the source data used to develop the model and ensure that the remaining variables of the bridge of interest, particularly exposure conditions and physical characteristics, matches those of the group of bridges whose data was used to develop the model.

Table 2.6. Explanatory variables for concrete and steel structures (Ford, et al., 2012).

Type	Concrete	Steel
Asset characteristics	Age	Age
	Type of wearing surface	Type of wearing surface
	Geometry	Span length
	Construction technique	Fatigue durability
	Bond strength between overlay and deck	
	Deck area	
	Deck distress	
Site characteristics	Freeze index	Freeze index
	Cumulative precipitation	Cumulative precipitation
		High temperatures
Loading characteristics	Highway functional class	Volume of truck traffic
	Traffic volume	Truck size distributions
	Accumulated truck loads	Truck axle configuration and weight
	Wheel locations	Road classification

Markovian Models.

The most popular deterioration models for bridge asset management are Markovian models. Markovian models define the predicted condition C_p at age a as a function of the current condition C_i and a matrix of transitional probabilities **T**. This is defined by Eq. 1 below:

$$C_p(\mathrm{a}) = C_i * \mathbf{T}^{\mathrm{a}-1} \qquad \textbf{(Eq. 1)}$$

The condition variables are vectors. As an example, they may represent the percentage of a bridge deck that is in each of the condition states:

$$C_i = [\mathrm{CS1} \quad \mathrm{CS2} \quad \mathrm{CS3} \quad \mathrm{CS4}]$$

Alternatively, the elements may represent other dimensions, such as the percentage of the bridge deck with a HCP reading indicating that corrosion is unlikely, the percentage with a HCP reading indicating that corrosion may be occurring, and the percentage with a HCP reading that indicates corrosion is probably occurring[2]. The vector may be extended to incorporate multiple metrics.

[2] HCP testing indicates whether corrosion cells are present or not, but does not directly measure corrosion. As a result, the values are only an indicator and cannot determine if corrosion is occurring with certainty. Refer to ASTM C876, *Standard Test Method for Corrosion Potentials of Uncoated Reinforcing Steel in Concrete,* for the testing procedure and data analysis used for HCP testing.

An example of a 4x4 transitional matrix **T** appears as the following:

$$\mathbf{T} = \begin{bmatrix} t_{11} & t_{12} & 0 & 0 \\ 0 & t_{22} & t_{23} & 0 \\ 0 & 0 & t_{33} & t_{34} \\ 0 & 0 & 0 & t_{44} \end{bmatrix}$$

The diagonals $t_{i,i}$ represent the probability that the component will remain in the given condition state between inspections. The values $t_{i,i+1}$ represent the probability that the component will move to the subsequent condition state between inspections. Note that the zeroes in the lower left of the matrix prohibit the component from moving to a better condition state. This is a key assumption in Markov models and prevents benefits from repairs from being incorporated. In theory, bridges may be categorized by maintenance and repair work histories and separate transitional matrices may be developed for different maintenance strategies. However, maintenance records are not typically sufficient to develop this data.

The zeroes in the upper right of the matrix reflect the assumption that the component cannot jump between condition states that are not directly next to each other. Some Markov models do consider this scenario, but because available data does not distinguish between areas that move from CS1 to CS3 and areas that move from CS2 to CS3 in inspections any non-subsequent transitional probabilities are difficult to define. This is not a concern for NBI condition rating data, partly because the bridge decks that jump multiple states can be identified and mostly because the quick global deterioration required for this to occur is rare.

Another issue with the Markov model is that the transitional probabilities are assumed to remain constant throughout the life of the structure. This means that the probability of further deterioration depends only on the current state of the component, and not on the history of the component but this has not been observed to be accurate in practice. As a result, Markov/Weibull models are also popular. Markov/Weibull models use the general structure of a Markov model but incorporate a Weibull survival probability function to turn the transition matrix into a time-dependent function. In this way, they more accurately characterize changes in deterioration rates with age.

One challenge yet to be fully addressed in deterioration models is the inclusion of maintenance strategies and their effects. Some groups state that deterioration models are intended to only model deterioration and should not include condition improvement due to maintenance. However, because of the interest in comparing maintenance strategies and the benefits to service and service life, some groups do consider maintenance strategies in their analyses (Michigan Transportation Asset Management Council, 2018). While most maintenance and rehabilitation activities have been in practice for a while, their service life benefits are not well-characterized. These activities may improve service life by increasing the condition rating of the bridge deck or decreasing the deterioration rate. Analyses of these benefits is limited in literature, and mainly focuses on improvement in condition since more time, data, and intensive analysis is required to evaluate effects on deterioration rates. One group determined the average improvement in general NBI deck condition rating for various activities. The data was collected via a survey of state DOTs, but does not consider the pre-treatment condition, which greatly affects the performance of the repair or maintenance practice over time (Zhang, Labi, Fricker, & Sinha, 2017). If the initial improvement due to the maintenance is known, and the same deterioration rates or transitional probabilities are assumed, then the additional service life due to the maintenance may be calculated using the Markov, Markov/Weibull, or other deterioration models.

2.3.2 Mechanistic Models

As stated at the start of the section, mechanistic models estimate service life by using material and structural behavior to predict performance based on the physical properties of specific structures. This relies on an in-depth understanding of the degradation mechanisms of the materials and structures. For example, concrete bridge decks are subjected to many different types of deterioration, but typically fail due to chloride-induced corrosion, especially in marine environments or where deicing salts are used. Steel structures are largely assumed to fail due to fatigue or corrosion in mechanistic models. Only concrete is discussed further since concrete deterioration modeling is more prevalent in literature and practice.

There are different commercially available and in-house software to perform service life modeling of corrosion related damage in reinforced concrete. These models are based on different durability codes and guidelines developed in the U.S. and Europe. The guides were developed for modeling of new structures, but the concepts may be adapted to develop models for existing structures. However, when modeling existing structures, the data and information required to support the models is often unknown due to the unavailability of the construction records for the structure. Some parameters may be determined through testing, but the information is still uncertain due to limitations of the tests, such as precision limits. The available service life models generally estimate the time required for corrosion to initiate and then to propagate to cause concrete cracking, delamination, and spalling (damage).

Service life modeling can be performed in a deterministic or probabilistic approach, depending on the desired level of confidence and available information on the input parameters. In consideration of the variability inherent in existing concrete elements, a probabilistic modeling approach is preferred. This approach determines the percentage of corrosion-related damage in existing elements with time based on statistical distributions of key parameters considered to govern corrosion. Modeling approaches may be based on durability and service life codes and guidance reports such as the Fédération International du Béton (fib) Bulletin 34 Model Code for Service Life Design (fib Bulletin 34), the ACI 365 committee publications, and the Concrete Society Technical Report No. 61 (Bamforth, P. B. 2004). The models require test data characterizing the exposure conditions and condition of the material but in the absence of test data, these publications also provide suggested reasonable assumptions for some of the input parameters.

Commercially available software for service life modeling of concrete damage related to corrosion of embedded reinforcing steel include Life-365™, Concrete Works, and STADIUM®. The user manual of Life-365 (2018) provides guidance on the effect of supplementary cementitious material, such as silica fume, fly ash and slag, on the diffusion properties of concrete. Membranes and sealers are modeled by modifying the rate of chloride build-up. The efficiency of those are assumed to start at 100% and decay with time for an assumed life of 20 years and 5 years for membranes and sealers, respectively. These values can also be modified by user for project specific parameters. The effect of corrosion inhibitors on the chloride threshold is also discussed in the Life-365 user manual as well as the Concrete Society Technical Report No. 61 (TR-61) (Bamforth, P. B. 2004). STADIUM® offer a Bridge Deck Tool to simulate corrosion risk over time. WJE's in-house service life modeling tool offers similar capabilities with a more customizable structure, where the user may modify any of the critical parameters to project-specific values. It also incorporates best practices from available codes and guidelines, and WJE's long experience with durability related projects and in-house research.

Input parameters for the service life model can be conceptually separated into exposures (loads) and resistances to corrosion. For chloride-induced corrosion, exposure input parameters include chloride surface concentration and chloride build-up time. Resistance input parameters include concrete cover;

apparent diffusion coefficient; concrete ageing factor; temperature; and propagation time. For carbonation-induced corrosion, exposure input parameters are atmospheric carbon dioxide concentration, temperature and relative humidity. For existing bridges, it is recommended to establish the exposure and resistance input parameter values based on test results of material samples, if feasible.

In the absence of local data, some models incorporate default values for exposure condition parameters depending on user's input for geographical location. The annual temperature profiles are usually based on a database compiled from meteorological data. The surface chloride concentration and the rate of chloride buildup are based on the type of exposure in addition to the geographical location.

As an example, Life-365 service life prediction model for chloride-induced corrosion includes seven exposure conditions, four of those (marine tidal, marine splash, within 800 m of the ocean, within 1.5 km from ocean) are included as options only when a geographical location within a coastal region is selected. A set of build-up rates and maximum surface concentration values are suggested by the Life-365 Manual (2018) for these marine exposure conditions, regardless of the geographical location. The other three exposure condition options are for bridge decks and parking structures exposed to deicing salts. These are based on a database of deicing salt application practice gathered from surveys performed by the Salt Institute between 1960 and 1984, and data related to chloride build-up rates for U.S. highways from Weyers et al. (1993). These values were also compared against chloride content data in literature for bridge decks and parking structures. The model assumes build-up rates that varies with the geographical location; it is assumed as 85% and 70% of the values shown in Figure 2.5 for urban and rural bridges, respectively. Higher maximum surface concentration are assumed for regions of greatest use of deicing salt, shown in light blue in the Figure 2.5, than that assumed for the rest of the regions.

The output of these models would be the predicted performance of the bridge deck with time. The service life of the structures can then be estimated based on a predefined end-of-service-life criterion. The end of service life should be evaluated based on the specific performance and usage requirements for the bridge and may be related to functional or structural concerns. Functional concerns can be either usage-related or corrosion-related and can include substandard design features, or the number of potholes or spalls on a deck. Structural concerns can include items such as section loss of reinforcing steel due to corrosion or loss of development length for reinforcing steel due to spalls and delamination.

2.3.3 Advantages and Disadvantages

State DOTs and transportation asset managers generally use deterioration models instead of mechanistic models. However, mechanistic models may be required when comparing alternative rehabilitation and condition-based maintenance strategies. The advantages and disadvantages of each are summarized in Table 2.7.

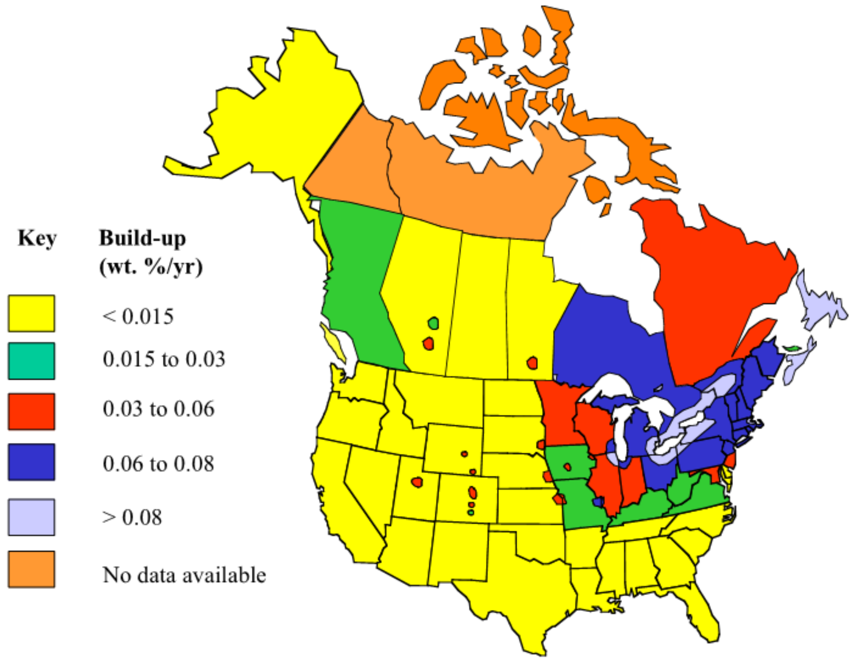


Figure 2.5. Chloride build- up rates by region of North America, User manual of Life 365 (2018).

Table 2.7. Comparison between deterioration and mechanistic models.

Type of Model	Advantages	Disadvantages
Deterioration	• Easy to develop and validate since they rely on accessible condition data • Can be integrated with LCCA models for budget allocation purposes	• Have high uncertainty due to scatter of the data used to develop the model • Different models are required for bridges of different exposures, functional classes, design, and materials • Cannot accurately predict deterioration of bridges using new materials, construction methods, maintenance procedures, or other technologies due to reliance on historical data
Mechanistic	• Can be used if historical data is not available or if changes in condition cannot be assessed visually, e.g., development of chloride contamination	• Require detailed, expensive data collection programs and uncommon expertise to interpret the results • Different models are required for individual bridges

2.4 Life Cycle Cost Analysis

Life cycle cost analysis (LCCA) is a well-established analytical tool used to compare costs between alternative designs and strategies. An LCCA estimates the sum of all costs associated with the full life of a structure, from "cradle-to-cradle". This typically includes any costs involved in initial design and construction, operation, maintenance, and end-of-life demolition. Transportation asset management agencies prefer LCCAs to short-term cost comparisons because short-term comparisons only consider the initial costs, and technologies with lower initial costs often have higher long-term maintenance and repair costs. In other words, short-term cost analyses are only capable of considering short-term benefits. Since strategies incorporating preventive maintenance generally provide substantial long-term benefits, they can be identified as unfavorable in short-term analyses, which may be erroneous. Since LCCAs can identify long-term savings, they can determine whether or not the lower maintenance costs are worth the initial investment.

The first step to conducting an LCCA for bridge management is to determine the alternative maintenance strategies that will be considered. This involves developing different activity profiles that define which maintenance and rehabilitation activities will take place and when. Service life estimates are required for this step, and deterioration models are used to select the timing of the activities as well as which activities are most appropriate based on the expected condition of the asset. Each of the chosen activity profiles has an associated cash flow. The next step involves estimating those costs. If alternatives share the same activities, then the costs associated with those activities are often omitted since LCCA is a comparative tool that focuses on cost differences.

Costs may be considered to fall under two categories: agency costs and user costs (Hawk, 2003). Agency costs are incurred directly by the agency and include the following:

- Design costs,
- Construction costs,
- Maintenance costs,
- Rehabilitation costs, and
- Salvage value.

Salvage value is the worth of the structure at the end of its life and can either be a negative value, representing a cost, or a positive value, representing savings or a recovered value. Demolition costs would be considered negative salvage value. If the structure has useful life left or its constituents can be recycled or reused, then the salvage value would be positive.

User costs are costs to the bridge users. While they do not directly affect the agency, they affect the agency's clients and their satisfaction with the agency's service. As a result, it is generally considered good practice to include user costs in LCCAs although there are some exceptions. For example, user costs may not be important in the decision-making process due to funding constraints of the agency. The following three user costs are typically considered:

- Vehicle operating costs,
- Travel delay costs, and
- Crash costs.

Crash costs are included because work zones increase the likelihood of vehicle accidents. The first two costs rely on the construction duration, the detour length or traffic congestion caused by the project, and the number of users that will be affected. If the bridge has a high ADT, then user costs can easily outweigh the agency costs and redefine which alternative is less expensive. To avoid user costs from dictating the shortest maintenance activity, which typically coincides with the most expensive activity in terms of agency costs, the user costs and agency costs are generally weighed or scaled based on the objectives on an agency.

The next step in a LCCA is the transformation of all future costs to the present value. Economic resources (i.e. currencies) have a time-dependent value due to their ability to be put to productive use and yield returns. For example, the money placed in a savings account today will accrue interest and grow with time. The sum of the original value and its cumulative interest in any future year is considered equivalent to the original value placed in the account in the present year. The conversion between present values (PV) and future values (FV) is executed using Equation 2.1:

$$PV = FV_n * \frac{1}{(1+r)^n} \qquad \text{Eq. (2.1)}$$

Where FV_n represents the future value at year n and r is the real discount rate. In bridge LCCA, real discount rate represents the opportunity cost paid by taxpayers for not being able to invest or spend their tax money as they like. It does not consider inflation, and if the funding for the expenditures will be borrowed, then the real discount rate would be the borrowing rate. Reasonable rates fall between 2% and 4%, and a value may be selected using rate data maintained by the federal Office of Management and Budget, but values are generally set by the owner in project requirements.

2.5 Uncertainty and Risk Management

2.5.1 General Risk Management Procedures

FHWA currently requires that states develop a risk-based Transportation Asset Management Plan (TAMP). Risk is defined as the product of the probability of an event and the consequences of the event. It can be a threat if the consequence is harmful, or an opportunity if the consequence is desirable. The federal guide, *Incorporating Risk Management into Transportation Asset Management Plans*, provides a 7-step procedure for accounting for risk as described briefly below (FHWA, 2017):

1. **Establishing the Context.** This step involves identifying the goals, objectives, and performance targets that the risk-management program and the TAMP are intended to meet. General issues and trends that the agency has faced in the past and expects to face in the future are identified as well.
2. **Identifying Risks.** The issues and trends identified in Step 1 are refined and an exhaustive list of specific risks is made. Risk management is to address threats, opportunities, uncertainty, and variability. All risks to short-term and long-term goals should be considered.
3. **Analyzing or Assessing Risks.** The risks from Step 2 are quantified and/or ranked. The federal government recognizes that the likelihood of the event creating the risk cannot be estimated in most scenarios due to lack of data and the consequence is also difficult to define. As such, this step is generally qualitative. Probabilities and consequences are ranked on a qualitative scale from "low" to "high" or "severe" based on the collective experience of the risk-management group. They are then mapped on a "heat map" to identify the severity of the risk. An example of a heat map is provided in Figure 2.6.
4. **Evaluate and Prioritize Risks.** In this step, the agency decides which risks are tolerable and which are to be addressed. This is typically done by setting a risk "threshold." Any risks above the threshold are to be mitigated in the following step.

5. **Identify Risk Mitigation and Management Strategies.** Strategies for addressing the intolerable risks identified in Step 4 are developed in this step. If the risk is a threat, then the agency considers how to neutralize it. If it is an opportunity, then the agency considers how to capitalize on it. Sometimes the agency will not have any control over the likelihood of the event, such as the likelihood of economic downturns or natural disasters. In this case, the agency considers how to mitigate the consequence or develops contingency plans.
6. **Monitor and Respond to Risks.** This step involves monitoring and communicating risks and their effects on performance to stakeholders who will be affected or can help mitigate the consequences. If an event occurs, then the performance consequences and actions of the agency are to be evaluated. The federal guide suggests creating a risk register in which the complete list of risks, their management plans, and a point of contact who is responsible for the plan are identified. This document is intended to be dynamic and updated periodically.
7. **Execute Risk Plan.** The final step identified by the guide is to follow through and execute the plan developed in the previous steps. The plan is inherently dynamic as some risks are mitigated, others are capitalized, and new risks are developed. Risk registers and performance should be reviewed periodically to ensure the risk management plan remains up-to-date.

As an example of a risk management strategy, the Arizona DOT categorizes its risks based on the types of consequences associated with each event in order to ensure a complete risk register is developed (ADOT, 2018). The categories are the following:

- **Agency Risk.** Events with consequences that affect the implementation of the TAMP and achievement of the performance targets set by the TAMP. Examples include changes in leadership and public policy.
- **Financial Risk.** Events with consequences that affect available funding for long-term programs and plans, such as inflation and inaccuracies in predictive financial models.
- **Program Risk**. Events with consequences that affect the ability of the agency to deliver project programs that meet performance targets on time. Examples include inaccurate cost estimates and unexpected deterioration.
- **Asset Risk.** Events with consequences that affect individual assets, such as structural deterioration and extreme events.
- **Project Risk.** Events with consequences that affect rehabilitation and replacement construction projects. Examples include construction delays and scope creep.
- **Activity Risk.** Events with consequences that affect maintenance activities and cause inadequate repairs. Examples include lack of contractor experience and environmental conditions during construction.

This set of categories is easy to follow because the risks are divided by scale and presented in decreasing order. It helps the risk manager assess how consequences may cascade through the bridge management plan. For example, if inflation exceeds expectations, then available funding for projects may decrease. This is considered a financial risk, but the consequences of decreased funding include reprioritization of projects, which would be a program risk. The reprioritization and rescheduling of projects permits further deterioration of low-priority assets, which is an asset risk. Specific rehabilitation projects will be redefined and maintenance activities may be dropped, which are classified as project and activity risks respectively.

The federal guide provides a list of common types of risk that agencies should consider as well (FHWA, 2017):

- **Current and Future Environmental Conditions.** This includes extreme weather events, changing climate conditions, and seismic activity. For example, states on the west coast will need to consider seismic activity while states in the southeast should consider consequences due to hurricanes. Areas where average temperatures are expected to increase may want to consider shortened service life due to accelerated deterioration mechanisms.
- **High-Risk, High-Value Assets.** High risk can be caused either by a large likelihood of the event occurring or a costly consequence. Assets that fall under this category include bridges that have extensive deterioration and a high chance of becoming functionally obsolete in the near future. Bridges with high ADT loading or with no redundant corridors may also be considered critical assets. These assets require increased investment or monitoring.
- **Inaccurate Financial Forecasts.** This was described previously in the Financial Risk category identified by the Arizona DOT. Predictions of revenues and expenditures in the future rely on assumptions and estimations. They may be inaccurate due to uncertainties in the estimations or inaccurate assumptions. This is why it is important to have experienced personnel review assumptions embedded in the models. The discussion in the next subsection describes how to incorporate uncertainty in the parameters and variables in estimations. While it is intended for uncertainties in the deterioration models and life cycle cost analysis, the methods described apply to financial forecasting models as well.
- **Inaccurate Information and Decision Data.** This is similar to the Inaccurate Financial Forecasts category, but applies to the data and assumptions used in deterioration models and cost analysis. Inaccuracies in data collection are already well-managed by the extensive collection of bridge inspection guides, forms, and courses available to inspectors. Some level of uncertainty due to operator judgment is considered unavoidable. This results in uncertainty in model outputs, which may be characterized by probabilistic modeling, sensitivity analysis, and Monte Carlo simulation. These are described in more detail in the following subsection.
- **Changes in Legislative Requirements.** The federal government continuously updates and makes new standards that must be met by state and local agencies. Costs associated with meeting updated standards may redefine project prioritization and available funds.
- **Changes in Demand.** This includes increasing or decreasing ADT, truck weights, and axle spacing. These changes affect deterioration rates and predictions.
- **Changes in Operation Personnel and Priorities.** This is similar to the Agency Risk category defined by the Arizona DOT. Decreased staffing and loss of staff expertise can impede good data collection and model development. Staff turnover is often associated with a shift in priorities, and this prevents long-term management plans from being fulfilled and cost savings from being realized.
- **Hostile Acts, Malfeasance, and Accidents.** Managing risks in this category primarily involves developing contingency plans and response strategies. Events that are considered include oversize truck crashes and extreme events, such as fires or floods.

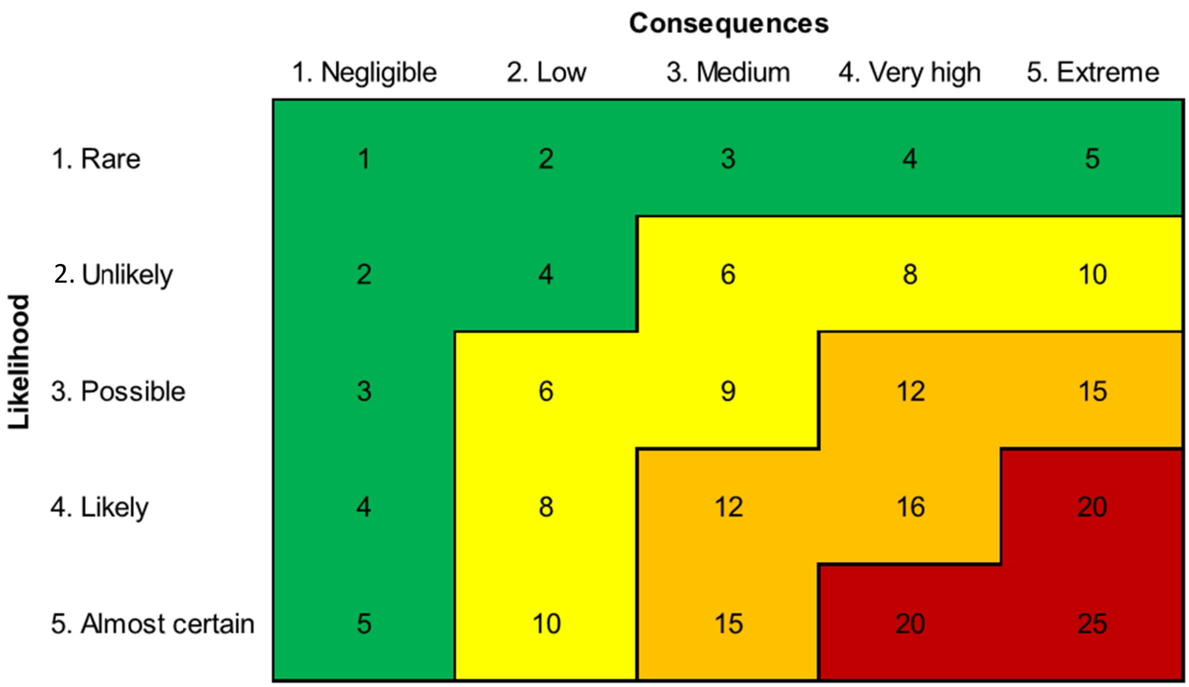


Figure 2.6. Risk management heat map used by the Iowa DOT (IowaDOT, 2018).

2.5.2 Handling Uncertainties in Modeling

When uncertainties are not incorporated in a model, the model is considered to be deterministic. Deterministic models can be advantageous because they are fast and simple, and they produce only one output that is easy to interpret: the final estimate. However, because management decisions rely so heavily on these estimates, inaccuracies can have costly impacts. As a result it is important to understand the confidence and uncertainty of the estimate and to ensure that the risk of an incorrect estimate is low.

The primary sources of uncertainty in modeling are from the parameters and assumptions used to calculate the output (Ashley, Diekmann, & Molenaar, 2006). For deterioration models, this would include the coefficients and transitional probabilities determined by a regression analysis, the improvements in condition rating due to repair activities, the timing of the maintenance activities, and many other factors. These values vary depending on the effectiveness and quality of the repair or maintenance job, the condition state and history of the bridge, the environmental exposure experienced by the bridge, the funding available to the agency, and other practical considerations. Examples of uncertain parameters in LCCAs include the discount rate, the agency and user costs, and any hidden costs due to unexpected deterioration from collisions, extreme events, and unknown deterioration mechanisms. The uncertainties in the agency and user costs can be further broken down into uncertainties regarding the material and labor cost estimates for each activity, the timing, duration, and scope of each repair and maintenance activity, traffic congestion delays, detours and delay-induced diversions, and more.

Each quantitative parameter, such as a transitional probability or maintenance cost, can theoretically be described by a probabilistic distribution with statistical parameters. This is an effective way to begin incorporating uncertainty, but the distribution is not always known, especially if there is limited data and samples. Additionally, the statistical parameters have some level of uncertainty as well. If the distribution is not known, then a sensitivity analysis may be appropriate. A sensitivity analysis is conducted by changing a parameter by one unit, recalculating the estimate, and reporting the change in the final output. This permits the significance of the parameters to be ranked and any unacceptable dependencies to be identified for correction.

If there is enough data to determine the probabilistic distributions with confidence, then uncertainty may be assessed using a Monte Carlo simulation. Monte Carlo simulations are conducted by randomly selecting a value from each input parameter distribution and determining the deterministic output for that combination of inputs. This deterministic calculation is repeated on the order of several thousand iterations to create a distribution of outputs. The distribution with the best fit is chosen to describe the uncertainty in the output. Sensitivity analysis can be combined with probabilistic distribution. For example, if the type of distribution describing the parameter is uncertain, the sensitivity of the estimate to the distribution type can be analyzed by re-running the analysis with different distribution types.

2.5.3 Qualitative vs. Quantitative Risk Analysis

It is clear that general risk management in transportation asset management relies on qualitative risk analysis while risk management of estimations preferably relies on quantitative risk analysis. There is significant discussion in literature and risk management manuals regarding when each type of analysis, qualitative or quantitative, is appropriate. While the hard numbers produced by quantitative analysis initially appear preferable, quantitative analysis also has many disadvantages that may make qualitative analysis more appealing (Ashley, Diekmann, & Molenaar, 2006).

The type of risk analysis largely depends on the purpose of the risk assessment. The purpose of the risk management plans in the TAMPs is to prioritize risks and develop mitigation measures and contingency plans in response to events that are associated with high risk. While the quantitative analysis can (in theory) provide precise rankings, the qualitative analysis is sufficient and requires considerably less work. Additionally, most of the events considered by the agencies, such as loss of personnel, do not have sufficient data and records to estimate probabilities and likelihoods from, making a fully quantitative analysis highly inaccurate. This consideration extends to uncertainties in models as well. If the distributions of the variables are not well known, a fully quantitative analysis can inspire misleading confidence in the risk values and lead to poor decisions. Quantitative analyses also require many more assumptions than qualitative analyses, which leads to inaccuracy if the assumptions are not met.

However, when the goal of the risk assessment is to develop contingency costs or schedules, then a quantitative risk analysis is preferred. States such as Texas, Colorado, and Washington provide guidance on developing contingency plans and spreadsheet tools to aid in estimation, and emphasize that while quantitative analysis is inherently data-driven, it still relies on engineering judgment and expertise as well (Engineering and Regional Operations, Development Division, Design Office, SAEO, 2018; TxDOT, n.d.). Methods of estimating contingencies vary in the level of effort required and refinement of the output. If the variance of the input variables is known and the output is a simple sum or product of the input variables, then the variance of the output can be calculated directly. The three-point method is a relatively simple analytical method wherein the average estimate, an optimistic estimate, and a pessimistic estimate are produced (Harris, 2009). The statistical distribution of the estimate is not known, but in addition to a deterministic average, a range is provided. This is often sufficient for small projects. Projects on the order of 1 million USD often use Monte Carlo simulation due to the inherently more costly consequences of an incorrect estimate. Even more powerful tools include probability trees and influence diagrams or fault tree analysis (Ashley, Diekmann, & Molenaar, 2006). In these analyses, a graphic representation of different chains of events is developed. The probability of each event and consequence is required to determine the risk associated with each chain, making these data-intensive methods. However, they are widely applicable and well-suited to evaluation of assessing risks associated with technical performance.

2.6 Optimization Strategies

The last module of the proposed portal requires an optimization strategy. Formulating an optimization problem involves defining an objective function, or a set of objective functions, and a series of constraints. The objective function(s) reflects the goals of the decision-maker and is most commonly related to bridge performance and/or maintenance and repair costs in the context of bridge management. Examples of constraints include a minimum acceptable general NBI deck condition rating and a maximum yearly maintenance cost. Information from the deterioration models and life cycle cost analyses is required to optimize the system, but uncertainty is rarely incorporated as a constraint or as an objective in the problem formulation. Because trade-offs are of great interest to decision-makers, the portal will use a multi-objective optimization strategy, described in the next sub-section and Chapter 3. Other algorithms are also presented below for completeness.

2.6.1 Multi-Objective Optimization Methods

Bridge management systems often use multi-objective optimization methods to identify the maintenance strategy that will provide the best performance at the lowest cost. The most common multi-objective optimization strategy is the linear weighted sum (LWS) method, in which each objective function is assigned a weight and then summed. This changes a multi-objective problem into a single-objective problem. While intuitive and simple to execute, this method is best suited for multi-objective problems wherein the objective functions do not conflict with each other. However, in the context of bridge systems, better performance is often associated with higher costs. As a result there is a trade-off between them, which is best described by a Pareto frontier. A theoretical Pareto frontier is shown graphically in Figure 2.7 (Chircop & Zammit-Mangion, 2013). This Pareto frontier has two objective functions, μ_1 and μ_2. The values μ_1* and μ_2* represent the optimal solutions for each individual objective function, without consideration for the other. The frontier shows the series of combinations of μ_1 and μ_2 that provide optimal solutions. Multiple optimums exist because each objective function can be further optimized at the expense of the other between μ_1* and μ_2*. Any values to the left of the frontier are infeasible; values to the right of the frontier are feasible, but not optimal. The utopia point μ^u is a theoretical, non-feasible value wherein both functions are fully optimized. The Pareto frontier shown only considers two objectives, but Pareto frontiers may have n dimensions as suits the decision-maker. For instance, if a third objective minimizing the uncertainty in the estimates was to be included, then the Pareto space would be three-dimensional.

The Pareto frontier is useful in analyzing trade-offs between decisions, but can be difficult to define. The most common method of generating the Pareto frontier in bridge management systems is the ε-constraint method, which is executed by the following steps:

1. The optimal solutions for each single objective are found, independent of the other objectives but subject to all constraints.
2. All objectives except one are turned into constraints by setting them to constants. The remaining, non-constrained objective is re-optimized under the new set of constraints.
3. Step (2) is repeated for a series of constraint values until the full dimension is explored.
4. Steps (2) and (3) are repeated for each objective function.

There are various systems by which the constraint values are chosen, and some are better at creating a well-characterized Pareto frontier than others (Chircop & Zammit-Mangion, 2013). This depends to some extent on the shape and continuity of the frontier, and how the scales of the objective functions compare. A filter is often required to remove points that are not globally optimal.

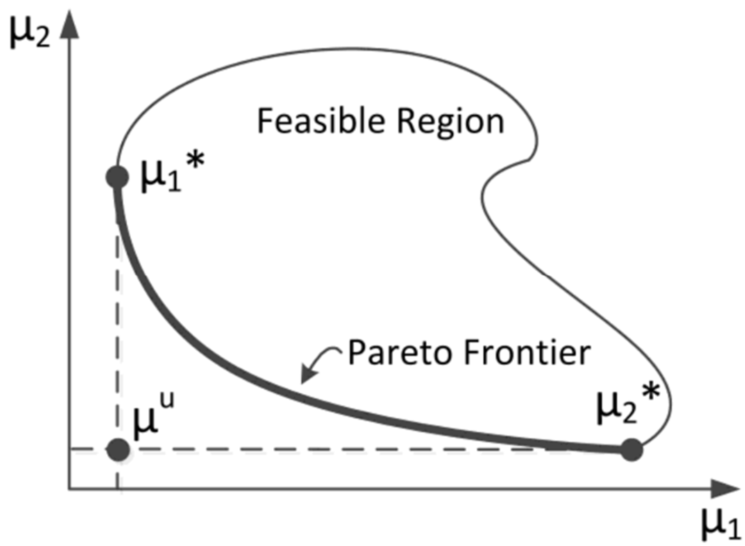


Figure 2.7. Theoretical graphical representation of a Pareto frontier between two objectives, μ_1 and μ_2 (Chircop & Zammit-Mangion, 2013).

2.6.2 Evolutionary Algorithms

Alternatively, some groups rely on evolutionary algorithms. Evolutionary algorithms are designed to mimic optimization processes used by nature, and their terminology reflects this origin. The most common evolutionary algorithms used in bridge management are genetic algorithms (GAs) and shuffled frog leaping (SFL) (Elbehairy, 2007).

In GAs, the objective function is referred to as a "fitness function", and its value is said to be the fit of a solution. The procedure begins by randomly generating a population of candidate solutions. The candidate solutions are an array of input variables and called "chromosomes." The fit for each chromosome is calculated and a probability function is used to select which chromosomes will "reproduce" based on their fitness. The parent chromosomes are crossed over by combining their array values to create the next generation of chromosomes. Each new chromosome also has a probability of experiencing mutation, wherein randomly-selected array values are changed. This reproduction process is repeated until the fitness of the population no longer changes, signaling that the algorithm has arrived at the optimal solution (Carr, 2014).

GAs can test multiple combinations of input variables simultaneously and are flexible regarding the type of data they can handle. Traditionally, the chromosomes are binary, but more recent methods have made GAs capable of using non-binary chromosomes that more directly reflect discrete and continuous variables. However, because each generation must be more fit than the previous generation, GAs can become trapped in local optima. The mutation step is incorporated to help the solution escape local optima, but the entire procedure must be re-run multiple times to improve the chances of the GA finding the global optimum.

The SFL method is similar to the GA method, but is better at exploring the global feasible space with many, locally-focused searches (Elbehairy, 2007). The SFL method begins by randomly generating a population of frogs (identified as chromosomes in a GA, and solutions in calculus-based methods). The frogs are divided evenly into groups, called "memeplexes." Each memeplex has a set of frogs with varying fits. Within each memeplex, the frog with the worst fit is identified and improved via a random evolutionary process inspired by the frog with the best fit. If the new frog is not improved compared to the original worst frog, then the evolutionary process is repeated using the frog with the best fit in the entire population. If this still fails, then an entirely new frog is randomly generated. This evolutionary cycle is repeated X times, as determined by the algorithm developer, before all the frogs are re-shuffled into a new set of memeplexes and the evolutionary procedure is repeated. This is continued until the frogs' fits no longer improve. As for GAs, because the SFL depends on chance, it must be re-run multiple times to ensure the global optimum is found.

2.6.3 Other Optimization Algorithms

Instead of an evolutionary algorithm, AASHTOWare BrM contains an optimization function that builds a Pareto frontier between system utility and cost. The utility refers to the condition rating of a system of bridges and the cost is from the maintenance and rehabilitation activities. The user can choose to optimize the utility given the budget constraints provided to the system, or minimize the cost given the required minimal utility. Additional constraints regarding the activities and projects expected to occur in the bridges' lifetimes may be selected if desired as well.

3 BRIDGE DECK PRESERVATION PORTAL FRAMEWORK

3.1 Framework Overview

This section discusses the framework of the bridge deck preservation portal (BDPP). A flowchart presenting an overview of the framework is presented in Figure 3.1. As shown in the flow chart, the portal mainly consists of five modules with sub-modules as follows:

1. User Inputs
2. Selection of Maintenance Actions
    a. Filters and Thresholds
    b. Maintenance Activity Plans
3. BDPP Algorithms
    a. Service Life Extension Estimate (SLEE)
    b. Deterioration Model (DM)
    c. Life-Cycle Cost Analysis (LCCA)
4. Optimization
5. BDPP Output

The first step is for the user to acquire all the required inputs for the portal and as many optional inputs as possible. Inputs are categorized based on whether they provide information regarding: (1) physical characteristics of the deck, (2) deck condition, (3) exposure conditions, or (4) user knowledge, preferences and constraints. The quality of the input data will directly affect the quality of the output data.

After completing all the inputs, the BDPP will use the input data to recommend specific maintenance actions to the user. The maintenance actions will be selected based on the results of four primary filters including: (1) deck type, (2) type of wearing surface, (3) type of deterioration, and (4) bridge deck condition. The user will have the option to select additional maintenance actions or remove recommended maintenance actions from analyses. Although the BDPP is designed mainly to select the most appropriate "immediate" maintenance action, conducting an appropriate life-cycle cost analysis (LCCA) requires complete analysis of all the future maintenance activities that could be completed during the considered life-cycle period. Therefore, the portal will allow addition of planned or expected actions throughout the life of the deck to construct a "Maintenance Activity Plan". This will aid in calculating a comprehensive LCCA including future maintenance actions. The user may provide a pre-determined plan or allow the BDPP to develop a plan automatically. If such actions are unknown or difficult to predict, the BDPP can still complete all the analyses with only the immediate maintenance action considered.

The third module in the BDPP includes all the data analysis algorithms. This is essentially the "brains" of the portal where the maintenance action's effect on the bridge deck is analyzed. The first algorithm is used to estimate the service life extension due to the maintenance action under consideration using one of the three different approaches described below:

- Option 1: User Input service life estimates – Experience based
- Option 2: User Input service life estimates – Mechanistic Models
- Option 3: BDPP maintenance action service life estimating algorithm

The first two approaches are optional user input while the third approach was developed specifically during this project based on a literature search of service life estimates for the different maintenance options. The literature-based service life estimate is then adjusted based on different factors, such as pre-existing conditions and/or contractor experience with the maintenance action.

Once the structure-specific service life extension is estimated, the second algorithm develops the deterioration model that describes how the deck's condition deteriorates for the remainder of its life. This model is based on the deterioration models developed for the FHWA in the LTBP program. The maintenance actions are assumed to provide service life extension by slowing the deterioration rate of the deck. An estimate of improved condition is calculated based on the original deterioration rates as well. The new deterioration model can be used to determine which follow-up maintenance action is appropriate once the original maintenance action is no longer effective. Maintenance activity plans may be built automatically in this manner such that the type of maintenance necessary and its timing are identified for the remaining life of the deck.

The third algorithm is used to calculate the life cycle cost (LCC) for the different maintenance plans considering a 100-year time period as a default. This sub-module was designed to accept input to calculate both agency and user costs. Note that default agency costs for the different maintenance actions were collected from a limited literature search. To improve the reliability of the results, the user should input their own costs associated with the different maintenance options. User costs are also included as optional input. If not inputted, the BDPP will use simplifying assumptions to estimate user costs in the LCCA.

In all the algorithms, the risk and uncertainty associated with the results of each maintenance activity plan is calculated as a variability in the estimated service life extension and life cycle costs. This is done by employing a probabilistic approach for the service life estimation as will be detailed in the later sections.

Following all the analyses, the BDPP conducts an optimization analysis to rank the different maintenance activity plans. The method selected for this optimization is the Linear Weighted Sum Method, which is one of the simplest and most widely used techniques for multi-objective optimization. The BDPP will allow the user to choose which objectives to include in the optimization, including minimizing life-cycle cost (with or without user costs), minimizing initial cost, and maximizing service life extension, and decide how to weigh the importance of each objective.

Finally, the results of the analyses will be presented to the user. The maintenance activity plans will be ranked. The expected service life benefits, life cycle and initial costs, improved general NBI deck condition rating, and variability in the service life extension and agency life cycle cost estimates will be provided for each option.

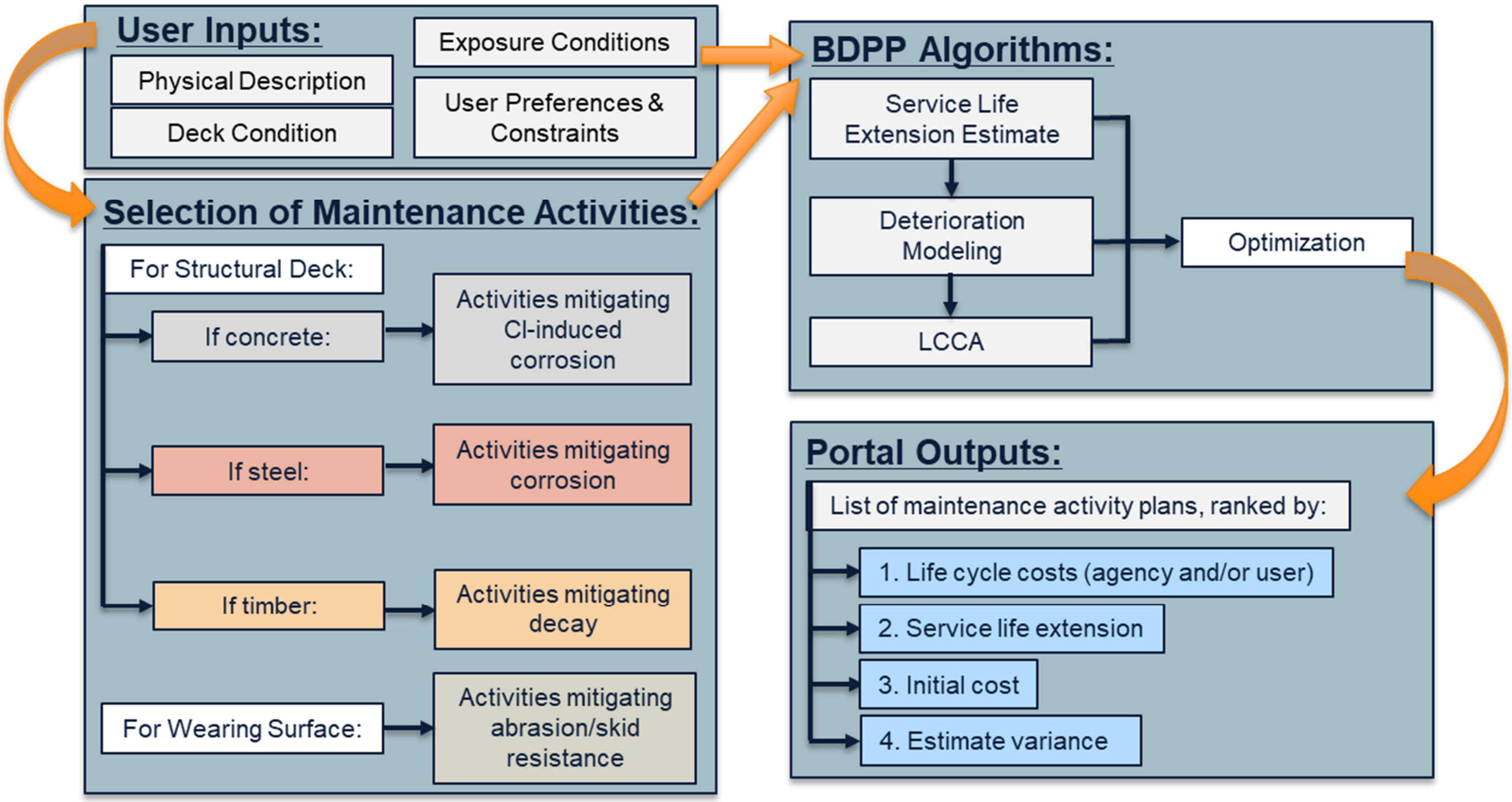


Figure 3.1. Graphic showing high-level BDPP framework overview.

3.2 Input List

This section presents the general inputs for the bridge deck. The majority of these inputs can be taken directly from bridge inspection reports, which can be input manually by the user. Alternatively, if the BDPP interfaces with a data repository used by the state or the LTBP InfoBridge, then this value may be obtained automatically from digital records. Inputs describing environmental exposure can be obtained by interfacing with NOAA and other federal agencies.

The BDPP user will have to input data regarding the (1) physical characteristics, (2) condition, and (3) exposure of the bridge deck. Most of these inputs are required, i.e., the BDPP will not work if the input is missing. The fourth input category, (4) user knowledge, preferences and constraints, is generally not required, but is highly recommended. The BDPP has default values and assumptions embedded in it for ease of use, but if more accurate data or information is available to the user, this can significantly improve the quality of the analyses. The quality of the BDPP output depends on the quality of the inputs. The optional user knowledge, preferences and constraints are intended to decrease the uncertainty and risk associated with the results.

Each of the inputs will be used in at least one of the modules to aid in the selection of the maintenance action and/or complete part of the analyses. The modules at which the inputs will be used are:

- MA: Selection of Maintenance Actions
- SLEE: Service Life Extension Estimate
- DM: Deterioration Model
- LCCA: Life Cycle Cost Analysis
- Opt: Optimization

3.2.1 Physical Description

The definitions of the inputs included in this section are shown in Table 3.1 along with the modules where each input will be used.

Table 3.1. Physical description inputs definitions.

Input	Definition	Module
Year constructed	Defines the year of deck original construction	DM
Deck structure type	The type of bridge deck is limited to CIP concrete, precast concrete panels, open steel grating, closed steel grating, steel plates, timber, and other, in accordance with the federal SA&I sheet. If the bridge is identified as "other", then the base material (concrete, steel, or timber) must be provided, even though this is not provided to the federal government. The BDPP cannot accept decks that use other materials, such as FRP	MA
Wearing surface type	The type of wearing surface is limited to monolithic concrete, integral concrete overlay, latex concrete overlay, low slump concrete overlay, epoxy overlay, bituminous overlay, wood or timber, gravel, and other, in accordance with the federal SA&I sheet	MA
Bridge length and width	Defines the deck geometric properties	LCCA

3.2.2 Deck Condition

This section presents inputs related to bridge deck condition as shown in Table 3.2. They may be categorized as general NBI data, element-level data, and in-depth inspection data. Note that only the general NBI data is required. Following modules rely on the general NBI ratings for analysis despite their generality for several reasons. First, element-level data is only required by the federal government for bridges on the national highway system and may not be available for all bridges. Second, historic element-level data is typically not available and therefore the associated deterioration models required for the service life module are not in place yet. And third, in-depth inspection data may be used for mechanistic modeling, but these models must be re-developed for each bridge, making it infeasible to embed them in the BDPP.

An '*' indicates that the input is optional.

Table 3.2. Deck condition definitions.

Input	Definition	Module
NBI deck rating	General NBI deck condition rating from the most recent inspection report, Item 58 on the SA&I sheet submitted to the federal government	MA, SLEE, DM
Historic NBI deck data	General NBI deck condition ratings from previous inspections. Not all historic data is necessary; this is to identify the years when the rating decreased	DM
Deck deterioration model	Years in which the general NBI deck condition rating is expected to decrease from its current condition to 8, 7, 6, 5, and 4 (as applicable) according to the deterioration model provided by LTBP portal or the newly developed InfoBridge portal	DM
Element-level condition data *	Element-level data for the deck and wearing surface reported in accordance with AASHTO MBEI, most recent version. Refer to Table 3.3 for the distress types considered by the BDPP	MA
Chloride content at rebar depth*	Chloride content of the concrete at the depth of the rebar, as reported by in-depth inspection. This information can be used by the user to determine if concrete cover should be removed and if partial- or full-depth repairs are necessary	MA
GPR data*	Defines the cover of reinforcement in concrete bridge decks. This information can be used by the user to determine existing cover and preferred maintenance actions	MA
Half-cell potential quantities*	Provides estimates for the percentage of the concrete bridge deck area with reinforcing steel that is probably corroding, the percentage that may be corroding, and the percentage that is likely not corroding. This can be used to refine the condition rating and determine if partial- or full-depth repairs are necessary at actively corroding areas	MA

Table 3.3. Distress types considered for decks and wearing surfaces.

Reinforced concrete deck	Prestressed concrete deck	Steel deck	Timber deck	Wearing surface
Delamination/ spall/patched area	Delamination/ spall/patched area	Corrosion	Decay/section loss	Delamination/ spall/patched area/pothole (wearing surfaces)
Exposed rebar	Exposed rebar	Cracking	Check/shake	Crack (wearing surface)
Efflorescence/rust staining	Exposed prestressing		Crack (timber)	Effectiveness (wearing surface)
Cracking (RC)	Efflorescence/rust staining		Split/delamination (timber)	
Abrasion/wear (PSC/RC)	Cracking (PSC)		Abrasion/wear (timber)	
	Abrasion/wear (PSC/RC)			

3.2.3 Exposure Conditions

This section presents inputs related to the loads experienced by the bridge deck, both vehicular and environmental. An '*' indicates that the input is optional.

Table 3.4. Exposure conditions definitions.

Input	Definition	Module
ADT and %ADTT	Average daily traffic and percent average daily truck traffic, as reported on the SA&I sheet	SLEE
Primary chloride source	Identifies the primary source of chlorides as either deicers, marine, or none. Deicers are further categorized as brines, rock salt, magnesium chlorides, and miscellaneous. If the deck has marine exposure, then the approximate distance from the shore is requested. Not reported on the SA&I but required from user	MA, SLEE
Number of annual deicing events	Number of times deicers are applied to the bridge deck each year	SLEE
Number of freeze-thaw cycles	Number of freeze-thaw cycles experienced each year	SLEE
Average temperature	Average temperature experienced at the bridge location each year	SLEE
Scheffer index*	Decay hazard measure based on the average temperature and days with precipitation in each month. Required only for timber bridges	SLEE

3.2.4 User Knowledge, Preferences and Constraints

The following inputs are almost all optional, as shown by the '*'. However, they provide context and are assumed to decrease uncertainty in the analysis. The user should provide them if they are able.

Table 3.5. User knowledge, preferences and constraints definitions.

Input	Definition	Module
Primary purpose of maintenance	Identifies whether the primary purpose of the current maintenance is to extend corrosion-controlled or decay-controlled service life, improve skid resistance, or improve ride quality	MA
Defined analysis period*	Defines the analysis period desired for LCCA. If no value provided, 100 years is assumed	LCCA
Proposed maintenance plans*	Defines pre-determined maintenance activity plans that the user would like evaluated. User must identify the maintenance actions sequentially and may provide the years in which the maintenance actions are to be completed	DM, LCCA
Contractor experience	Number of projects completed in the district historically for each maintenance activity. Determines whether the maintenance action considered is well-established or experimental	SLEE
Cost of maintenance actions*	Agency costs to conduct maintenance actions under consideration	LCCA
Service life extension*	Expected service life extension offered by each maintenance action under consideration based on the user's past experience or agency policy	DM
Construction time for maintenance action*	Expected closure time required to complete each maintenance action under consideration	LCCA
Bypass/detour length*	Detour distance users have to travel to bypass the bridge, according to SA&I sheet	LCCA
Vehicle operating costs*	Cost to users for extra mileage to their vehicles	LCCA
Traffic delay costs*	Cost to users for extra time required to travel detour	LCCA
Discount rate*	Factor used to convert future cost to present value	LCCA
Inflation*	Added cost to maintenance actions due to inflation	LCCA

3.3 Maintenance Actions

In order to select maintenance actions, the BDPP references a database of maintenance actions. A database developed based on a limited literature review is provided in Appendix B and includes the following maintenance actions as shown in Table 3.6.

Table 3.6. List of maintenance actions included in the portal.

Concrete Decks/Wearing Surfaces		Timber Decks/Wearing Surfaces	
1	Roughening the wearing surface*	13	Applying a surface preservative treatment
2	Crack sealing of concrete	14	Applying a fumigant or preservative
3	Applying a penetrating sealer	15	Stress-laminating timber decks
4	Applying a healer-sealer	16	Replacing timber planks or runners
5	Placing a polymer chip seal	Overlays[3]	
Bituminous Wearing Surfaces		17	Placing a HMA overlay
6	Crack sealing of asphalt	18	Placing a modified asphalt overlay
7	Repairing asphalt pavement	19	Placing a HMA overlay with a waterproofing membrane
8	Applying a bituminous surface treatment	20	Placing a PCC/HPC overlay
Steel Decks/Wearing Surfaces		21	Placing a SFC overlay
9	Installing studs	22	Placing a UHPC overlay
10	Painting a steel deck	23	Placing a LMC/PMC overlay
11	Metallizing a steel deck	24	Placing a VESLMC overlay
12	Replacing grid plates	25	Placing a thick polymer concrete overlay
		26	Placing a thin polymer overlay

*This may also be executed on bituminous wearing surfaces.

The above list conspicuously does not include patching/partial-depth concrete repair. While partial-depth repairs are typically required in the procedures for placing overlays on concrete decks, patching/partial depth repair is not considered an independent maintenance action that can stand by itself. This is because patching classifies as routine maintenance rather than preventive maintenance. Standalone partial-depth repairs can be used to improve deck condition by restoring ride quality and concrete integrity, but do not slow rate of deterioration or provide a service life extension. A description of partial-depth concrete repair is included in Appendix B for completion

The list also does not include cathodic protection (CP) and electrochemical chloride extraction (ECE), which may be considered on a case-by-case basis but are rarely implemented on bridge decks. Cathodic protection may be applied to the reinforcement in a concrete deck, or directly to a steel deck. However, impressed current systems are expensive and require significant maintenance, and as such they are more commonly used to protect the substructures, which are outside the scope of the bridge deck preservation portal. Sacrificial CP systems are more feasible; for example, for concrete decks, sacrificial anodes may be placed during partial-depth repairs. Steel grids may be galvanized, either by hot-dip galvanizing in the shop prior to field installation (which is not a maintenance action) or by metallizing in the field (which is included in Table 3.6). However, sacrificial CP systems are also rarely installed on bridge decks. Similarly, ECE is not typically used on bridge decks because of its expense and the need for an extended closure time. Because of the rarity of these maintenance actions for bridge decks, ECE and CP were not included in the database.

[3]Acronyms: HMA means hot-mixed asphalt, PCC means portland cement concrete, HPC means high-performance concrete, SFC means silica fume concrete, UHPC means ultra-high-performance concrete, LMC means latex-modified concrete, PMC means polymer-modified concrete, and VESLMC means very early strength latex-modified.

If a user would like to include them for consideration, they may enter these options into the database by providing a profile for each, which will be allowed by the developed portal.

A profile was developed for each of the actions in Table 3.6, which includes a description of the action and its general procedure, the user inputs that will filter it out from consideration and conditions under which it is appropriate, a default unit cost, and a discussion of expected service life and the factors controlling the life of the maintenance action. This effort is similar to NCHRP project 14-36, Proposed AASHTO Guide for Bridge Preservation Actions. One objective of NCHRP 14-36 was to develop a catalog of bridge preservation actions and in response, Hearn (2019) developed a database of action profiles containing similar information to the database found in this document. Much of the information in the proposed BDPP database, particularly relating to the thresholds used in the Filters and Thresholds module, relies on Hearn's work. However, the BDPP database is different in several ways. First, the NCHRP 14-36 database is for the entire bridge structure while the BDPP database focuses on the deck. As such, where the NCHRP 14-36 database lumps all concrete and modified-concrete overlays into one profile, the BDPP database separates them out into PCC/HPC, SFC, LMC/PMC, VESLMC, and UHPC overlays so agencies can complete a more detailed comparison. Second, because the BDPP database will be implemented in software, additional information, called "filters," that describes when the maintenance action is considered appropriate for a bridge deck has been provided. This information is generally understood by a human user of the proposed AASHTO guide and does not need to be stated, but requires explicit definition in the portal logic. Finally, the NCHRP 14-36 database provides a singular value for the service life of maintenance actions as a guideline. Because service life plays an important part in the BDPP algorithms, the BDPP profiles provide reasonable service life ranges for each maintenance action and reflect how the exposure conditions of the bridge affect the assumed service life. This information is used to provide more refined service life estimates, as discussed in Section 3.4, *BDPP Algorithms*.

This section focuses on the Filters and Thresholds module. The database only includes maintenance actions that address the degradation mechanisms identified in Section 3.3.1, *Degradation Mechanisms Considered*. Each maintenance action has a set of filters that will signal the BDPP to remove the action from consideration if they are true. This prevents inappropriate actions from being considered. Each action also has a set of thresholds below which they are deemed appropriate and recommended by the BDPP. This selection process is described in more detail in Section 3.3.2, *Filters and Thresholds*. The BDPP will move forward with analysis of the recommended maintenance actions unless the user interactively chooses a different set. The possibility of building a maintenance action plan describing the long-term maintenance of the bridge deck for use in the LCCA is discussed in Section 3.3.3, *Maintenance Activity Plan*.

3.3.1 Degradation Mechanisms Considered

There are a number of degradation mechanisms that can control the remaining life of a bridge deck. The most common ones are categorized by deck material and are briefly described below. The scope of the service life algorithm is outlined in the context of these deterioration mechanisms and the available user inputs described above. Other distress conditions affecting the bridge deck such as impact damage to concrete decks or connection damage in steel and timber decks are not covered under this scope.

Concrete decks

Chloride-induced corrosion. The service life of bridge decks located in states that use deicing salts or in marine or brackish environments is typically controlled by chloride-induced corrosion. Chlorides build up at the surface of the concrete and diffuse to the depth of the rebar over time. Corrosion begins once a sufficient concentration of chlorides builds up at the rebar depth. The time required for chlorides to reach the rebar depends on the depth of concrete cover, the permeability and mixture design of the concrete, and the amount of chloride exposure. The amount of chloride required to cause corrosion, known as the chloride threshold, depends on the mixture design of the concrete and the presence of any protective coatings on the rebar. When steel begins to corrode in concrete, the products form a naturally protective layer, called the passivating layer, that prevents moisture from reaching the intact steel underneath. Chlorides are dangerous to a natural passivating layer because they can penetrate the layer and make it easier for moisture to reach the un-corroded steel. More rebar cover, higher cement contents, decreased permeability, and the presence of a zinc galvanization layer or epoxy coating extend the time to corrosion initiation. Once corrosion has begun, rust products form and their increased volume compared to the original ferric metal exerts expansive, tensile stress on the surrounding concrete. When enough products have formed, the concrete cover can crack and eventually delaminate from the bar. Delaminations turn into spalls that expose the corroding rebar. This compromises the cross-section of the deck and the ride quality, and accelerates further deterioration if left unchecked.

Abrasion/wear. When concrete bridge decks are not exposed to chlorides, or when they contain soft aggregates that are not sufficiently abrasion-resistant and see high amounts of traffic, the service life of the deck may be controlled by abrasion or mechanical wear. This is a safety issue rather than a structural integrity concern and can be effectively treated. Abrasion will require treatment, but rarely requires bridge replacement as chloride-induced corrosion does.

Other deterioration mechanisms. Concrete can experience many other deterioration mechanisms, but most of these are relatively rare and therefore are not discussed in detail here. Two that should be noted are alkali-silica reaction (ASR) and carbonation-induced corrosion. In previous decades, bridge decks have failed due to ASR deterioration. ASR in decks occurs when alkalis in the cement paste react with reactive silica in the aggregates to form a gel. When the gel is exposed to moisture, it expands and causes cracking and strength deterioration. This can be effectively mitigated at the time of construction by using low-alkali cements and non-reactive aggregates, and as a result is not a major concern unless these materials are unavailable. Preservation actions for ASR affected decks will need to be addressed on a case-by-case basis as the deck may require replacement.

Deterioration caused by carbonation-induced corrosion is a slow process typically and rarely controls service life. However, when it occurs it is a widespread issue in the element due to decreased pH. Concrete pore solution has a high alkalinity with a pH of about 12.5. Uncoated steel in this environment forms a protective layer out of the initial corrosion products that inhibits further corrosion. However, as ambient carbon dioxide permeates into the concrete, it reacts with the paste to form calcium carbonate, which lowers the pH to about 9. The carbonation front is the depth in the concrete where the pH jumps from 9 to 12.5 within a very short distance, often over just a few millimeters. The carbonation front advances to the rebar slowly, but once it does, the steel depassivates and the protective layer dissolves. Uniform corrosion of the rebar begins and causes cracking, delaminations, and surface spalling as chloride-induced corrosion does.

It is important to understand that the service life estimation implemented by the BDPP is based on the general NBI deck condition rating, which does not distinguish between failure mechanisms. However, for concrete bridge decks, the BDPP assumes that abrasion/wear and chloride-induced corrosion control maintenance needs and service life. ASR is not considered because ASR mitigation strategies implemented after construction are relatively ineffective. Deterioration may be slowed by inhibiting moisture ingress, but there are no maintenance actions that can improve the strength of a deck experiencing ASR cracking and it is unrealistic to expect moisture-inhibiting maintenance activities to be fully effective. Therefore bridges subject to ASR degradation are better addressed on a case-by-case basis than an algorithmic approach. Finally, carbonation-induced corrosion is not considered due to its slow nature; it is assumed that bridges will need replacement due to increased traffic or other deterioration mechanisms before carbonation-induced corrosion will take effect.

Steel decks

Fatigue. The cyclic loading from traffic causes fatigue in the connections of steel decks. This is the most common cause of steel deck distress and results in cracking and unsound connections. Fatigue is of particular concern for welded, open-grid steel decks (Florida Department of Transportation). Rivets are much less susceptible to fatigue than welds, and the concrete wearing surface in closed grid steel decks provides stiffness such that the deck does not deflect as much.

Corrosion. Corrosion can be expected to occur whenever the steel is exposed to moisture. For open-grid systems which dry off quickly, section loss due to corrosion is of little concern. However, steel decks with asphalt wearing surfaces can experience accelerated corrosion if the waterproofing membrane above the deck fails and water that has permeated the wearing surface collects on the steel (Florida Department of Transportation). The presence of chlorides will accelerate the corrosion rate as well.

The BDPP considers maintenance actions that target these two deterioration mechanisms.

Timber decks

Fungal Decay. Decay is the primary mechanism of deterioration in timber bridge decks and is typically caused by fungi. There are three types that may damage the wood: stain, mold, and decay. Stain and mold fungi are relatively harmless as they stain the wood but do not compromise strength. However, they can weaken the preservative treatment and make the wood more susceptible to decay fungi. Their presence also indicates that the moisture content and temperature is suitable for decay fungi to prosper. Decay fungi are classified as brown rot, white rot, or soft rot. Brown and white rot fungi cause weight loss of about 70% and 97%, respectively, in advanced stages. Brown rot causes severe strength loss of up to 60% even in the early stages when only 1% to 5% of the weight is lost. When timber is attacked by white rot, the strength loss is roughly the same as the weight loss. Soft rot fungi does not cause much strength loss. Fungal decay can be difficult to protect against because it is difficult to detect early on. In the incipient phase, the fungi is not visible but can still cause significant strength loss. In the intermediate phase, the wood has already become discolored and/or softened and has very little strength left. Decay is considered advanced when there are voids in the wood (Ritter & Jeffrey, 1990).

Fungi and other biological agents that cause decay require sufficient water and oxygen and suitable temperatures. Temperatures between 70˚F and 85˚F are generally preferred by the biological agents, and activity slows when the temperature is below freezing or above 90˚F. The decay hazard index, commonly called the Scheffer index, indicates how favorable a local climate is for decay based on temperature and the number of days with rainfall (Carll, 2009).

Decay due to Insects. Deterioration due to insects is often considered decay as well. Termites, beetles, bees, wasps, ants, and marine borers all use wood as food and/or shelter and compromise the cross-section of the member. For bridge decks, only drywood termites, carpenter ants, and carpenter bees are assumed to be a concern. Beetles only affect freshly-cut timber and marine borers require the wood to be underwater. Most termite species require contact with soil and high levels of moisture and as such do not have access to decks. Drywood termites are the exception, as they do not build their nests in soil and prefer wood with a moisture content of only 5% to 6%. Drywood termites are confined to the southern border of the United States and along the Pacific and Atlantic coasts up to northern California and North Carolina (Ritter & Jeffrey, 1990).

Carpenter ants are present throughout the United States but are especially common in the northeastern states and in wooded areas. They prefer moist and rotting wood with moisture contents above the fiber saturation point and, therefore, their presence indicates a compound issue wherein the wood is already rotting due to fungus or bacteria, and is losing strength due to the building activities of the ants. Carpenter bees also use wood exclusively for shelter. They have a wide range that stretches across the continental United States, but infestations are not common. When they occur, damage is substantial (Ritter & Jeffrey, 1990).

Abrasion/impact. Physical deterioration of timber decks is most commonly due to tire abrasion. Tires can wear or mar the surface, thereby reducing the effective wood section.

Wood metal corrosion. This type of deterioration occurs when iron fasteners and other connectors corrode due to the presence of moisture. The relatively acidic anode and the ferric ions it releases deteriorate the wood and reduce strength severely. The moisture present also encourages fungal decay. This is a risk for timber structures with embedded iron-based components.

Other deterioration mechanisms. There are several other mechanisms by which decay or physical deterioration may occur. Bacteria colonize and decompose untreated wood in wet environments, but many can degrade preservatives and compromise the resistance of treated wood against other organisms, such as decay fungi. However, the process by which bacteria consume treated timber occurs over long periods of time, much longer than the time required for decay fungi, insects, and vehicles to affect the structure.

Physical agents include ultraviolet light and chemical attack from strong acids or bases. Chemical attack usually occurs due to accidental spills and are not systematic enough to be considered in the BDPP. Degradation due to ultraviolet light, like decay due to bacteria, takes a significantly long period of time as ultraviolet radiation only affects the top surface. The cross-section can be compromised if the affected area is frequently removed such that new, undamaged timber is exposed. This may be done by tire abrasion, but this damage is then considered abrasion/impact damage instead of ultraviolet radiation degradation (Ritter & Jeffrey, 1990).

For timber decks, the BDPP only considers maintenance actions that address deterioration due to decay fungi or abrasion, and wood metal corrosion. Insect infestations can compromise structural integrity severely, but are relatively random and difficult to predict. Long-term decay due to bacteria is considered unlikely to contribute to deterioration significantly before timber will need to be replaced due to decay fungi or abrasion.

Table 3.7 below summarizes the degradation mechanisms considered for concrete, steel, and timber bridge decks.

Table 3.7. Degradation mechanisms considered by the BDPP according to material type of bridge deck.

Concrete	Steel	Timber
Chloride-induced corrosion	Fatigue	Abrasion/impact
Abrasion/wear	Corrosion	Wood metal corrosion

3.3.2 Filters and Thresholds

The BDPP uses the following four user inputs to filter out inappropriate actions:

1. Deck structure type
2. Wearing surface type
3. General NBI deck condition
4. Primary purpose of maintenance

The first two inputs were presented in Section 3.2.1, *Physical Description*, the third was presented in Section 3.2.2, *Deck Condition*, and the fourth was presented in Section 3.2.4, *User Knowledge, Preferences and Constraints*. The deck structure type, wearing surface type, and general NBI deck condition are reported according to the FHWA Recording and Coding Guide. The deck structure and wearing surface types are used to remove maintenance actions that are inappropriate for the material and/or geometry of the bridge to be maintained. The general NBI deck condition rating and the primary purpose of the maintenance are used to remove maintenance actions that could not adequately address the type and extent of degradation.

As an example, consider a healer-sealer. Healer-sealers are typically applied to concrete with fine cracks and a high crack density in order to prevent moisture and chlorides from penetrating the concrete to underlying steel and thereby protect the steel from corrosion. The deck structure type does not matter for this maintenance action; while a healer-sealer could clearly be used on any concrete deck, it could also be used on a steel deck with a concrete wearing surface. Timber decks rarely have concrete wearing surfaces (we are aware of only one in South Dakota with a concrete wearing surface) but because it is a possibility, timber decks are not filtered out. Instead, the wearing surface type is an important filter for this action. Healer-sealers are not applicable to epoxy overlays, bituminous overlays, wood or timber, or gravel wearing surfaces. They also should only be considered when the deck is in good condition; if the deck is in fair condition, then this indicates that the deck has more advanced distress in need of repair. General NBI condition ratings of 7 to 9 indicate good condition so healer-sealers are removed from consideration if the user inputs a 5 or 6. Finally, healer-sealers are only used to extend service life. They cannot improve ride quality or skid resistance, and so if the user indicates one of these options is the primary purpose of the current maintenance, then a healer-sealer is removed from consideration. Table 3.8 provides the filters based on the four user inputs discussed for each of the maintenance actions included in the proposed database in Appendix B.

In some select scenarios, maintenance actions may have complex filters. For example, timber decks are typically constructed with planks that have been treated with an oil-based preservative. They also commonly have bituminous wearing surfaces and waterproofing membranes. However, if a bituminous overlay is placed when the deck is young, the asphalt binder and oil-based preservative on the surface of the planks tend to interact. The preservative will dissolve the binder, resulting in leakage under the deck and compromising the asphalt wearing surface. Therefore it is best practice to hold off on placing bituminous overlays on timber decks for at least two years after the deck is constructed. While not shown in Table 3.8, these complex filters are provided in the Appendix B.

Additionally, some maintenance actions have filters based on element-level condition data or in-depth inspection data. For example, for any maintenance action addressing skid resistance, there must be some level of abrasion/wear present. If none is reported, then maintenance actions that only address skid resistance should be removed. Because not every action has filters based on element-level condition data, these filters are not shown in Table 3.8. Filters based on element-level condition data are provided in Appendix B.

Once actions are filtered based on material type, general NBI condition, and the maintenance purpose, specific actions may be recommended based on the element-level condition data, specifically the type of distress or defect observed and its extent. The extent of distress above which the maintenance action is considered inappropriate is called a 'threshold' in the context of the BDPP. All element-level thresholds in the BDPP are currently based on Hearn (2019). Returning to the healer-sealer example, the thresholds considered appropriate for healer-sealers are presented in Table 3.9. The amount of delaminations/spalls/patches, efflorescence or rust staining, cracking, and abrasion/wear is limited. Note that a larger extent of cracking is permitted for reinforced concrete decks than for prestressed concrete decks. No exposed prestressing or rebar is permitted. Hearn (2019) also provides thresholds for the total amount of distress permitted for different types of decks, including reinforced concrete decks, top flanges or slabs and prestressed decks or top flanges. This implicitly excludes steel and timber decks or wearing surfaces, as the filters in the BDPP did previously. Because the filters are in place, only Hearn (2019) thresholds pertaining to specific distress types are used in the BDPP.

Table 3.8. Exclusion filters for the maintenance actions currently in the proposed database for the BDPP.

Maintenance Action	F1. Deck Structure Type - Exclude	F2. Wearing Surface Type - Exclude	F3. General NBI Deck Condition - Exclude	F4. Primary Purpose of Maintenance - Exclude
Roughening the wearing surface		Wood or timber Gravel	6 5	Extended service life
Crack sealing of concrete		Epoxy overlay Bituminous overlay Wood or timber Gravel	6 5	Improved skid resistance Improved ride quality
Applying a penetrating sealer		Latex concrete Epoxy overlay Bituminous overlay Wood or timber Gravel	6 5	Improved skid resistance Improved ride quality
Applying a healer-sealer		Epoxy overlay Bituminous overlay Wood or timber Gravel	6 5	Improved skid resistance Improved ride quality
Placing a polymer chip seal		Bituminous overlay Wood or timber Gravel	6 5	Improved ride quality Extended service life

Maintenance Action	F1. Deck Structure Type - Exclude	F2. Wearing Surface Type - Exclude	F3. General NBI Deck Condition - Exclude	F4. Primary Purpose of Maintenance - Exclude
Crack sealing of asphalt		Monolithic concrete Integral concrete Latex concrete Low slump concrete Epoxy overlay Wood or timber Gravel		Improved skid resistance
Repairing asphalt pavement		Monolithic concrete Integral concrete Latex concrete Low slump concrete Epoxy overlay Wood or timber Gravel		Improved skid resistance Extended service life
Applying a bituminous surface treatment		Monolithic concrete Integral concrete Latex concrete Low slump concrete Epoxy overlay Wood or timber Gravel		Improved ride quality
Installing studs	CIP concrete Precast concrete panels Timber	Monolithic concrete Integral concrete Latex concrete Low slump concrete Epoxy overlay Bituminous overlay Wood or timber Gravel	6 5	Extended service life Improved ride quality
Painting a steel deck	CIP concrete Precast concrete panels Timber		5	Improved ride quality Improved skid resistance
Metallizing a steel deck	CIP concrete Precast concrete panels Timber		5	Improved ride quality Improved skid resistance

Maintenance Action	F1. Deck Structure Type - Exclude	F2. Wearing Surface Type - Exclude	F3. General NBI Deck Condition - Exclude	F4. Primary Purpose of Maintenance - Exclude
Replacing grid plates	CIP concrete Precast concrete panels Closed steel grating Steel plates Timber			Improved ride quality Improved skid resistance
Applying a surface preservative treatment	CIP concrete Precast concrete panels Open steel grating Closed steel grating Steel plates		6 5	Improved ride quality Improved skid resistance
Applying a fumigant or preservative	CIP concrete Precast concrete panels Open steel grating Closed steel grating Steel plates		9 8 7	Improved ride quality Improved skid resistance
Stress-laminating timber decks	CIP concrete Precast concrete panels Open steel grating Closed steel grating Steel plates			Improved skid resistance
Replacing timber planks or runners	CIP concrete Precast concrete panels Open steel grating Closed steel grating Steel plates		6 5	
Placing a HMA overlay				Extended service life
Placing a modified asphalt overlay				
Placing a HMA overlay with a waterproofing membrane	Open steel grating			
Placing a PCC/HPC overlay	Timber			
Placing a SFC overlay	Timber			

Maintenance Action	F1. Deck Structure Type - Exclude	F2. Wearing Surface Type - Exclude	F3. General NBI Deck Condition - Exclude	F4. Primary Purpose of Maintenance - Exclude
Placing an UHPC overlay	Timber			Improved ride quality
Placing a LMC/PMC overlay	Timber			
Placing a VESLMC overlay	Open steel grating Closed steel grating Steel plates Timber			
Placing a thick polymer concrete overlay	Open steel grating Closed steel grating Steel plates Timber			
Placing a thin polymer overlay	Open steel grating Closed steel grating Steel plates Timber		6 5	Improved ride quality

Table 3.9. Thresholds for healer-sealer, as proposed by Hearn (2019).

Distress Type	Quantities			
	CS1	CS2	CS3	CS4
Delamination/spall/patch	-	< 10%	0%	0%
Efflorescence/rust staining	-	< 10%	0%	0%
Cracking (RC)	< 40%	< 20%	< 10%	0%
Cracking (PS)	< 20%	< 10%	< 5%	0%
Abrasion/wear	-	< 10%	0%	0%
Exposed PS	-	0%	0%	0%
Exposed rebar	-	0%	0%	0%

3.3.3 Maintenance Activity Plan

The Filters and Thresholds module described above rejects inappropriate maintenance actions using the filters and selects the most appropriate maintenance actions for the current condition of the bridge using the thresholds. The maintenance action is to be executed in the year of analysis, and then the bridge deck may either be left unmaintained (excluding routine maintenance) until the end of its service life or another maintenance action may be executed once the first maintenance action exhibits diminished effectiveness. Once the second maintenance action has lost its effectiveness, a third may be selected and so on. This string of maintenance actions through the life of the bridge deck is considered the maintenance activity plan.

While the primary objective of the BDPP is to evaluate which maintenance action is best to execute in the current year and subsequent maintenance actions may be of little interest to the user, developing full maintenance activity plans is important to the BDPP because of the choice to use LCCA as the cost comparison method. LCCA is best used as a comparative tool between different activities plans considered over the same time period. If an activity plan is intended to be implemented for a bridge deck, considering only initial actions may lead to non-representative life cycle costs. This is particularly important for cyclic maintenance activities, which generally have smaller unit costs than condition-based maintenance activities but need to be implemented repeatedly at shorter intervals for the full benefit to be realized. By ignoring follow-up cyclic maintenance actions, the full benefits and costs of these actions are not reflected in the LCCA and comparison between them and condition-based maintenance actions will be inaccurate. This can affect the final ranking of the actions.

Maintenance activity plans may be developed by one of two ways in the BDPP. The user may instruct the BDPP to analyze predetermined maintenance activity plans the user provides, or the user can permit the BDPP to develop maintenance activity plans automatically by cycling between the service life modules and the Filters and Thresholds module. In the first method, the BDPP does not need to engage the Filters and Thresholds module and jumps straight to calculating the service lives of the maintenance actions proposed by the user and their effects on the service life of the bridge deck.

The second method is automated and is mapped out as a flow chart in Figure 3.2. The BDPP enters the user inputs into the Filters and Thresholds module and arrives at a set of proposed maintenance actions appropriate for the bridge under consideration. Each proposed action is saved separately as the start of a unique maintenance activity plan, as shown in the yellow box in Figure 3.2. The BDPP then estimates the service life of the maintenance action using the SLEE module and the general NBI deck condition rating at the end of this period using the DM module. Using the new general NBI deck condition rating, the BDPP runs the Filters and Thresholds module again and proposes a new set of maintenance actions as the second action in the activity plan. Each of the first maintenance actions branches out into a new set of activity plans. The process is repeated until the general NBI deck condition rating reaches 4, considered the time when the deck requires rehabilitation and the preservation period is over, or end-of-service-life in the context of the BDPP. In this way, the BDPP generates multiple maintenance activity plans for LCCA.

The automated version can generate a vast number of maintenance activity plans since the number of plans is multiplied with each cycle. Because the analysis cost required to conduct LCCA of each plan is small, there is no mechanism that eliminates activity plans from further consideration at this stage. Only the few with the best rankings will be presented to the user, as described in the Optimization module.

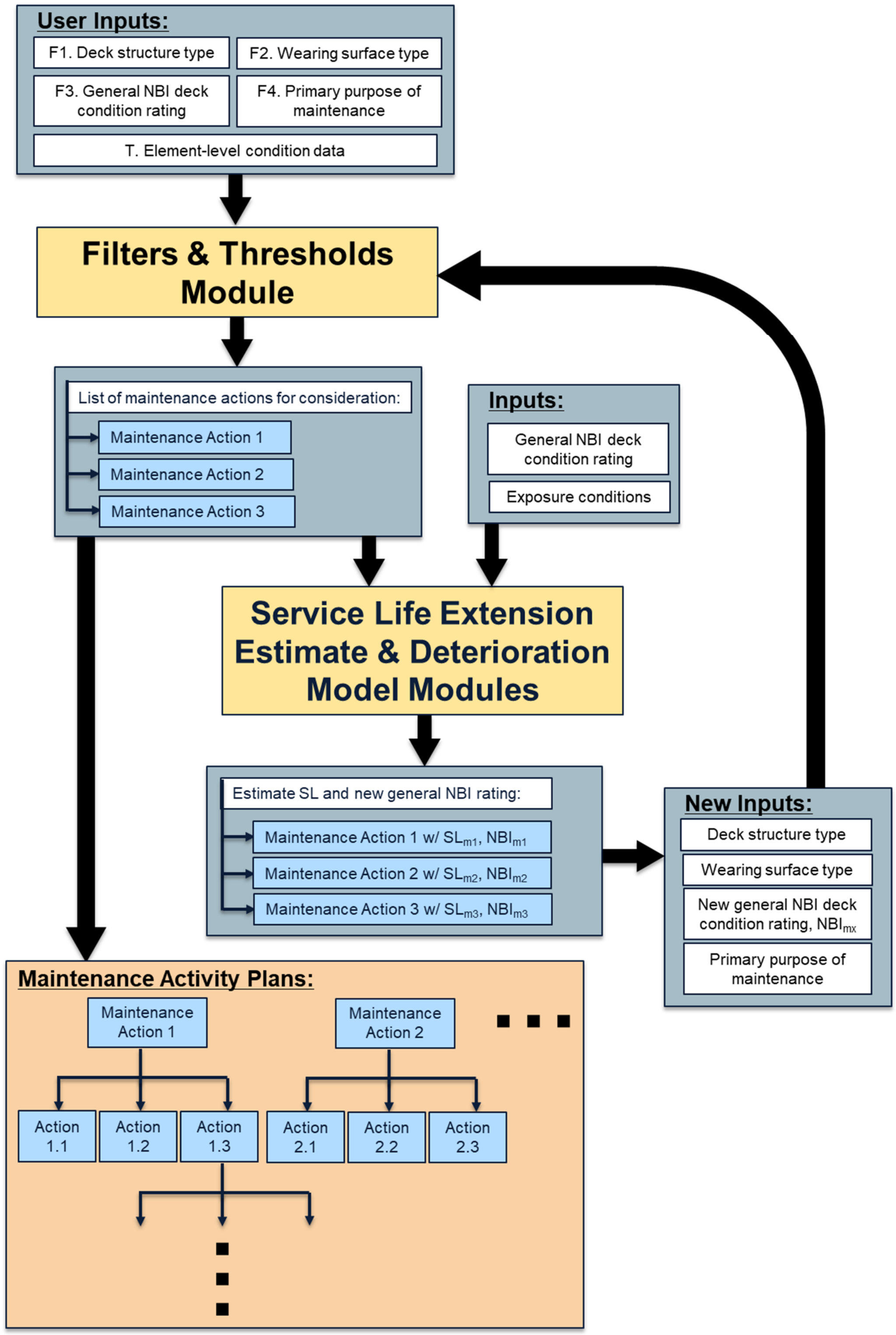


Figure 3.2. Graphic flow chart showing how the BDPP can develop maintenance activity plans automatically.

3.4 BDPP Algorithms

This section describes the calculations and assumptions embedded in the SLEE, the DM, and the LCCA modules. The SLEE module uses the user inputs describing the exposure conditions of the deck and the service life information in the action profiles to estimate how long the maintenance action will be effective. The BDPP assumes that the service life of the maintenance action is equivalent to the service life extension of the deck. The DM module uses the deterioration model information collected from the LTBP portal and determines decreased deterioration rates based on the service life extension offered by the maintenance actions. The decreased deterioration rates are applied for the extended life of the bridge deck. The DM module will additionally calculate the amount by which the general NBI deck condition rating is expected to increase based on the original deterioration rates, which is not used in further analysis but is of interest to the user. Once the DM module is complete, the full life cycle of the bridge deck will be known. The LCCA will determine the life cycle cost of the bridge based on the unit costs of the maintenance actions provided in their profiles, or input by the user. Both agency costs and user costs are considered, although agency costs are emphasized. Finally, risks associated with uncertainty in the input information are represented by probabilistic distributions. The probability density functions for the agency life cycle costs and remaining service life are determined using assumed probabilistic distributions for the exposure conditions, construction quality, and agency unit costs by Monte Carlo simulation.

3.4.1 Service Life Extension Estimate

The service life extension offered by the maintenance action may be determined by one of two ways. The user may provide the estimate, or the BDPP may determine the service life extension using its SLEE algorithm. This first method gives the user the freedom to use an estimate based on their experience. Experience-based estimates are considered more accurate than the estimate provided by the SLEE algorithm because they are unique to the region being considered whereas the SLEE algorithm uses service life estimates from across the nation and assumes a value based on the severity of the exposure conditions. Additionally, the SLEE module assumes that the service life estimate of the maintenance activity is equivalent to the service life extension it provides to the deck. This is not necessarily true, as discussed later in this subsection, and the user may consider this in their estimate. The purpose of the SLEE algorithm is to provide a default value in lieu of user input.

In general, literature contains an abundance of information on service life expectancy of the various maintenance actions. Service life is dependent on the failure mechanism, and as described in Section 3.3.1, *Degradation Mechanisms Considered*, only failure due to material degradation or due to abrasion is considered such that there are two categories of service life, an abrasion-controlled service life and a degradation-controlled service life. Actions that improve skid resistance are assumed to have an abrasion-controlled service life and actions that extend the service life of the deck are assumed to have a degradation-controlled service life. Some actions may have both. For example, roughening the wearing surface addresses skid resistance and does not protect the deck from material degradation. Therefore this action has an expected abrasion-controlled service life between 8 and 50 years. Crack sealing concrete only addresses corrosion of the underlying steel and does not improve skid resistance; as a result, this action has an expected degradation-controlled service life between 5 and 10 years. A bituminous surface treatment may be applied to seal asphalt cracks and extend the service life of underlying steel, or to renew the surface roughness and improve the skid resistance of the wearing surface. As a result, this action has an abrasion-controlled service life of 7 to 15 years and a degradation-controlled service life of 5 to 8 years. If the user indicates that the bridge deck has issues retaining skid resistance, then the BDPP will only consider abrasion-controlled service life. If the user indicates that the maintenance is to address material degradation or ride quality, then the BDPP will only consider degradation-controlled service life.

Based on a limited literature review, representative ranges that reflect common minimum and maximum expectations of service life were selected for each maintenance action and are reported in the profiles in Appendix B. A service life at the upper end of the range would be expected under favorable conditions while a service life at the lower end of the range would be expected under the most unfavorable conditions. The lower bound chosen for each maintenance action is selected based on the assumption that the maintenance action was installed or carried out such that there are no construction defects. Much shorter service lives have been reported when installation issues compromised the installation quality. For example, a thin polymer overlay may be expected to have a minimum service life of 7 years. However, they can fail after only 1 year if the surface is not prepared and dried adequately prior to installation. The BDPP would consider 7 years to be the minimum rather than 1 year.

The lower bounds for the maintenance actions were also adjusted due to the key assumption in the following Deterioration Model module that the service life of the maintenance action is equivalent to the service life extension of the deck. In practice, this requires the maintenance action to remain 100% effective for its entire life, indicating that no further deterioration takes place for the duration of the maintenance action. However, this is rarely true. As an example, a penetrating sealer typically has a service life of about 3 or 4 years but chlorides will begin to enter the concrete after the first year and the sealer's effectiveness will continue to decrease throughout the rest of its life. As another example, sealed cracks in asphalt also lose effectiveness with time and the point at which 25% of the seal has cracked (75% effectiveness) is commonly identified as the end-of-life of the seal. To prevent over-estimation of the service life extension offered by the maintenance action, particularly when the deck has a low NBI condition rating, the service life lower bounds for the actions were decreased for bridge decks of NBI ratings equal to or lower than 7, based on engineering judgment and experience, to represent the minimal expected service life extension.

The specific service life extension assumed in the BDPP is determined by multiplying the upper bound service life by a set of reduction factors representing the exposure conditions, current deck condition, and contractor experience, as shown in Equation 3.1. Note that the assumed service life extension cannot be less than the lower bound.

$$SLE_{ma} = max\{SLE_{upb} * f_{ADTT} * f_{Cl-} * f_{pec} * f_{FT} * f_{exp} * f_{Sch} * f_{temp} * f_{RH} \text{ , } SLE_{lob}\} \quad \text{Eq. (3.1)}$$

Where:
SLE_{ma} = the assumed service life extension offered by the maintenance action,
SLE_{upb} = the upper bound considered possible for the service life extension,
f_{ADTT} = the reduction factor associated with traffic loads,
f_{Cl-} = the reduction factor associated with chloride exposure,
f_{pec} = the reduction factor associated with the pre-existing condition of the deck,
f_{FT} = the reduction factor associated with the number of freeze-thaw cycles experienced by the deck,
f_{exp} = the reduction factor associated with the experience of the contractor,
f_{Sch} = the reduction factor associated with the Scheffer index,
f_{temp} = the reduction factor associated with the average temperature,
f_{RH} = the reduction factor associated with the average relative humidity,
SLE_{lob} = the lower bound considered possible for the service life extension.

Note that not all the factors will affect the service life of each maintenance action. If the exposure condition has no effect on the service life (e.g. average temperature will have little impact on the life of a PCC overlay) then the factor is 1.0 so that it does not modify the predicted service life of the maintenance activity. If the exposure condition does affect the service life, then the factor will be decreased with increasing severity. For example, because asphalt overlays are subject to fatigue on steel bridge decks, their service life is expected to decrease with increasing ADT. The service life estimated by this method is not permitted to be lower than the lower bound of the representative range identified in literature or adjusted ranges for decks with lower NBI ratings as described previously. The assumed minimum service life and maximum service life and the factors applicable to each of the maintenance actions included in Appendix B are presented in Table 3.10 and Table 3.11.

If the reduction factor does control the service life of the maintenance action, the exposure is categorized as either low, medium, or high. The definitions for low, medium, and high exposure for each factor and the corresponding values are provided in Table 3.12 and discussed below.

ADTT. An average daily traffic (ADT) count of 50,000 vehicles is considered very high while an ADT of 5,000 is considered moderate or low (Williamson, Weyers, Brown, & Sprinkel, 2007). Percentage of ADTT typically varies from 8% to 12%. Assuming about 10% truck traffic, an ADTT of at least 5,000 trucks would then classify has high exposure and an ADTT of 500 trucks or less would classify as low exposure. This is calculated by multiplying the ADT by the percent ADTT.

Chloride. Chloride exposure is assumed to be low if there are no chlorides or if deicers are rarely used. Areas with less than 5 annual deicing events are assumed to have such infrequent salt application that it would take a long time for chlorides to reach the rebar and build up to a concentration required to cause corrosion. Areas that experience at least 20 annual deicing events presumably lay brine solutions or other deicers frequently enough that chlorides build up and diffuse to the steel quickly and exposure is assumed to be relatively severe for these conditions. While the type of deicing agent is requested by in the user inputs, it is currently not considered in the reduction factors. Further refinement based on the aggressiveness of the deicing agents may be incorporated in future iterations of the BDPP.

Pre-existing, general NBI condition. Repairs generally last longer when the bridge is in good condition. When corrosion, decay, or other material degradation has begun, the resulting distress is observed both in the bridge deck and the repair. Rather than identifying low, medium, and high "exposure" categories, each possible general NBI deck condition rating (9, 8, 7, 6, and 5) has its own corresponding value for the reduction factor. If the deck has a rating of 5, then rehabilitation is considered an alternative option to maintenance. Therefore a rating of 5 is considered "high exposure", i.e., the shortest service life.

Average temperature. Average temperatures in the United States vary from under 32˚F to over 70˚F. The temperature reduction factor applies only to maintenance of steel, and therefore indicates corrosion rate. Corrosion cannot progress if the concrete has frozen due to the absence of an electrolyte. Therefore locations that spend a large amount of time below freezing (assumed to be areas with an annual average temperature less than 45˚F) are assumed to have low exposure. Areas with an average annual temperature of at least 60˚F are assumed to represent the most severe exposure found in the United States and therefore classify as high exposure.

Average relative humidity. Relative humidity varies in the states from very low in the southwest (less than 25%) to very high along the east coast (greater than 70%). In the absence of pollution and chlorides, steel is susceptible to corrosion when the relative humidity is above 80%, which indicates when the steel is wet. Because pollutants are generally present, high exposure is classified as a relative humidity of at least 70%. An average RH of less than 35% is assumed to be low exposure.

Scheffer index. The Scheffer index is used exclusively when determining the service life of timber and timber repairs. It is calculated using the average temperatures and days of rainfall of each month. Higher Scheffer indices indicate a greater potential for decay (higher temperatures and more rainfall) and vice versa. Based on data from 1971 to 2000 (Carll, 2009), Scheffer indices less than 35 are prevalent in most of the western half of the United States, excluding the Pacific coast, which reaches indices of about 60. The southeast states typically have an index ranging from 65 to 100 and the tip of Florida reaches a Scheffer index of 150. The Midwest and northeast states generally have indices ranging from 35 to 65. Based on these distributions, a Scheffer index less than 30 is assumed to be low exposure and a Scheffer index greater than 55 is assumed to be high exposure.

Number of freeze-thaw cycles. This factor is primarily applied to asphaltic repairs. The annual average number of freeze-thaw days (wherein each day is expected to correspond to one cycle) experienced in the United States varies from under 25 to over 150 (Haley, 2011). The southern states generally see no more than 75 cycles annually while the northern states typically experience 75 to 125 cycles. Western states such as Montana, Idaho, Wyoming, Colorado, and New Mexico have areas that experience 150 to 250 cycles each year. As a result, low exposure is assumed to be areas with less than 25 annual cycles while high exposure is assumed to be areas with at least 100 cycles each year.

Contractor experience risk. The surface preparation, installation procedure, and environmental conditions during installation all affect the installation quality and therefore the service life. It is assumed that contractors that have completed the proposed maintenance previously are better able to accommodate environmental challenges and are more likely to provide high quality due to their past experience. Therefore contractors that have completed at least 5 similar projects correlate to "low exposure" while contractors that have completed only 1 similar project or no similar projects correlate to "high exposure".

The impact of these exposures and conditions vary due to reliance on generalized or simplified information and uncertainty in future conditions. Therefore statistical distributions have been developed for the BDPP to account for this variance. The reduction factors have been described with triangular probability distributions rather than deterministic values. When the maintenance action's service life is being estimated, values for each factor are selected randomly from the described distributions. These distributions are defined by a minimum possible value X_{min}, the maximum possible value X_{max}, and the most likely value X_{mode}, as shown in Figure 3.3. The assumed distributions are described in Table 3.12 and Figure 3.4 shows the distributions for the ADTT reduction factor graphically. Repeated random sampling from these distributions is performed through the implementation of Monte Carlo Simulations to obtain service life estimates. This process is described further in Section 3.4.4, *Risk and Uncertainty*.

Table 3.10. Reduction factors that control abrasion-controlled service life for maintenance actions that address skid resistance.

Maintenance Action	ADTT	Chloride	No. of F-T cycles	Contractor experience	Min. Expected SL (yrs.)**	Max. Expected SL (yrs.)
Roughening the Wearing Surface	X		X	X	8	25
Installing Studs	X	X		X	*	*
Applying a Bituminous Surface Treatment	X			X	5	10
Placing a HMA Overlay	X		X	X	5	15
Placing a Modified Asphalt Overlay	X		X	X	10	15
Placing a Thick Polymer Concrete Overlay	X			X	7	25
Placing a Thin Polymer Overlay	X			X	7	15
Placing a Polymer Chip Seal	X			X	7	15
Replacing Timber Planks or Runners	X			X	*	*

*Reviewed literature did not provide sufficient information to estimate service life for this action.
**Min. expected life should be lowered with general NBI bridge deck ratings equal to or lower than 7. Refer to Appendix B.

Table 3.11. Reduction factors that control degradation-controlled service life for maintenance actions that extend service life and/or address ride quality.

Maintenance Action	ADTT	Chloride	Pre-existing general NBI condition	Scheffer index	No. of F-T cycles	Avg. temp.	Avg. relative humidity	Contractor Experience	Min. Expected SL (yrs.)**	Max. Expected SL (yrs.)
Crack Sealing of Concrete			X		X			X	5	10
Crack Sealing of Asphalt	X		X		X			X	3	7
Applying a Penetrating Sealer	X							X	3	6
Applying a Healer-Sealer	X		X		X			X	5	10
Repairing Asphalt Pavement	X		X		X			X	2	7
Applying a Bituminous Surface Treatment	X		X		X			X	5	8
Applying a Surface Preservative Treatment							X	X	3	5
Installing a Fumigant or Preservative			X	X				X	*	*
Painting a Steel Deck (underside)		X			X	X	X	X	15	30
Metallizing a Steel Deck (underside)		X				X	X	X	15	30
Placing a HMA Overlay		X	X					X	5	15
Placing a Modified Asphalt Overlay		X	X					X	10	15
Placing a HMA Overlay with a Waterproofing Membrane	X	X	X					X	10	20
Placing a PCC/HPC Overlay		X	X					X	10	30
Placing a SFC Overlay		X	X					X	15	30
Placing an UHPC Overlay			X					X	*	*
Placing a LMC/PMC Overlay		X	X					X	15	30

Maintenance Action	ADTT	Chloride	Pre-existing general NBI condition	Scheffer index	No. of F-T cycles	Avg. temp.	Avg. relative humidity	Contractor Experience	Min. Expected SL (yrs.)**	Max. Expected SL (yrs.)
Placing a VESLMC Overlay		X	X					X	15	30
Placing a Thick Polymer Concrete Overlay			X					X	15	25
Placing a Thin Polymer Overlay	X		X					X	7	20
Replacing Grid Plates	X	X				X	X	X	18	30
Replacing Timber Planks or Runners				X				X	15	30
Stress-Laminating Timber Decks	X		X	X				X	*	*

*Reviewed literature did not provide sufficient information to estimate service life for this action.

**Min. expected life should be lowered with general NBI bridge deck ratings equal to or lower than 7. Refer to Appendix B.

Table 3.12. Definitions for low, medium, and high exposure associated with each reduction factor.

FACTOR	Exposure	Exposure Description	X_{min}	X_{mode}	X_{max}
ADTT	Low	Less than 100	0.95	1.0	1.0
	Medium	Between 100 and 5,000	0.8	0.9	1.0
	High	More than 5,000	0.6	0.8	1.0
Chloride	Low	No chlorides, or Deicers and < 5 annual deicing events	1.0	1.0	1.0
	Medium	Marine, or Deicers and 5 < annual deicing events < 20	0.8	0.9	1.0
	High	Deicers and > 20 annual deicing events	0.7	0.8	0.9
Pre-existing general NBI condition	--	9	1.0	1.0	1.0
		8	0.90	0.95	1.0
		7	0.70	0.80	0.90
		6	0.55	0.65	0.75
		5	0.50	0.55	0.65
Average Temperature	Low	Less than 45˚F	0.9	1.0	1.0
	Medium	Between 45˚F and 60˚F	0.8	0.9	1.0
	High	Greater than 60˚F	0.7	0.8	0.9
Average RH	Low	Less than 35%	0.95	1.0	1.0
	Medium	Between 35% and 70%	0.9	0.95	1.0
	High	More than 70%	0.8	0.9	0.95
Scheffer Index	Low	Less than 30	1.0	1.0	1.0
	Medium	Between 30 and 55	0.8	0.9	1.0
	High	More than 55	0.7	0.8	0.9
No. of F-T Cycles	Low	Less than 25 per year	1.0	1.0	1.0
	Medium	Between 25 and 100 per year	0.8	0.9	1.0
	High	More than 100 per year	0.7	0.8	1.0
Contractor Experience Risk	Low	Has completed at least 5 similar projects	0.95	1.0	1.0
	Medium	Has completed between 2 and 5 similar projects	0.8	0.9	1.0
	High	Has completed 0 or 1 similar projects	0.7	0.8	1.0

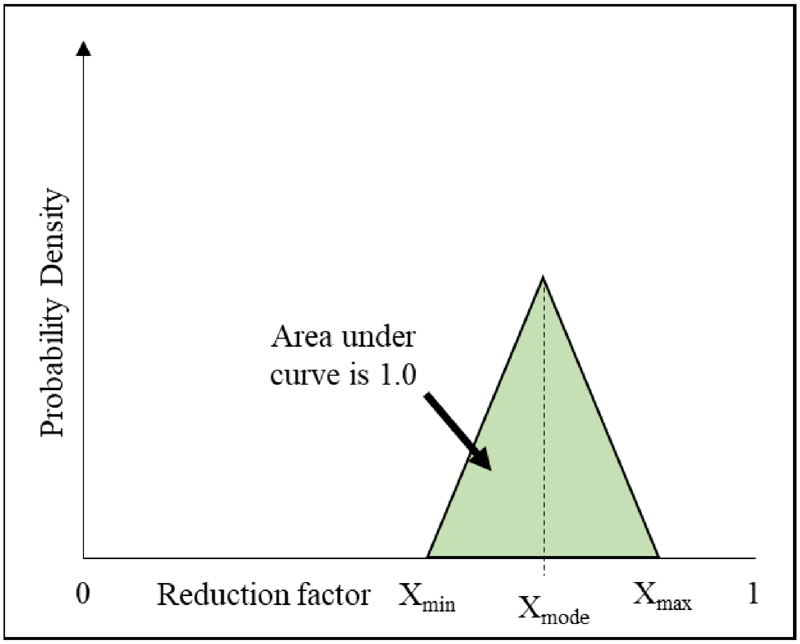


Figure 3.3. Nomenclature of a triangular distribution used to describe a reduction factor. The distribution does not need to be symmetric.

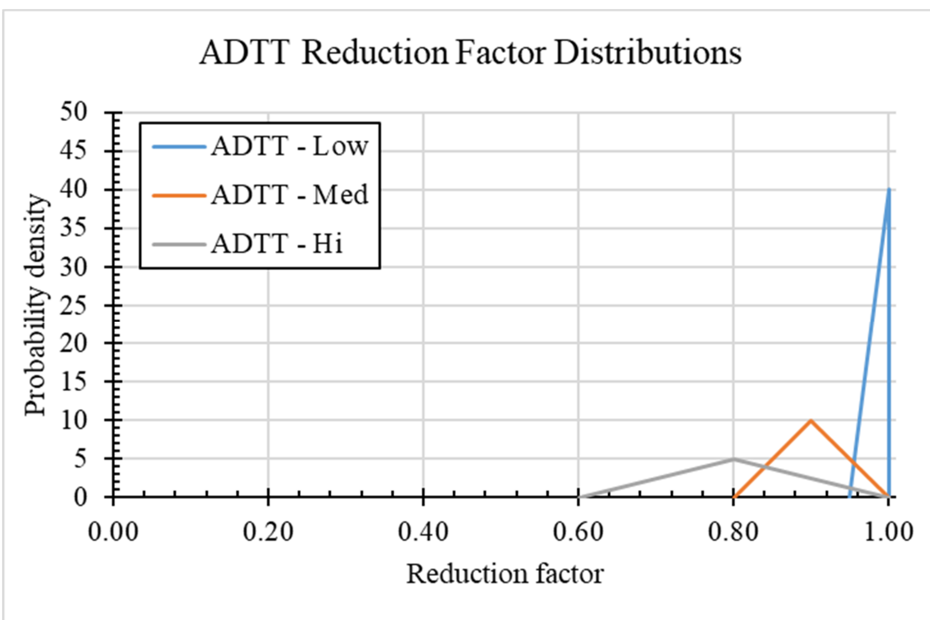


Figure 3.4. Triangular probability distributions describing the reduction factors for low, medium, and high exposure associated with ADTT.

3.4.2 Deterioration Model

The purpose of this algorithm is to provide an estimate of the time until rehabilitation is needed given the current condition of the bridge deck and the maintenance activity plan under consideration. For the purpose of this report and in the context of the BDPP, "time until rehabilitation" is considered equivalent to "end of service life." This is not strictly true as service life does not end until the bridge deck is replaced. Replacement most typically occurs once the bridge deck has a general NBI condition rating of 4 or less. Decks are often rehabilitated when the deck has a general NBI condition rating of 4 or 5 until the entire bridge is replaced. However, because the BDPP is focused on preventive maintenance, extensive rehabilitation actions and replacement are not considered.

Please note that since the element level ratings are relatively new, the majority of the bridge inventories do not include historic data or if they do, the element-level data does not use the same scale and vocabulary as specified by AASHTO's latest Manual of Bridge Element Inspection (MBEI). As such, while the element level rating can be used for filtering maintenance activities, only general NBI ratings are used for deterioration models and improved condition estimation. This approach is further explained in the next sections.

Failure Criterion

Service life is considered to end under the following failure criterion:

$$\boldsymbol{NBI\ Deck\ rating\ \leq\ 4.0}$$

When the general NBI deck condition rating drops to 4, it is assumed that extensive rehabilitation or replacement is required. This is slightly conservative as rehabilitation and condition-based maintenance are not entirely clear-cut and rehabilitation may be considered if the general NBI deck condition rating is 5 or 6. Many of the maintenance actions overlap. For example, a concrete overlay would be considered condition-based maintenance if a small portion of the deck is spalling, but rehabilitation if a large area of the deck is experiencing spalling. The best distinguishing factor is the scale and cost of the activity rather than the type of activity.

By this reasoning, element-level condition data are more suitable for setting failure criteria. As discussed in Section 3.3.2, *Filters and Thresholds*, Hearn (2019) uses element-level condition data to set thresholds determining when specific maintenance actions are considered appropriate. The thresholds recommended for rehabilitation are presented in Table 3.13 and Table 3.14. They are categorized by deck type in Table 3.13 and by distress type for concrete bridge decks in Table 3.14.

Table 3.13. Ranges of element-level condition data for which rehabilitation of concrete decks is suggested, based on deck type (Hearn, 2019).

NBE Elements	CS1	CS2	CS3	CS4
12 - RC Deck	No limit	< 40%	< 20%	< 10%
16 - RC Top Flange	No limit	< 40%	< 20%	< 10%
38 - RC Slab	No limit	< 40%	< 20%	< 10%

Table 3.14. Ranges of element-level condition data for which rehabilitation of concrete decks is suggested, based on distress type (Hearn, 2019).

Defect	CS1	CS2	CS3	CS4
1080 - Delam/Spall/Patch	No limit	< 40%	< 20%	10%
1090 - Exposed Rebar	No limit	< 40%	< 20%	10%
1100 - Exposed Prestressing	No limit	< 20%	< 10%	5%
1110 - Cracking (PSC)	< 30%	< 20%	< 10%	5%
1120 - Efflor/Rust Staining	No limit	< 40%	< 20%	10%
1130 - Cracking (RC and Other)	No limit	< 40%	< 20%	10%
1190 - Abrasion/Wear (PSC/RC)	No limit	< 40%	< 20%	10%

Use of element-level condition data is especially beneficial when considering service life because it can distinguish between the end of abrasion-controlled service life and the end of corrosion-controlled service life, and the other deterioration mechanisms discussed previously. However, predictive deterioration models using element-level condition data as input currently are not widespread and, therefore, element-level condition data is currently unsuitable for use in the algorithm.

Modeling Bridge Deck Deterioration

The purpose of the DM module is to model how the maintenance changes the deterioration of the bridge deck. This subsection walks through the calculation steps used to develop the new model and provides a graphic example.

As described in Section 3.2.2, *Deck Condition*, the expected deterioration of the bridge deck without maintenance is input by the user. Using the LTBP InfoBridge portal, the BDPP collects the time at which the general NBI deck condition rating is expected to decrease to 8, then 7, then 6, then 5, and finally 4, depending on the starting general NBI condition rating of the bridge. These values have a high level of uncertainty, particularly as the rating decreases. Alternatively, the user may provide more accurate estimates from mechanistic or other models. In this scenario, because mechanistic models do not express deterioration in terms of the general NBI deck condition rating, the user and the modeler would need to decide what damaged condition is synonymous to a general NBI deck condition rating of 4. They may additionally correlate damaged conditions as described by the mechanistic model to the rest of the other general condition ratings and input the times to the equivalent damage conditions to describe the deterioration curve. Input from a mechanistic model is assumed to be more precise than the deterioration models collected from the LTBP portal.

The algorithm knows the current condition and age of the structure, the estimated times at which the general NBI deck condition rating will drop, and the estimated remaining service life assuming no maintenance (time at which the general NBI deck condition rating will become 4). These points form the dashed lines in Figure 3.5, which represent the deterioration from the current condition to the end of service life assumed by the BDPP. A theoretical deterioration curve is shown for comparison in Figure 3.5. The expected general NBI deck condition ratings are shown as well as a reminder that general NBI deck condition rating is a discrete scale in practice, not a continuous scale as implied by the theoretical deterioration curve and the assumed deterioration lines. The assumption of linear deterioration rates between general NBI condition ratings approximates the deterioration adequately for the purpose of this algorithm.

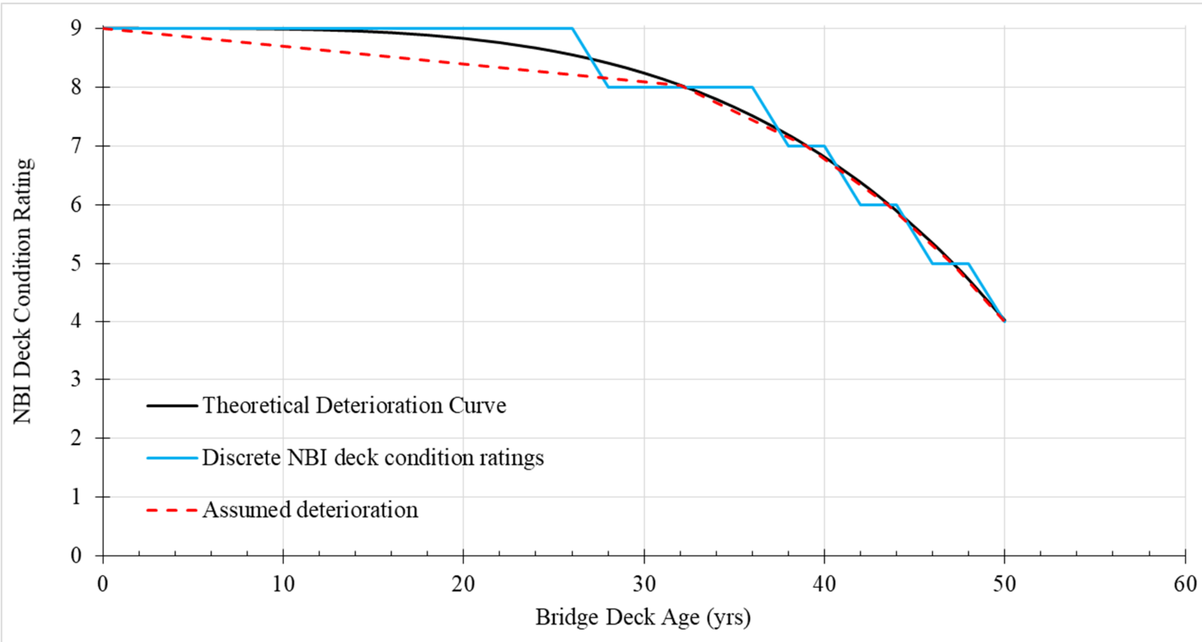


Figure 3.5. Theoretical bridge deck deterioration patterns.

The BDPP must consider how a maintenance activity plan affects this deterioration. Maintenance actions may extend service life by improving the current condition of the structure and/or slowing the deterioration rate of the structure. Ideally, the precise increase in general NBI deck condition rating and the new deterioration rate would be known, which would permit the effects of the maintenance activities to be plotted as a piecewise function on the deterioration curve shown.

However, this is not a feasible path moving forward for several reasons. Accurate deterioration rates associated with specific maintenance actions are not known and would require significant effort from the state DOTs to obtain.

In the absence of deterioration rate data, many deterioration models represent maintenance activities simply by improving the general NBI condition rating by a set amount according to the type of activity. The deterioration is then assumed to continue at the same rate as if the curve had been shifted to the right, as demonstrated in Figure 3.6. The assumption that the maintenance does not change the deterioration rate is a simplification of actual processes. If the maintenance is applied early in the life of the structure, the deterioration rate of the maintained bridge will be slower. Additionally, the amount by which to increase the general NBI condition rating for each maintenance activity is difficult to determine, especially for maintenance activities that extend life purely by slowing deterioration rate. For example, some states consider a deck that has been repaired to have returned to condition 9, the as-built condition. However, others suggest that the deck can never return to a condition of 9 and that once deterioration has begun, the maximum general NBI condition rating after repairs may be an 8. Or, the increase in general condition rating may be back-calculated based on the service life extensions experienced in the field. For example, one study calculated the average increase in general NBI deck condition rating for a variety of deck maintenance activities based on a survey of state DOTs (Hong & Hastak, 2007). However, the work done so far is relatively coarse. These values do not consider pre-existing conditions or reflect geographical trends, and they are based on experience-based estimates.

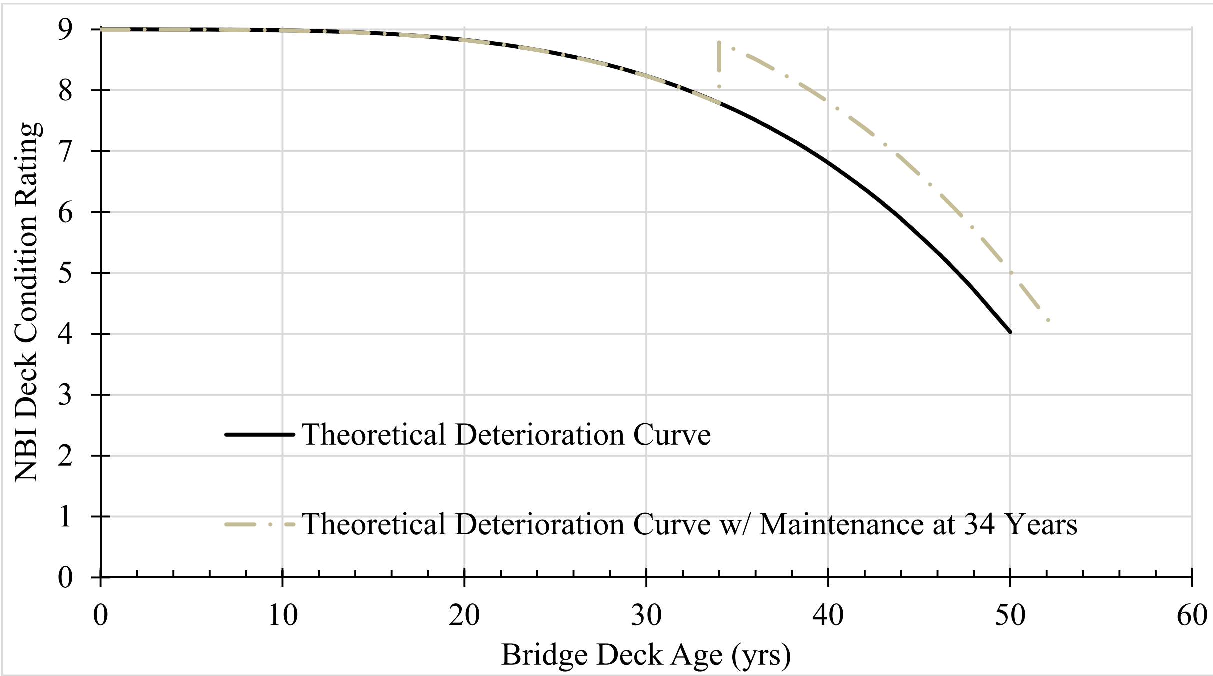


Figure 3.6. Example of a common method of calculating service life extension of a maintenance activity using a deterioration model.

For the BDPP, it was determined that the following method provides the most reasonable description of deterioration. Consider the deck shown in Figure 3.7. The current condition of the deck is NBI = 8 at initial time T_i of 32 years, the estimated end of service life $T_{f,0}$ is 50 years, and the deck is expected to experience deterioration rates of m_{87} between general NBI deck condition ratings 8 and 7, m_{76} between general NBI deck condition ratings 7 and 6, m_{65} between general NBI deck condition ratings 6 and 5, and m_{54} between general NBI deck condition ratings 5 and 4.

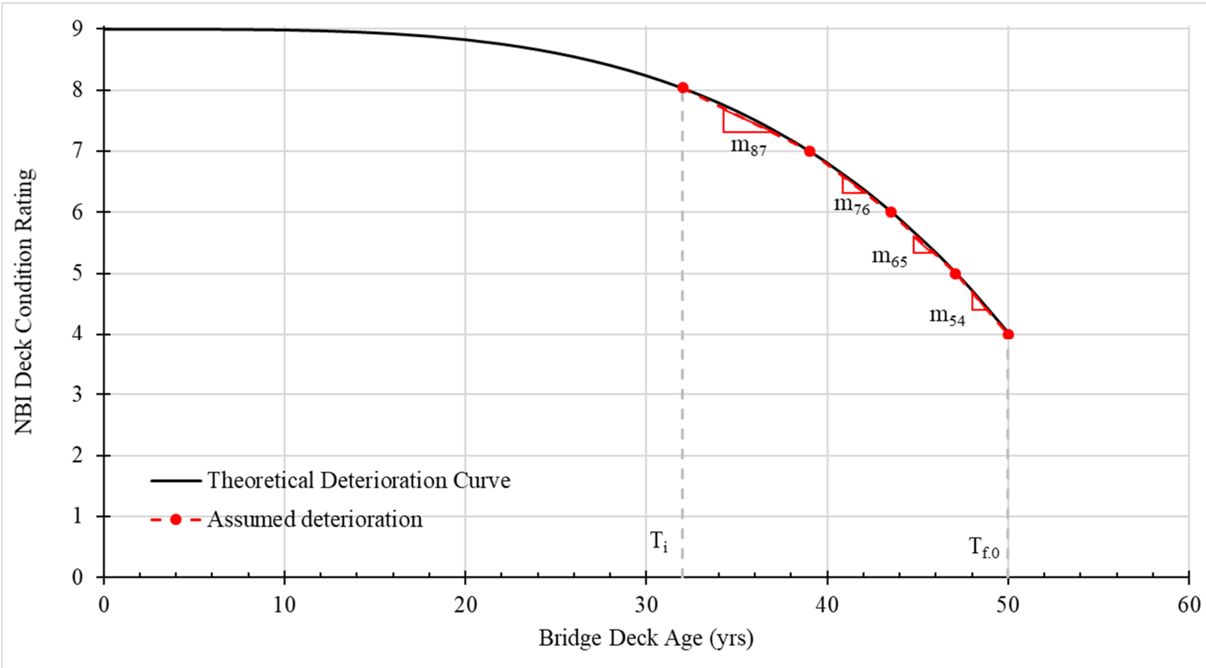


Figure 3.7. Definitions of parameters describing the deterioration of a bridge deck.

Now consider a maintenance activity (Activity 1) is selected and the associated service life extension of the activity is T_1. In order to describe the new deterioration model, the maintenance activity is assumed to decrease the deterioration rate. The new set of deterioration rates $m_{ij,n}$ are calculated according to Equation 3.2:

$$m_{ij,n} = \frac{m_{C1}}{m_{net}} m_{ij} \quad \text{Eq. (3.2)}$$

$$i = 9, 8, 7, 6, 5$$
$$j = i - 1$$

The indices i and j define which rate is being modified. Slopes m_{C1} and m_{net} are defined as shown in Figure 3.8. Slope m_{net} is defined as the net deterioration rate between the current condition and end-of-life. The service life extension offered by Activity 1, T_1, is added to the initial estimate of time of end-of-life, $T_{f,0}$, to get a new net deterioration rate m_{C1}. The ratio of the new net rate to the original net rate is applied to all the original deterioration rates for the remaining life of the bridge deck. This results in the new deterioration curve shown in Figure 3.9.

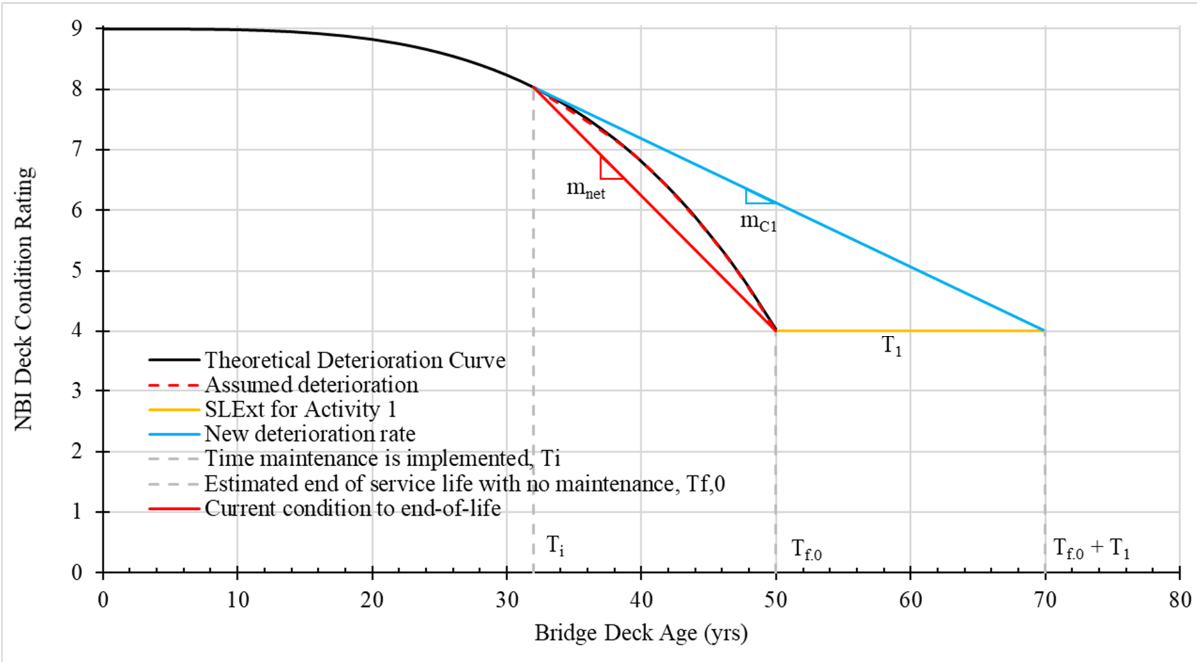


Figure 3.8. Definitions of the net deterioration rate m_{net} and the adjusted net deterioration rate m_{C1}.

Currently, the first maintenance activity in the plan is of primary concern to the user. However, as discussed in Section 3.3.3, *Maintenance Activity Plan*, users may wish to evaluate a sequence of activities if they are considering cyclical actions, such as healer-sealers, which are most effective when applied every 3 to 5 years. Additionally, because the BDPP compares the alternatives using life cycle cost analysis, consideration of likely maintenance activity plans through the full life of the bridge deck may reveal additional long-term benefits or costs. If the user wishes to evaluate a sequence of activities, this same calculation procedure may be used for each activity. If the activity is number n in the sequence defined by the activity plan, then new deterioration rates $m_{i,j,n}$ and a new service life $T_{f,n}$ are calculated using the previous rates $m_{ij,(n-1)}$ and assuming the "current year" is now the year describing end-of-life of the previous maintenance activity (n-1). When building maintenance activity plans automatically, the BDPP assumes that subsequent maintenance actions will be applied only when the previous maintenance action has reached the end of its service life. This was shown in Figure 3.2.

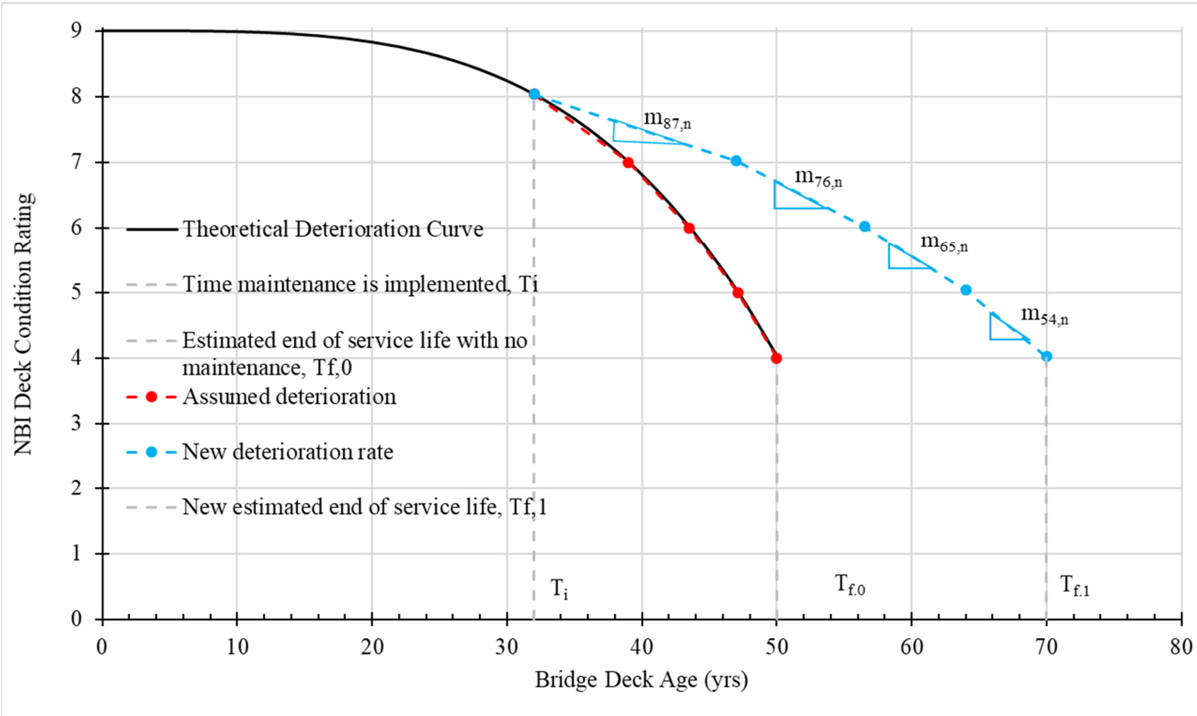


Figure 3.9. Assumed deterioration curve after maintenance activity 1 is applied, based on the calculations and assumptions of the BDPP.

While the BDPP does not use improvements in general NBI condition rating in further analysis, this improvement is still of interest to users. It may be used in other deterioration models or may play a role in the user's choice, if improved condition is a priority. Therefore, in addition to presenting a new deterioration model that shows slowed deterioration rates, the BDPP provides an estimate of condition improvement.

The BDPP back-calculates the improved condition rating using the original deterioration rates m_{ij} as identified in Equation 3.2. It assumes that deterioration rate m_{ij} applies for as long as the condition rating is between indices i and j. If the condition increases above 9, then a rate of m_{98} is assumed. The result is shown graphically in Figure 3.10 using the same example as was used to demonstrate the deterioration model development. The back-calculation provided a new general NBI deck condition rating of 8.63 after the maintenance is executed, resulting in an improvement of 0.63. It is noted that NBI ratings are presented as integer numbers, however, this value represents theoretical improvement offered by the maintenance action, as a comparative means to aid in decision making.

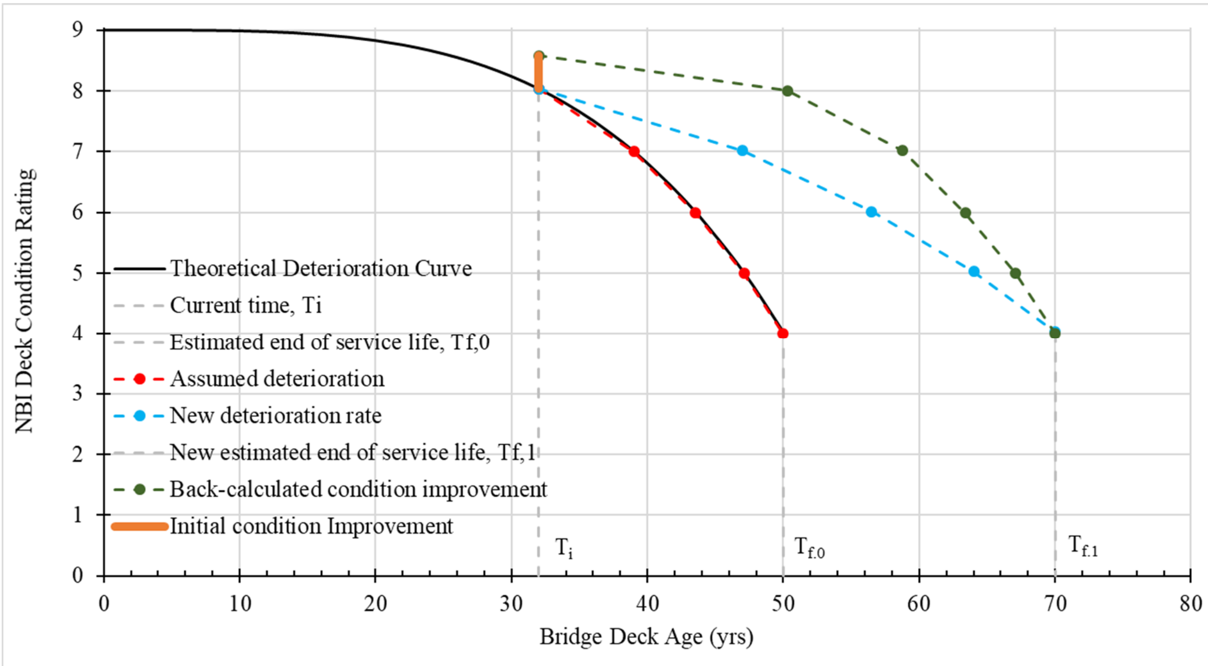


Figure 3.10. Demonstration of calculation of improvement in general NBI deck condition rating.

Discussion of the Service Life Algorithms

In summary, the SLEE module provides the estimated service life extension offered by the proposed maintenance, which is reported directly to the user, used to rank the proposals in the Optimization module, and provided as input to the LCCA module. The DM module develops the new deterioration model of the maintained deck, which is used to develop suitable maintenance activity plans and provide an estimate of improved general NBI condition to the user (although this will not be used in the Optimization module). The method by which these outputs are developed has some drawbacks, but was chosen because it is advantageous in the following ways:

Adaptability. When simplifying assumptions do not adequately distinguish between cases, algorithms are susceptible to consistently choosing a favored option above all others regardless of the input. The use of the reduction factors is one safeguard against this. If a national average or a probability distribution of service lives based on a national dataset were to be used, then all bridges would receive the same benefits from each maintenance action. This would lead to the systematic favoring of maintenance actions with long service life extensions and small costs, regardless of the exposure and deck conditions. However, by incorporating the reduction factors, the BDPP can capture bridge-specific conditions which may affect the relative service life extensions of the maintenance actions considered and their final ranking.

Concave Deterioration Curves. The process adapted by the BDPP results in a concave deterioration curve, in which the deterioration rate increases with time. Many of the calculation methods considered during the development of this algorithm resulted in a convex deterioration curve, wherein deterioration occurred at a decreasing rate. Examples of these types of curves are shown in Figure 3.11. A convex deterioration curve would not be an accurate representation of the degradation process, which occurs at an increasing rate, and would present a problem when selecting subsequent maintenance actions based on the projected condition. As seen in Figure 3.11, convex deterioration curve would severely underestimate the general NBI condition rating during the best times for preventive maintenance, when the rating is 7 and above, and as a result, the filtering module would remove the best options from consideration. Therefore, the concave deterioration curve output by the BDPP is highly desirable and more appropriate when used to automatically generating maintenance activity plans.

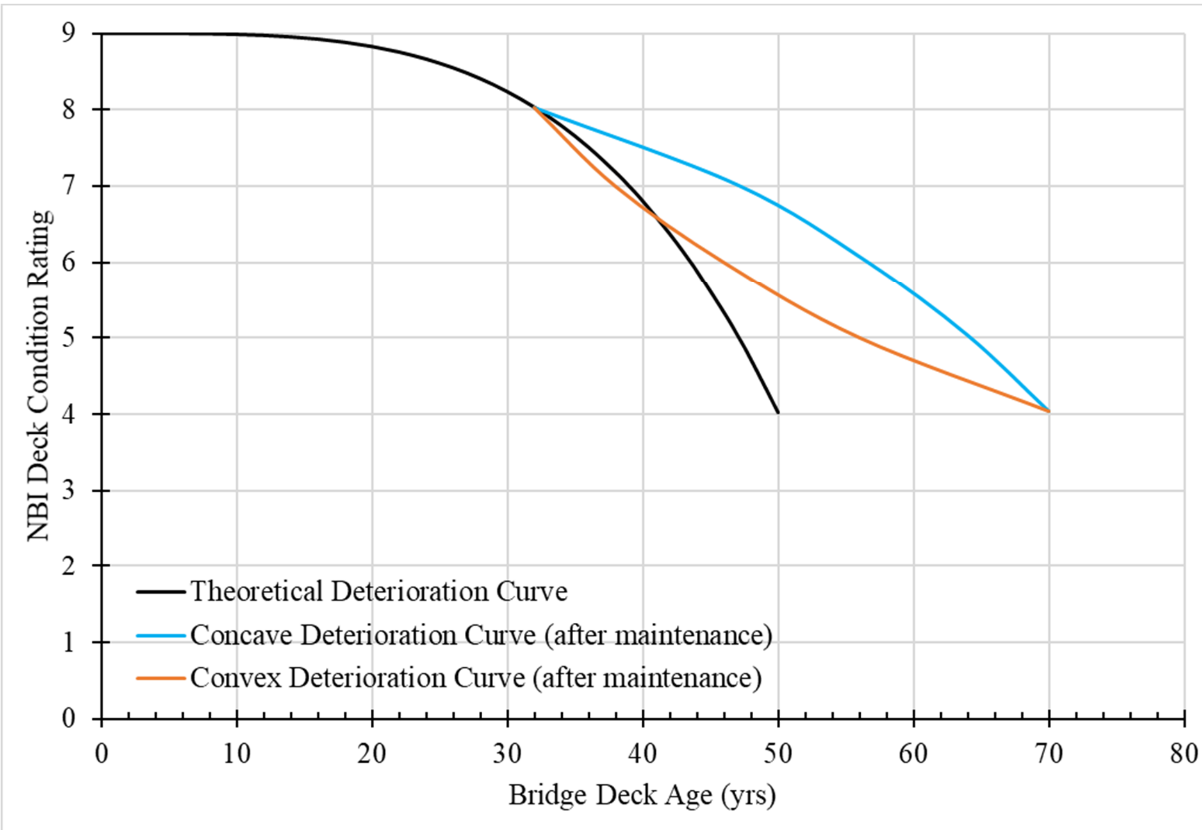


Figure 3.11. Image showing definitions of concave vs. convex deterioration curves.

Drawbacks that should be addressed in future iterations include the following:

Lack of Data. There is plenty of data supporting the service life of the individual maintenance activities, but little on their effects on bridge deck service life, deterioration rates, and condition rating. Efforts to describe these effects are either preliminary, as in the case of deterioration rates, or coarse and insensitive to how the benefits vary with the exposure and deck conditions, as is the case with service life extension and improved condition ratings. The reduction factors and bounds for the service life extension provide reasonable estimates based on experience. However, validation and further study is needed and the assumed extensions, rates, and improvements should be reconsidered as data becomes available.

Combined Parameters. As discussed previously, some maintenance activities improve condition, some slow the deterioration rate, and some extend service life in both ways. Ideally, these parameters would be considered separately so that an accurate deterioration model showing deck condition with time can be used to plan maintenance. Like other deterioration models, the BDPP represents service life benefits from both mechanisms in only one parameter. Unlike other models, it presents the benefits either by slowing the deterioration rates or by improving the condition, but these models are mutually exclusive. For further analysis, the BDPP uses the model that assumes all service life benefit is from a slowed deterioration rate. Recently, there has been a movement to measure the deterioration rates of different maintenance actions, particularly overlays. However, the rates measured in these studies will not be directly applicable to the BDPP because they will only represent the slowed deterioration rate and will not reflect the benefit of any improvement in the general NBI rating, which would need to be determined independently. At this point, if service life estimation will continue to rely on general NBI ratings, the calculation method will need to be adapted to incorporate both parameters separately instead of combining them into the deterioration rate.

The choice to describe the new deterioration model using slowed deterioration rates instead of improved condition ratings, as is done traditionally, has several paradoxical complications. First, the slowed deterioration rates should only apply for the service life of the maintenance activity, when it is effective, but the BDPP assumes deterioration rates are slowed for the remaining service life of the deck. This is tied with the assumption that the service life extension of the deck is the same as the service life of the maintenance activity. For this assumption to be true, the "slowed" deterioration rate during the life of the maintenance action would have to be zero, which is also inaccurate. This dilemma can be solved by investigating the relationship between the service life of the maintenance action and how it differs from the service life extension realized by the deck. For now, because assuming zero deterioration during a maintenance activity would result in a bridge deck that could last forever, the first approach was chosen.

The second complication is in the representation of condition-based versus cyclical preventive maintenance. Cyclical maintenance generally does not improve condition, and is well-described by assuming only the slowed deterioration rates as the BDPP does. Conversely, models that represent service life benefits by improved condition tend to describe deterioration after condition-based maintenance more accurately. This trade-off makes it difficult to determine which assumption should be used. However, the slowed-rate assumption was chosen over the improved-condition assumption for several reasons. First, attempts to develop assumed condition improvements for each maintenance activity are relatively immature and coarse. The extent of improvement depends on the same conditions represented by the reduction factors used to estimate service life extension, but thus far only general averages have been collected without consideration for exposure or pre-existing condition and studies are limited. Second, the general NBI condition rating scale has an upper bound of 9 but improvements can place the rating over 10. Anything greater than 9 in the model may be interpreted in practice as a 9, but then the expected general NBI rating will be overestimated over time. Additionally, specifying improvements that exceed 9 prevents validation of the numbers chosen to represent each activity since these values are not measurable in the field. While describing service life benefits purely with the deterioration rate is not ideal, as discussed above, it is considered to be more logical than describing service life benefits only by increasing general NBI condition ratings.

Finally, as noted at the beginning of this section, the deterioration model algorithm is only capable of analyzing general NBI condition data and cannot analyze element-level data. An algorithm based on element-level data was not considered at this time for two reasons. First, the portal needs to be widely applicable and element-level data is not available for all bridges in the states. Therefore, element-level data is only included in the filters and thresholds module, as an optional input. Second, the BDPP requires a deterioration model be input by the user (or pulled automatically from LTBP InfoBridge) for use as the baseline, "do nothing" scenario. All analysis relies on modifying this baseline deterioration model to obtain the deterioration model of the maintained bridge deck. However, baseline deterioration models from element-level data are still under development. Until element-level data-based deterioration models are established, the BDPP cannot rely on element-level data for its deterioration modeling algorithm.

3.4.3 Life-Cycle Cost Analysis

Once the service life algorithms are complete, the BDPP moves on to the LCCA algorithm. At this point, each maintenance activity plan being considered may be drawn out like the example plan in Figure 3.12, in which each maintenance activity and the time of its implementation are identified, and the time at which the deck will require rehabilitation, considered "end of service life" in the algorithm, is provided as well.

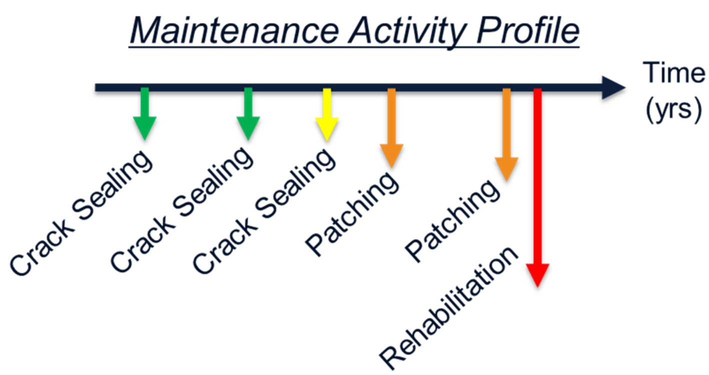


Figure 3.12. Example of a maintenance activity plan for a bridge deck.

The recommended time range for analysis is 100 years and the BDPP will use this analysis time unless the user indicates otherwise. State transportation agencies typically manage a 30-year long-term plan. However, the larger range assumed in the BDPP is required for LCCA to be a useful comparative tool. Shorter analyses mean long-term benefits and costs will not be represented, which could affect the ranking of the plans. At the end of the life of the deck, the BDPP assumes that rehabilitation is synonymous with replacement for the bridge deck. Both activities are costly and intended to re-set the bridge deck to an undamaged (and chloride-free, if applicable) condition.

Estimating Costs

The first step in the LCCA module is to determine the costs associated with each event in the life cycle of the deck. Two types of costs will be considered: agency costs and user costs. Agency costs are incurred directly by the agency and consist of the maintenance costs, rehabilitation/replacement costs, and salvage values. The profile for each maintenance action contains a default unit cost in USD per square foot or linear foot, as appropriate. This value is multiplied by the area of the deck or the length of the distress to determine the cost of the maintenance action. Alternatively, as noted in Section 3.2.4, *User Knoweldge, Preferences and Constraints*, the user may provide more accurate unit costs. For rehabilitation or replacement, the BDPP uses a default unit cost of $70/square foot. Again, the user may edit this value if they have a more accurate one available.

The analytical time range rarely coincides with the end of life of the asset being evaluated, in this case the deck. If the analysis time extends beyond the service life of the deck, then the deck is assumed to be rehabilitated/replaced and the same maintenance activity plan is applied in the following life cycle. When the analysis reaches 100 years, or the end of the analysis period, the salvage value of the bridge must be calculated to represent its remaining worth. At the start of its life, the bridge deck is assumed to have an asset value equal to $70/square foot times the deck area. At the end of its life, the deck is assumed to have a value of zero. The salvage value is estimated by interpolation based on the remaining service life of the bridge deck.

It is good practice to consider user costs in LCCA, but user costs are analyzed separately from agency costs in the BDPP. This is primarily because user costs can be orders of magnitude greater than agency costs due to the volume of users on the bridge. Therefore, the LCCA will favor options that shorten construction time and incur the lowest user costs, which often coincides with the actions that have the highest agency cost. Additionally, user costs are more difficult for agencies to estimate because they depend on user behavior. Transportation planning agencies generally use traffic demand models to determine the detour paths users will take and estimate the resulting system-wide congestion. These are complex models that may interface with the BDPP in subsequent iterations, but are infeasible to embed in the BDPP.

User costs are categorized as vehicle operating costs, represented as vehicle-miles-travelled (VMT), and travel delay costs, represented as vehicle-hours-travelled (VHT). VMT are costs to the user due to extra mileage on their vehicles. The BDPP assumes that all users bypass the bridge using the detour length input by the user. The unit cost assumed is $0.50/mile-user. VHT are costs to the user due to lost time spent travelling the extra distance. The BDPP assumes that users travel at an average speed of 20 mph if the road is urban and 50 mph if the road is rural. Literature on the unit cost for travel time is varied and the BDPP will assume $20/hr-user. The VHT user cost will be calculated by Equation 3.3:

$$VHT = \begin{cases} \frac{D}{20} * 20 * ADT * t_c & if\ road\ is\ urban \\ \frac{D}{50} * 20 * ADT * t_c & if\ road\ is\ rural \end{cases} \qquad \text{Eq. (3.3)}$$

Where D is the detour length (in miles) and t_c is the closure time (in days) associated with the maintenance action (to be included in the maintenance action profiles). It is assumed that the deck is fully closed throughout the closure time and no traffic flow is maintained.

The speeds, time value, and closure times assumed by the BDPP, and the assumption that all users will take the identified detour, are very simplifying assumptions and make this a crude user cost estimate. If the user has alternative unit costs or has evaluated the VMT and VHT separately, they may input these values instead.

The third unit cost identified by the FHWA is crash costs, which represent costs associated with an increased likelihood of accidents due to the construction work. This user cost is not included as it is difficult to quantify and has high uncertainty.

Calculating Present Value

Once all costs are estimated, they must be added to get the total life cycle cost of the bridge deck. Any future costs not incurred in the current year must be discounted according to Equation 3.4:

$$PV = FV_n \frac{1}{(1+r)^n} \qquad \text{Eq. (3.4)}$$

Where PV is the cost in the present (called the present value), FV_n is the cost n years from now (called the future value and calculated using inflation), and r is the discount rate. In accordance with common practice, the discount rate assumed is 4%. This may be changed by the user as desired.

Once all values are converted to present value and summed, the net present value can be divided by the service life of the deck to obtain the annual life cycle cost in USD per year. However, the present value is used for comparing maintenance plans.

It should be noted that this analysis assumes the current bridge deck is sufficient for future traffic demand and safety laws; it does not include any consideration for how these may change in the future. The bridge deck is always assumed to be replaced by an equivalent deck.

3.4.4 Risk and Uncertainty

Because states are federally required to consider risk in their asset management plans, some measure of risk is of interest to BDPP users. The risk of an event is the product between its likelihood and its consequences, and each event is considered separately. As discussed in Chapter 2, risk is rarely analyzed quantitatively due to an inability to quantify likelihoods and consequences. However, the BDPP requires a quantitative measure in order to incorporate risk in the Optimization module and consider it in the final ranking.

Types of Risks

For some types of risk, quantitative analysis is feasible. Due to the structure of its service life and LCCA modules, the BDPP is equipped to quantify risks associated with the uncertainties in input information and decision data. This is described by assigning probability distributions to the parameters of the algorithms, including the reduction factors and the unit costs.

For other types of risk, a quantitative analysis may be developed eventually, but due to limitations in current knowledge and/or the rarity of the types of events, they are excluded from the BDPP. This particularly pertains to risks associated with:

Changes in Demand. In Section 3.4.3, *Life-Cycle Cost Analysis*, it was clarified that changes in traffic demand are not considered by the BDPP. Future growth in traffic demand and truck weights due to population growth is expected, but the consequences of this growth are not understood well enough to incorporate in the deterioration models. Demand growth, or decay, may also occur if major factories or businesses change location. These events are difficult to predict and therefore are also excluded from the BDPP.

Current and Future Environmental Conditions. Within this type of risk, the federal guide focuses on extreme weather events, seismic activity, and climate change. These events and their likelihood and consequences are location-specific. Not all bridges will have extreme weather and seismic activity risks and those that do will have unique probability distributions describing the likelihood of the event. There will also be unique probability distributions for the likelihood of damage to the bridge deck and its extent. Because of the complexity of estimating these likelihoods and the consequences quantitatively, and because these risks are not nationally widespread, this type of risk should be considered in an independent and more in-depth analysis if it is a concern. While climate change is expected to be nationwide, changes in climate will vary regionally and predictions are uncertain. Therefore uncertainties in weather due to climate change are not incorporated in the BDPP.

Malfeasance, Hostile Acts, and Accidents. Events in this category include truck crashes, fires, and floods. They are expected to be relatively rare such that they are unlikely to occur more than once every few cycles, at most. If they were to occur during the 100-year analytical period, they would be considered an outlier in the analysis. Therefore, these risks are also not considered by the BDPP.

It is also worth noting that extreme events and accidents can be incredibly destructive to the entire bridge and may cause bridge rehabilitation or replacement to be required. If these events are frequent and severe damage is expected to occur once per life cycle, then the agency is likely more concerned with improving the robustness of the bridge and its deck or decreasing the likelihood of these events, and preventive maintenance to prevent material degradation is not of concern. If they are infrequent such that multiple life cycles will occur between events, then these events should not decide which preventive maintenance strategy is optimal.

The remaining types of risks identified by the FHWA are considered outside the scope of the BDPP because they are associated with system-level consequences rather than asset-level consequences. These risk types are:

- High-risk, high-value assets,
- Inaccurate financial forecasts,
- Changes in legislative requirements, and
- Changes in operation personnel and priorities.

In summary, the BDPP only considers risks associated with inaccurate information and decision data. These risks are represented using uncertainties.

Uncertainties

The BDPP is concerned with the events in which:

1. Remaining service life is over- or under-estimated due to:
    - Variability in environmental exposure and loads (ADT and %ADTT, chloride exposure, freeze-thaw cycling, Scheffer index, temperature, and relative humidity),
    - Variability in Construction quality, and
    - Inaccuracies inherent to deterioration models; or

2. Estimated agency life cycle cost (LCC) is over- or under-estimated due to:
    - Variable unit costs due to project-specific requirements,
    - Unrepresentative discount rate, and
    - Empirically derived service life predictions.

Remaining Service Life. Predicted service life of maintenance and repairs and of the bridge deck itself relies on the exposure of the bridge deck and the inherent material properties of the deck and wearing surface. Inaccuracies in the environmental exposure and loads stem from extrapolation of historic data and unpredictability of future conditions. Even disregarding trends such as increasing temperature and traffic and increasingly aggressive deicing practices, and assuming that conditions will follow historic weather and traffic patterns, there is still uncertainty in the temperature, amount of rainfall, number of freeze-thaw cycles, and other descriptors because they vary from year to year. Additionally, environmental data is not collected at each bridge but instead by monitoring stations that represent the nearby area. Variations within the area are expected.

Uncertainty in the material properties of the deck and its ability to resist the exposure loads is assumed to stem from variations in construction quality. The BDPP assumes that the construction quality is controlled by contractor experience. Any contractor, regardless of experience, is capable of producing high-quality maintenance or repair. However, less experienced contractors are more likely to be hampered by adverse environmental conditions and a lack of preparation to facilitate smooth and timely transition between steps in the procedure. Knowledge on how to handle adverse temperatures and weather, and when to prepare materials and equipment such that it is available when needed comes with experience. Therefore less-experienced contractors are considered to have a higher uncertainty in their construction quality. Additionally, if contractors are inexperienced because the maintenance action is new to the general region, then the specification from the agency may specify preparation or procedures that are not optimal for the area, thereby compromising quality and service life as well.

The uncertainties discussed above are represented in the BDPP by assuming that the reduction factors used to calculate service life of maintenance actions are represented by probabilistic distributions. Triangular distributions are assumed, and the ranges considered feasible and the most likely values for each factor were presented in Table 3.10 and Table 3.11. A graphic example for the reduction factor representing chloride exposure is also provided in Figure 3.13. These distributions are considered preliminary.

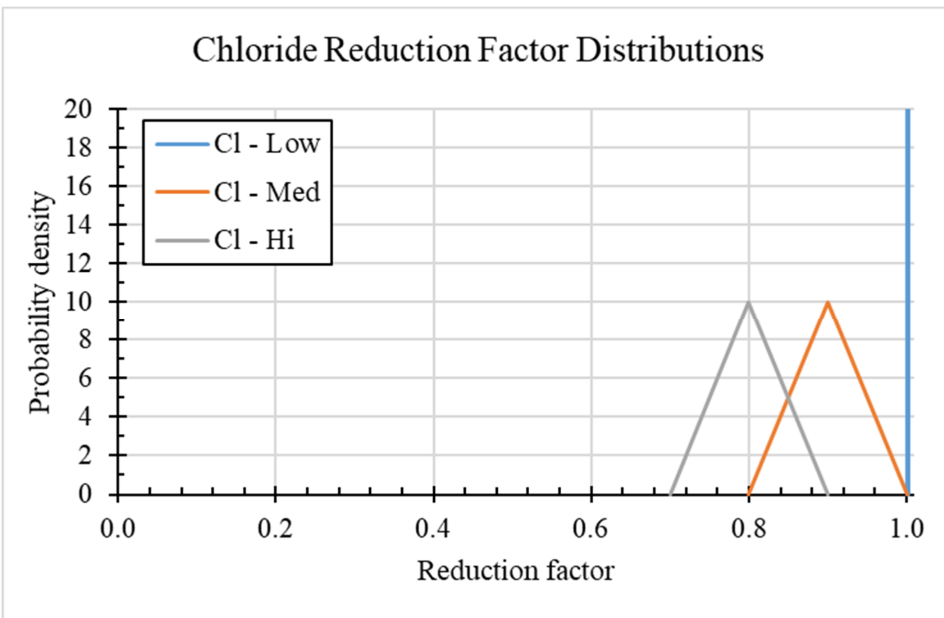


Figure 3.13. Triangular probabilistic distributions representing the reduction factors for low, medium, and high chloride exposures.

Alternatively, the BDPP could have avoided the use of distributions for each factor and assigned triangular distributions directly to the service lives of the maintenance actions based on the ranges found in literature. However, this is relatively inaccurate because the same probability distribution cannot be applied to represent the service life of bridges under different exposure conditions. The probability distribution for the life extension of a deck subjected to high "exposures", as defined in Table 3.12, should show that a relatively low service life has a higher probability. Conversely, the probability distribution for a deck with relatively benign exposures should assign high probabilities to long service life estimates and low probabilities to short service life estimates. Assigning uncertainties to the reduction factors instead permits the probability distribution for the service life to be tailored for each individual bridge deck.

The final source of uncertainty in the service life estimation module is from the deterioration model pulled from the LTBP portal. There is uncertainty in the deterioration rates, which may be represented by assuming probabilistic distributions for the times at which the general NBI deck condition rating is 8, 7, 6, 5, and 4. For now, the BDPP does not capture this uncertainty and assumes the deterministic values input by the user. To include this uncertainty in future iterations, the BDPP would need to coordinate with LTBP InfoBridge to obtain the correct distributions.

As described above, the user has the option to input their own expected service life. In this case, the assumed probabilistic distribution is a triangular distribution with the mode at the service life input by the user, a minimum possible value equal to 90% of the input service life, and a maximum possible value equal to 110% times the input service life. The user can modify these assumptions as well.

Thus far, the variation and uncertainty in the inputs to the SLEE and DM modules have been discussed. The probability distribution of the final service life estimate still needs to be determined. The BDPP does this using Monte Carlo simulation.

Agency LCC. Three types of variables or parameters were identified as the source of uncertainty in the LCC estimate: the service life prediction from the SLEE module, the unit costs of the maintenance actions, and the discount rate. The remaining service life prediction has already been explained. Uncertainties in the unit costs of the maintenance actions stem from the generality of the default values assumed. The default values in the maintenance action profile database represent the values from across the nation, but unit rates will vary by location and due to project-specific requirements. Therefore a statistical distribution for the unit costs should be assumed and developed based on a more extensive review of unit costs available in literature. Uncertainties due to the discount rate will not be considered. The discount rate will be taken as a deterministic value of 4% in accordance with standard policy by default, but the user may adjust this value if desired.

As with the service life extension, the probability density function (PDF) describing the agency LCC will be calculated using Monte Carlo simulation. This technique is explained in the next subsection.

Note that the user LCC is not evaluated probabilistically. Due to limited information and reliance on simplifying assumptions, a deterministic user LCCA was deemed more appropriate for the portal.

Monte Carlo Simulation

There are several ways to determine the probabilistic distribution of the output of a function that has probabilistic inputs. Calculating the output PDF from the input PDFs analytically is generally complicated or infeasible unless the distributions are normal distributions. The BDPP avoids normal distributions because they permit negative values to be selected and cannot describe skews in the data, and therefore are unrealistic representations of costs and service life. Because an analytical solution does not exist, Monte Carlo simulation is used instead.

Monte Carlo simulation develops the output PDF by running the calculation many (on the order of several thousand to several hundred thousand) times. In each run, the input values to be used in the calculations are selected randomly from the input PDFs. This generates a number n of input datasets, and each input dataset produces an output. At the end of the simulation, there are n outputs which are charted in a histogram. The final probability distribution of the output is determined by the histogram data.

Figure 3.14 summarizes the data flow in the context of the BDPP. The set of probabilistic inputs to the service life modules are the reduction factors only. In the first step, they produce the probabilistic output, the service life extension. The probabilistic service life extension and unit costs to the agency are then used in a separate Monte Carlo simulation to estimate the distribution of the life cycle costs to the agency.

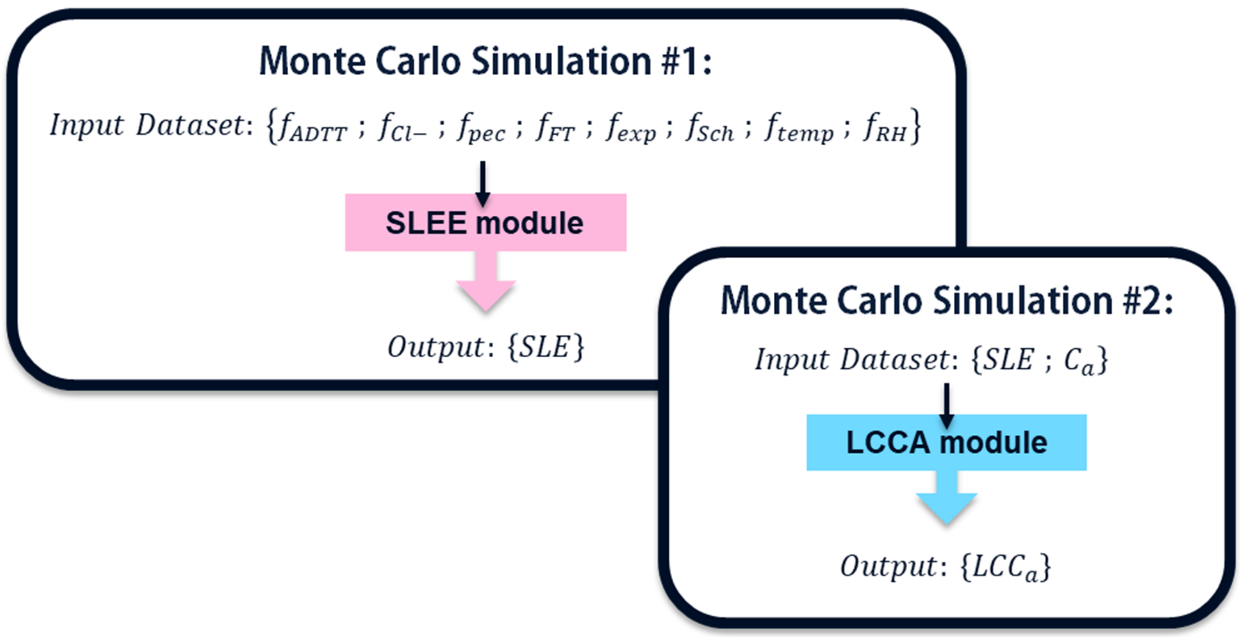


Figure 3.14. Summary of information flow through Monte Carlo simulations. SLE refers to service life extension, C_a refers to unit costs of maintenance, and LCC_a refers to agency life cycle cost. Note that the user life cycle costs are not evaluated probabilistically.

Risk vs. Uncertainty

This method of incorporating risk does not provide quantitative risk according to the widely-accepted definition "likelihood x consequence". The PDFs of the remaining service life and agency LCC describe the likelihood of the events that these variables are under- or over-estimated, but do not clearly address consequences.

Consequences for inaccurately estimating service life at first appear straightforward. If the service life is overestimated, then the agency will actually experience higher service life cycle costs than predicted. If the service life is underestimated, then the agency will benefit from lower service life cycle costs than predicted. The challenge is that the magnitude of the consequence varies with how inaccurate the service life estimate is. The likelihood that the service life is overestimated by 1 year would need to be multiplied by the consequence of overestimating the life by 1 year, and so on for 2 years, 3 years, 4 years, etc. Neither the final values nor their sum hold any physical meaning, making interpretation beyond a basic ranking system and inclusion in the Optimization module (discussed below) difficult. In comparison, knowing the probabilistic distribution of the agency LCC is much more informative.

The consequences for inaccurately estimating the agency LCC are not as straightforward because the consequences are realized on the system scale. If the agency experiences higher LCC than expected, then they lose the ability to spend on other assets. If the agency experiences lower LCC than expected, then they benefit by being able to spend more on other assets. The scope of the BDPP is narrowed to only one asset and therefore considering these consequences is outside of its capabilities.

In conclusion, the BDPP quantifies the variability in the expected service life and life cycle cost of the bridge deck instead of risk. The variability represents one component of risk, the likelihood, and is considered appropriate for the objective of the BDPP.

3.5 Optimization

The Optimization module is the final module in the BDPP. The purpose of this module is to aid the user in choosing the preferred maintenance activity plan by ranking the analyzed plans according to the user's priorities. The ranking is completed using the Linear Weighted Sum Method (LWSM), which is a multi-objective optimization method.

The multi-objective function represents the sum of three single-objective functions. The single objective functions are to: (1) minimize agency LCC; (2) maximize service life extension; and (3) minimize user LCC. The third objective function is optional and is not considered by default. Each of these values were determined for each maintenance activity plan in the previous algorithms. The 50-percentile values from the PDFs describing agency LCC and service life extension will be used deterministically in this module. Alternatively, the user may choose to use the 10-percentile or 90-percentile values instead.

The single objective functions are weighted according to their importance to the user, and the weights used were input by the user at the start of the BDPP. The sum of the weights must equal one. To prevent different orders of magnitude from causing one objective function to overrun the others despite its weighing factor, all values are scaled relative to their optimum value across the set of maintenance activity plans. For example, all agency LCCs are divided by the minimum agency LCC observed across all maintenance activity plans considered. All calculated service life extensions are divided by the maximum service life extension observed across all the maintenance activity plans considered, and so on for the remaining objectives. As an example, the scaled values for service life extension are calculated according to Equation 3.5:

$$S_{SLE,k} = \frac{SLE_k}{max\{SLE_1, SLE_2,\ldots, SLE_n\}} \quad \text{Eq. (3.5)}$$

Where S_{SLE} is the scaled value representing the service life extension for maintenance activity plan k,
SLE_k is the service life extension calculated assuming maintenance activity plan k,
n is the number of maintenance activity plans considered in analysis, and
k is a value from 1 to n.

The multi-objective function Z for maintenance activity plan k is therefore calculated according to Equation 3.6:

$$\text{maximize } Z_k = W_{LCCa}\, {}^{1}/_{S_{LCCa,k}} + W_{LCCu} * {}^{1}/_{S_{LCCu,k}} + W_{SLE} S_{SLE,k} \quad \text{Eq. (3.6)}$$

Where W_i is the weight associated with objective i,
S_i is the scaled value corresponding to objective i, and
i is LCCa (agency LCC); LCCu (user LCC); or SLE (service life extension).

Weight W_{LCCu} is assumed to be zero unless otherwise input by the user.

The ranking is determined by the Z values. Because the objective is to minimize Z, the maintenance activity plans with the smallest Z receive the highest ranking.

In addition, and to consider short term maintenance plans, a graphical representation that ranks the different maintenance actions based on initial cost and remaining service life will be presented to the user.

3.6 Portal Output

Sections 3.1 through 3.5 have explained the assumptions and calculations of the portal. The analysis is summarized in the output provided to the user.

The output will be a ranked list of the maintenance activity plans considered by the BDPP. The following will be identified for each maintenance activity plan:

1. Remaining service life - The PDF for the remaining service life will be provided graphically to the user. Key parameters (distribution type, expected value or 50-percentile, 90-percentile, 10-percentile and variance) will also be identified.
2. Agency LCC - The PDF for the agency LCC will also be provided graphically and the expected value (50 percentile), 90-percentile, 10-percentile, and variance will be identified.
3. User LCC,
4. Initial cost, and
5. Improvement in general NBI deck condition rating after initial maintenance action.

The user may also observe Pareto frontiers if desired. Either two or three of the listed output variables may be selected and their values plotted graphically to compare the performance of different maintenance activity plans without needing to adjust the weights and rerun the portal.

4 BRIDGE DECK PRESERVATION PORTAL EXAMPLES

Inspection reports were provided for example bridges in Iowa, Oregon, and North Carolina. The inspection reports included the Structure Inventory and Appraisal Sheet (SI&A sheet), which was used to extract inputs required by the portal. Three bridges were selected for the analysis to represent a wide range of age and current condition. These examples were used to validate the portal methodology and calibrate some of the parameters, including service life reduction factors, analysis period, and optimization function. Element level data were provided for some of these bridges, however, this data was not utilized in the analysis. This is to represent a more typical case, where only general NBI ratings are used. In addition, these examples are mainly intended to validate the portal algorithms, while the element level data are only implemented in the Selection of Maintenance Actions module.

Based on the framework discussed in the previous chapter, a MATLAB tool was developed to efficiently run the portal algorithms. First, the tool reads the user inputs as well as lookup tables for reduction factors and service life lower and upper bounds, presented in Tables 3.10 to 3.12, from an input spread sheet. Second, it identifies the applicable distribution parameters for each of the pertinent reduction factors. Third, it applies Latin Hypercube Sampling (LHS) based on the cumulative density functions of the defined distribution for each of the relevant reduction factors to generate N number of values for each factor. The LHS is a widely-used method to generate controlled random samples that are representative of the true variability of the factors. In addition, it saves computer processing time when running Monte Carlo simulations. Fourth, Monte Carlo simulations are performed considering N number of scenarios based on the samples generated by the LHS. For this analysis, N was selected to be 1000 scenarios, however, higher or lower number of scenarios can be adopted if the user chooses so. Monte Carlo Simulation runs each of these scenarios in the same manner as a deterministic approach and based on the results of these scenarios the distributions of the outputs are defined.

The BDPP algorithms are performed for each scenario (set of values of reduction factors) in the same order defined in the framework. The SLEE module estimates the service life extension based on Equation 3.1. New deterioration rates are then estimated based on the service life extension to form the new deterioration model. The tool then compute the improved condition rating by going back from the extended service life with the original deterioration rates. Then the tool switches to the life cycle cost analysis module where it consider the initial cost of applying the maintenance action and then a cost of deck replacement at the end of the extended service life. The life of the new deck is equal to the life of the old deck, which is described as the time period between the deck construction until it reaches a general NBI rating of 4 based on the original deterioration rates. Salvage value is estimated at the end of the predefined analysis period and then all the costs are converted into a present value to allow for comparison. At the conclusion of the analysis per the three modules for the N number of scenarios, the tool outputs the distribution of the service life extension and present value (agency LCC) as well as some representative statistics such as the 10th, 50th, and 90th percentile values of the service life extension, remaining service life, improved general NBI rating, undiscounted sum, and present value. The tool can also output a table of N rows that corresponds to the values of these parameters based on the N number of scenarios.

The aforementioned analysis is repeated for each maintenance action considered in the analysis through a loop in the MATLAB tool. The tool also generates the aforementioned results graphically where plots of the new and original deterioration models are generated. A bar chart of the initial cost versus the service life extension for the maintenance actions considered is also created, which can be used for short term planning. Optional post processing to create plots of resulted distributions of the service life extension as well as the present value can also be incorporated.

The examples investigated in this chapter considered deterministic values for the unit costs of the maintenance actions. The probabilistic nature of the life cycle cost analysis output stemmed from the probabilistic remaining service life input. The costs considered in the analysis were limited to agency costs for simplicity and due to limited information on some of the user cost inputs. The analysis period was set to the default value of 100 years, as a long term planning example.

Since these examples are intended as a pilot run of the portal framework, only single application of the maintenance action is considered in each alternative maintenance plan. The framework for developing a maintenance activity plan with multiple application of the same maintenance action or a mix of different actions is discussed in Section 3.3.3, *Maintenance Activity Plan*. The MATLAB tool could be expanded to include the development of a multi-action maintenance plan in a future effort.

As mentioned previously, the examples are focused on validating the portal algorithms. Therefore, the selection of maintenance actions module was not implemented. Instead, four appropriate maintenance actions were selected for the analysis. The three bridges presented in this chapter have concrete bridge deck, hence, the same maintenance actions were investigated for the three examples. These actions are listed in Table 4.1, with the associated lower and upper bound service life extensions as well as the assumed unit costs.

It is noted that the outputs presented later for the bridge examples are based on the assumed inputs and are not to be interpreted as recommended actions for the subject bridge decks. The unit cost plays a significant role in the maintenance selection process. The values listed in Table 4.1 are assumed based on literature, however, more accurate values that are representative of the local costs at each state should be implemented for maintenance planning. Deterioration models are collected from the LTBP portal while the reminder of the bridge information are collected from InfoBridge. Validation of these deterioration rates are out of the scope of the BDPP.

Table 4.1. Maintenance actions considered in the bridge examples.

Maintenance Actions	**Service life extension (years)**					**Unit Cost ($/sq.ft.)**
	Lower bound				Upper bound	
	NBI>7	7≥NBI>6	6≥NBI>5	NBI≤5		
Healer-Sealer	5	3	3	3	10	3
HMA Overlay with Membrane	10	8	7	6	20	10
PCC or HPC Overlay	15	10	8	7	30	20
Thick Polymer Concrete Overlay	15	10	8	7	25	15

4.1 NCDOT Bridge: ID 210495

4.1.1 Inputs

The bridge is 40 years old located in Buncombe County in North Carolina and passes over highway (I-40) (6A, 42B). The structure number is 210495. Last inspection was performed in 2018 which indicated deck rating of 6 - Satisfactory Condition. The primary source of chlorides was considered to be deicing salts. The climate historic data for that region, from 1980 to 2017, shows freeze thaw cycles ranging between 68 to 107 cycles per year and number of snowfalls between 21 to 67 days per year, as shown in Figure 4.1 (https://infobridge.fhwa.dot.gov/Data). For the purpose of this example, we assume that the number of snowfalls is equivalent to the number of deicing events although additional icing events will warrant more frequent deicer applications. This translates to exposure classes of Medium for freeze thaw and High for chloride exposure. The ADTT for this bridge is 98, which is classified as low (<100). For this example, it was assumed that the contractor is experienced, completed at least five similar projects, with the four investigated maintenance actions. The deck original deterioration model is described by the time at which the deck general NBI ratings are expected to decrease. This information is extracted from the LTBP portal as shown in Table 4.3.

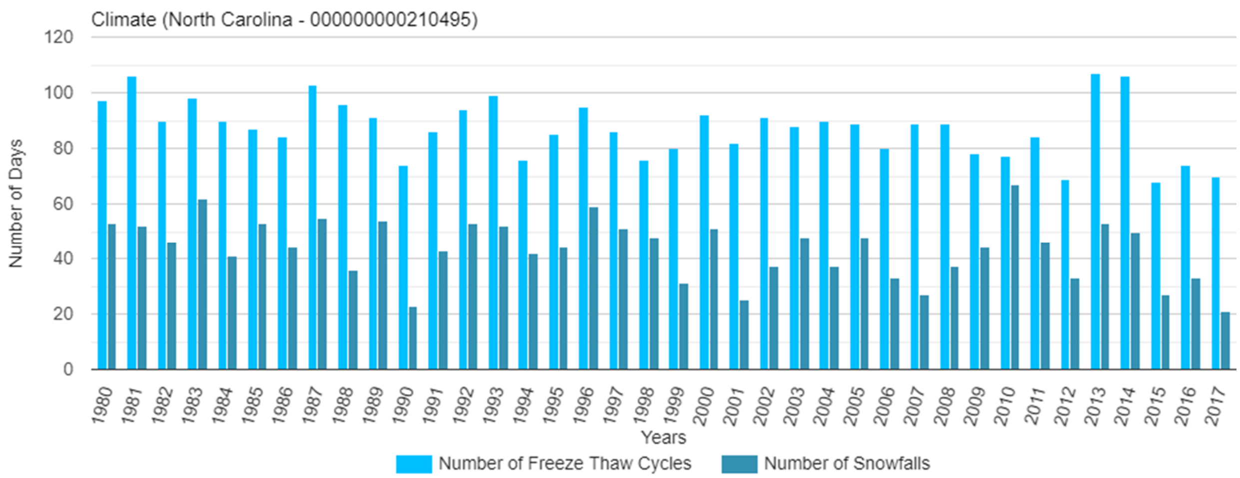


Figure 4.1. Freeze thaw cycles and number of snowfalls per year at the location of bridge 210495 (NC).

Table 4.2. BDPP inputs for bridge 210495 (NC).

	Variable	Value
Physical Description	Year constructed (27)	1979
	Deck structure type (107)	Concrete CIP
	Wearing surface type (108A)	Monolithic concrete
	Length (ft) (49)	221.1
	Width (ft) (52)	69.9
Exposure Conditions	Primary Chloride Source	Deicing Salt
	Chloride Exposure	High
	F/T exposure	Medium
	ADT (29)	1400
	%ADTT (109)	7
	Contractor experience	Experienced

Table 4.3. Deterioration model collected from LTBP portal for bridge 210495 (NC).

Deterioration Model	
NBI	Year
9	1979
8	2010
7	2017
6	2022
5	2028
4	2033

4.1.2 Outputs

This section discusses the outputs of the portal algorithms assuming the inputs listed above. The service life extension reduction factor were computed based on the exposure conditions. The new deterioration rates were estimated based on the service life extension achieved by the application of each of the maintenance actions at the year of the analysis (2019), as shown in Figure 4.2. The original deterioration rates in the absence of maintenance activities is shown in red. Since the reduction factors are described with probability distributions, the resulted service life extension and subsequently the new deterioration models are described in a probabilistic fashion. The blue line in the figures below represents the 50th percentile value for the deterioration model considering the effect of the maintenance action on extending the service life of the deck, and the magenta dotted lines represent the 10th and 90th percentiles. Figure 4.3 shows the initial cost that needs to be spent at the current year versus the estimated service life extension. The bar chart represent the 50th percentile and the error bars indicate the 10th and 90th percentile values. These values can be used for short term maintenance planning if the asset owner is only interested in preserving the deck for relatively short period (for example 10 to 20 years).

The improved general NBI rating for the deck is back calculated from the year at which the maintained deck reaches a rating of 4 using the original deterioration rate. For long term planning, the results of the SLEE and DM modules are integrated into the LCCA module to calculate the agency life cycle cost (LCC), also referred to as present value (PV), for each of the maintenance actions as well as a “Do Nothing” alternative. The BDPP tool output tabular summary for the results of SLEE and LCCA modules for each of the investigated actions. This summary is shown in Table 4.4 for the Healer Sealer as an example. For the given bridge deck example, the distribution of the resulted service life extension and the present value are presented in Figure 4.4 and Figure 4.5, respectively. As seen in the figures, the PCC or HPC overlay and thick polymer concrete overlay yielded the greatest service life extension, however, in terms of cost benefit ratio, represented in this context by the present value, the thick concrete overlay is showing better results. The BDPP uses the same logic through the optimization module to aid the user in selecting a maintenance plan.

The optimization module utilizes the 50th percentile values for the present value (agency LCC) and the remaining service life (RSL) for each of the maintenance actions, which are shown in Table 4.5 among other parameters. As mentioned previously, the user LCC is not included in this analysis. The user can assign weighing factors for the PV and RSL according to the user’s priorities. Table 4.6 shows normalized values for each of the actions based on the optimum LCC and RSL. The first row in the table represent the ratio of the minimum present value (agency LCC) out of the five alternatives to the present value considering the maintenance action. The second row shows the ratio of the maintenance action RSL to the maximum RSL. Table 4.7 shows examples of different optimization functions considering three different set of priorities. The first row indicate equal priority to both the RSL and the PV, the second row shows higher priority to PV and the third shows higher priority for RSL. For this example, the thick polymer concrete overlay is showing as the optimum action, based on the described user inputs, regardless of the given priority weights to the PV and RSL. This is because it is yielding both the minimum PV and maximum RSL as shown in Table 4.6.

Please note that the results above are affected by the fact that the assumed cost for thick polymer overlay is less than that of PCC or HPC overlay. This assumption is based on the smaller thickness required for thick polymer overlays as well as the lower cost related to traffic control as it needs less time to cure before opening bridge to traffic. This assumption also implies readily available contractors that can perform the work. In our experience, trial or new applications are generally associated with much higher cost than standard practices.

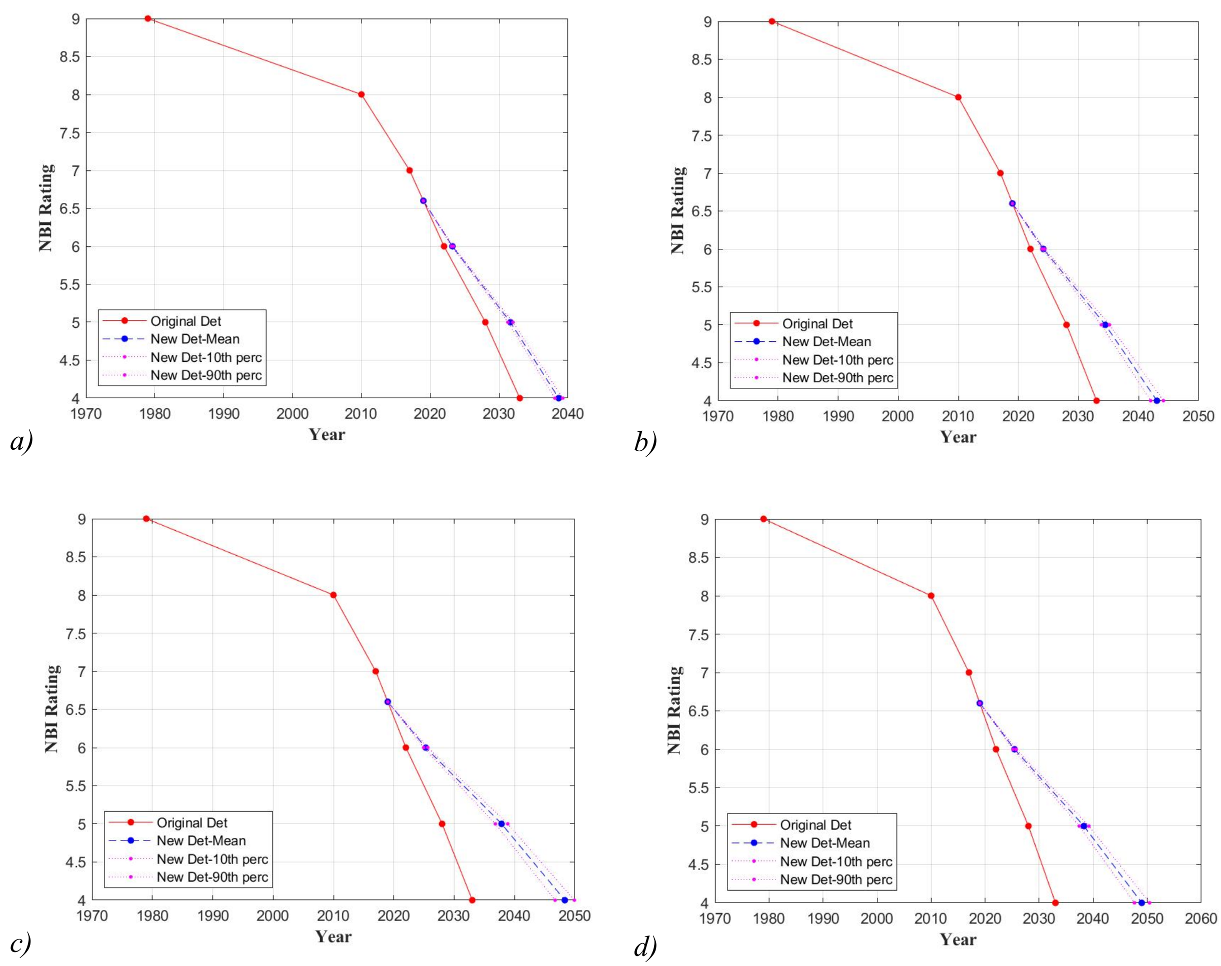


Figure 4.2. Deterioration model for bridge 210495 (NC) considering a) Healer-Sealer, b) HMA Overlay with Membrane, c) PCC or HPC Overlay, d) Thick Polymer Concrete Overlay.

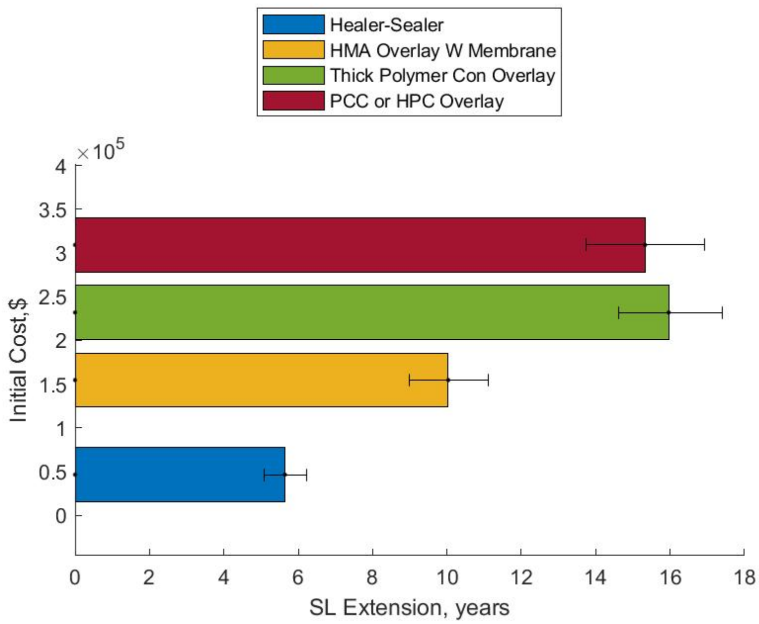


Figure 4.3. Initial cost versus service life extension for each of the investigated maintenance actions, bridge 210495 (NC).

Table 4.4. Summary of the results for the Healer Sealer alternative, bridge 210495 (NC).

Healer-Sealer				
Variable	Do Nothing	10th Percentile	50th Percentile	90th Percentile
Undiscounted Sum,$	1,722,934	1,667,357	1,656,195	1,644,594
Present Value,$	691,155	608,880	596,268	583,444
Improved NBI	7	7	8	8
Remaining SL, years	14.0	19.1	19.6	20.2
SL Extension, years	0	5.1	5.6	6.2
Initial Cost, $	0	46,365	46,365	46,365

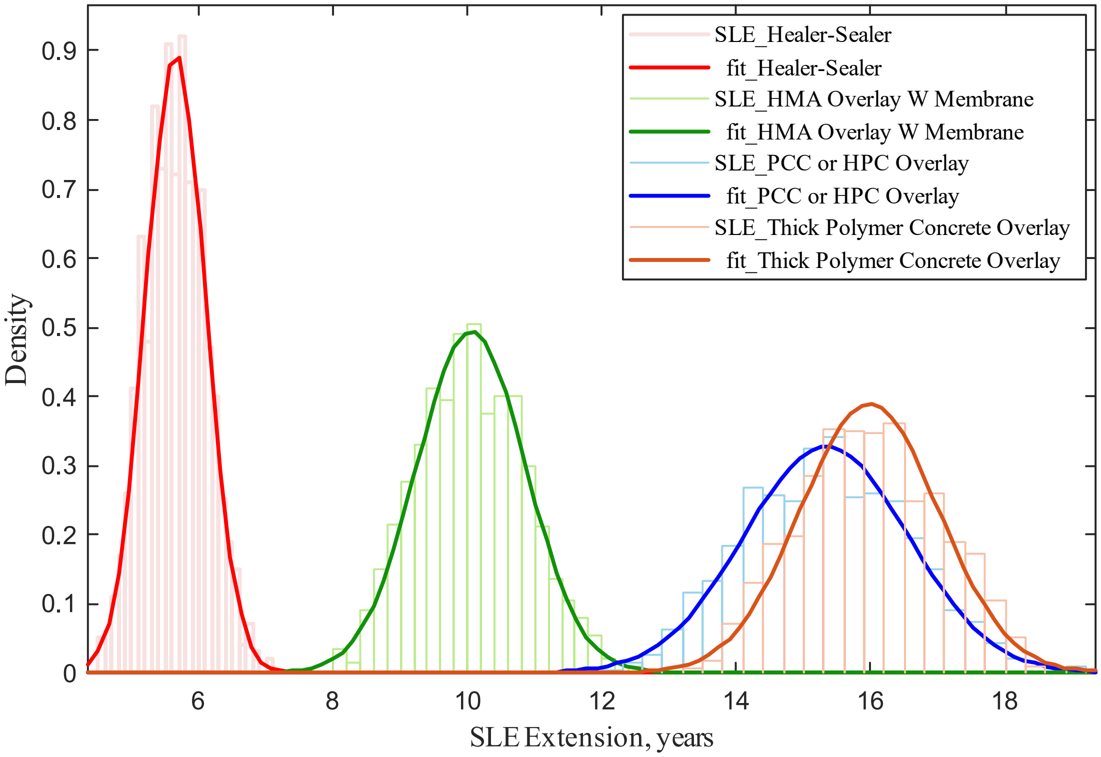


Figure 4.4. Distribution of the service life extension considering the investigated maintenance actions.

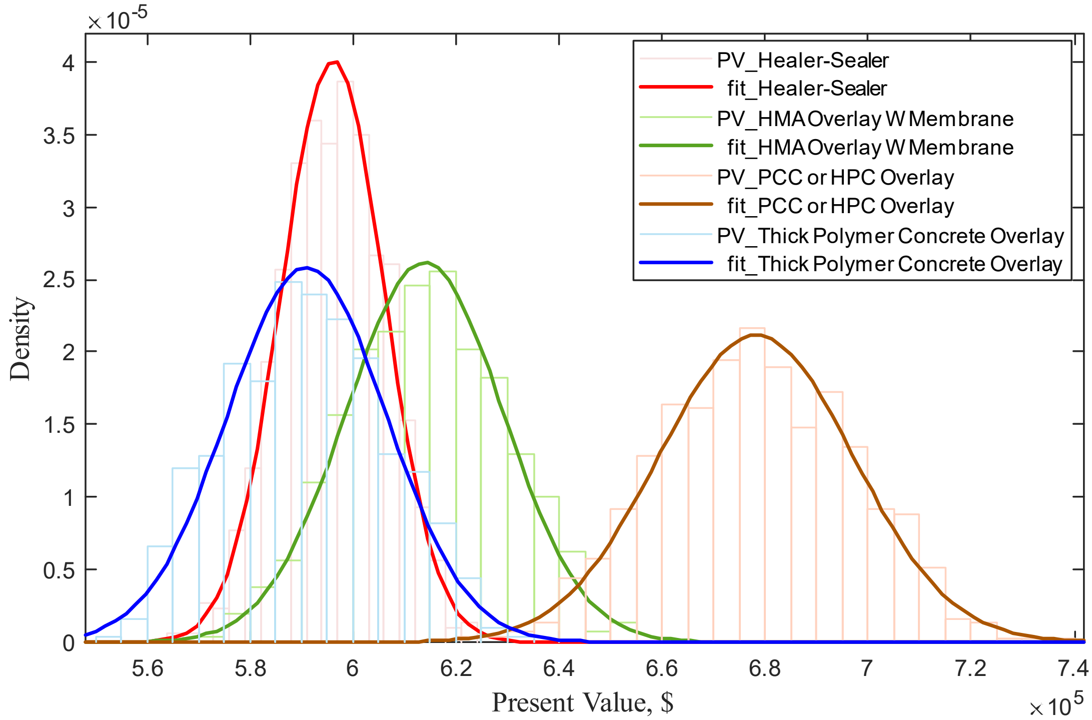


Figure 4.5. Distribution of present value considering the investigated maintenance actions.

Table 4.5. Tabular summary of the algorithm modules results for bridge 210495 (NC).

Variable	Do Nothing	Healer-Sealer	HMA Overlay with Membrane	PCC or HPC Overlay	Thick Polymer Concrete Overlay
	Deterministic	50th Percentile	50th Percentile	50th Percentile	50th Percentile
Undiscounted Sum, $	1,722,934	1,656,195	1,676,438	1,724,974	1,634,987
Present Value (PV), $	691,155	596,268	614,005	677,962	591,005
Improved NBI	6.6	7.5	8.0	8.2	8.2
RSL, years	14.0	19.6	24.0	29.3	30.0
SL Extension, years	0.0	5.6	10.0	15.3	16.0
Initial Cost, $	0	46,365	154,549	309,098	231,823

Table 4.6. Normalized agency LCC and remaining service life, bridge 210495 (NC).

Variable	Do Nothing	Healer-Sealer	HMA Overlay with Membrane	PCC or HPC Overlay	Thick Polymer Concrete Overlay
PV	0.86	0.99	0.96	0.87	1
RSL	0.47	0.66	0.8	0.98	1

Table 4.7. Optimization values for the maintenance actions, bridge 210495 (NC).

Variable	Do Nothing	Healer-Sealer	HMA Overlay with Membrane	PCC or HPC Overlay	Thick Polymer Concrete Overlay
	Deterministic	50th Percentile	50th Percentile	50th Percentile	50th Percentile
Equal Weight factors	0.67	0.83	0.88	0.93	1.00
Priority to PV (0.75*PV+0.25*RSL)	0.76	0.91	0.92	0.90	1.00
Priority to RSL (0.25*PV+0.75*RSL	0.57	0.74	0.84	0.95	1.00

4.2 ODOT Bridge: ID 08347A

4.2.1 Inputs

The bridge is 52 years old located in Klamath County in Oregon and passes over the Link River. The structure number is 08347A004 27544. Last inspection was performed in 2018, which indicated deck rating of 5 - Fair Condition. The primary source of chlorides was considered to be the deicing salts. The climate historic data for that region, from 1980 to 2017, shows freeze thaw cycles ranging between 111 to 171 cycles per year and number of snowfalls between 73 to 147 days per year, as shown in Figure 4.6. As for the previous example, we assume that the number of snowfalls is equivalent to the number of deicing events although additional icing events will warrant more frequent deicer applications. This translates to exposure classes of High for both freeze thaw and chloride exposures as shown in Table 4.8. The ADTT for this bridge is 400, which is classified as medium (between 100 and 5,000). For this example, it was assumed that the contractor is experienced with the healer-sealer and PCC or HPC overlay. Low contractor experience was assumed for HMA overlay with membrane and medium contractor experience for thick

polymer concrete overlay, as shown in Table 4.9. The time at which the deck NBI ratings are expected to decrease are extracted from the LTBP portal as shown in
Table 4.10. Note that some of the investigated maintenance actions are not recommended by the portal as discussed in Chapter 3 due to the general NBI rating; however, they were used for consistency between the examples.

Some inconsistencies were noted between the deck general NBI ratings reported in the provided inspection reports and those documented in the LTBP portal. The provided inspection reports indicate that there was an improvement in 2017 than conditions reported in previous years. No prior repairs are considered in the analysis and ratings based on numbers extracted from the LTBP portal were assumed.

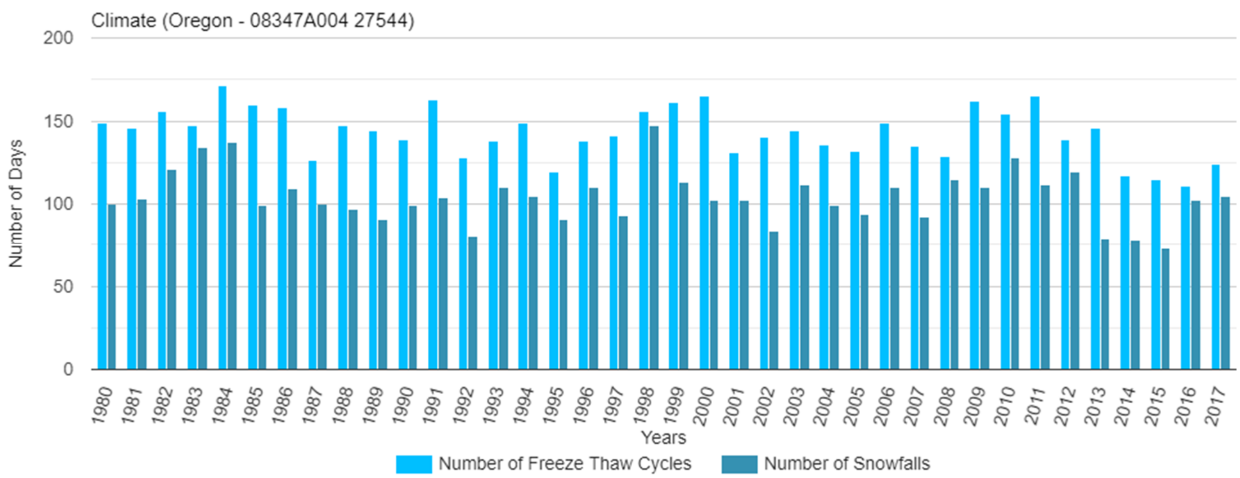


Figure 4.6. Freeze thaw cycles and number of snowfalls per year at the location of bridge 08347A (OR).

Table 4.8. BDPP inputs for bridge 08347A (OR).

	Variable	**Value**
Physical Description	Year constructed (27)	1967
	Deck structure type (107)	Concrete CIP
	Wearing surface type (108A)	Epoxy Overlay
	Length (ft) (49)	525
	Width (ft) (52)	26.5
Exposure Conditions	Primary Chloride Source	Deicing Salt
	Chloride Exposure	High
	F/T exposure	High
	ADT (29)	1300
	%ADTT (109)	23%

Table 4.9 Contractor experience assumed for bridge 08347A (OR).

Maintenance Actions	Contractor Experience Risk
Healer-Sealer	Low
HMA Overlay with Membrane	High
PCC or HPC Overlay	Low
Thick Polymer Concrete Overlay	Medium

Table 4.10. Deterioration model collected from LTBP portal for bridge 08347A (OR).

Deterioration Model	
NBI	Year
9	1967
8	2001
7	2009
6	2014
5	2020
4	2026

4.2.2 Outputs

The resulting deterioration rates due to the application of each of the maintenance actions were estimated based on the service life extension, as shown in Figure 4.7. Deterioration model for bridge 08347A (OR) considering a) Healer-Sealer, b) HMA Overlay with Membrane, c) PCC or HPC Overlay, d) Thick Polymer Concrete Overlay.Figure 4.7. Since the bridge is relatively old and is predicted by the assumed deterioration model to be due for rehabilitation (NBI rating of 4) in 7 years, the service life extension achieved by applying the maintenance actions would be toward the lower ranges reported in literature. Figure 4.8 shows the initial cost that needs to be spent at the current year versus the estimated service life extension. The results of SLEE and LCCA modules for each of the investigated maintenance actions are summarized in Table 4.11. The thick polymer concrete overlay yields the lowest present value (PV). However, the PCC or HPC overlay yields the greatest service life extension and subsequently the highest improved condition rating. The optimization results are shown in Table 4.13, which implies that the thick polymer concrete overlay would be recommended by the portal in the cases of equivalent priorities to the PV and RSL or a higher priority to the PV. If the user is prioritizing the RSL, the PCC or HPC overlay and thick polymer concrete overlay would be equally ranked higher than the other maintenance options. These results are limited to the assumed inputs and deterioration model. Note that accurate ccost information is of paramount importance for the quality of the results.

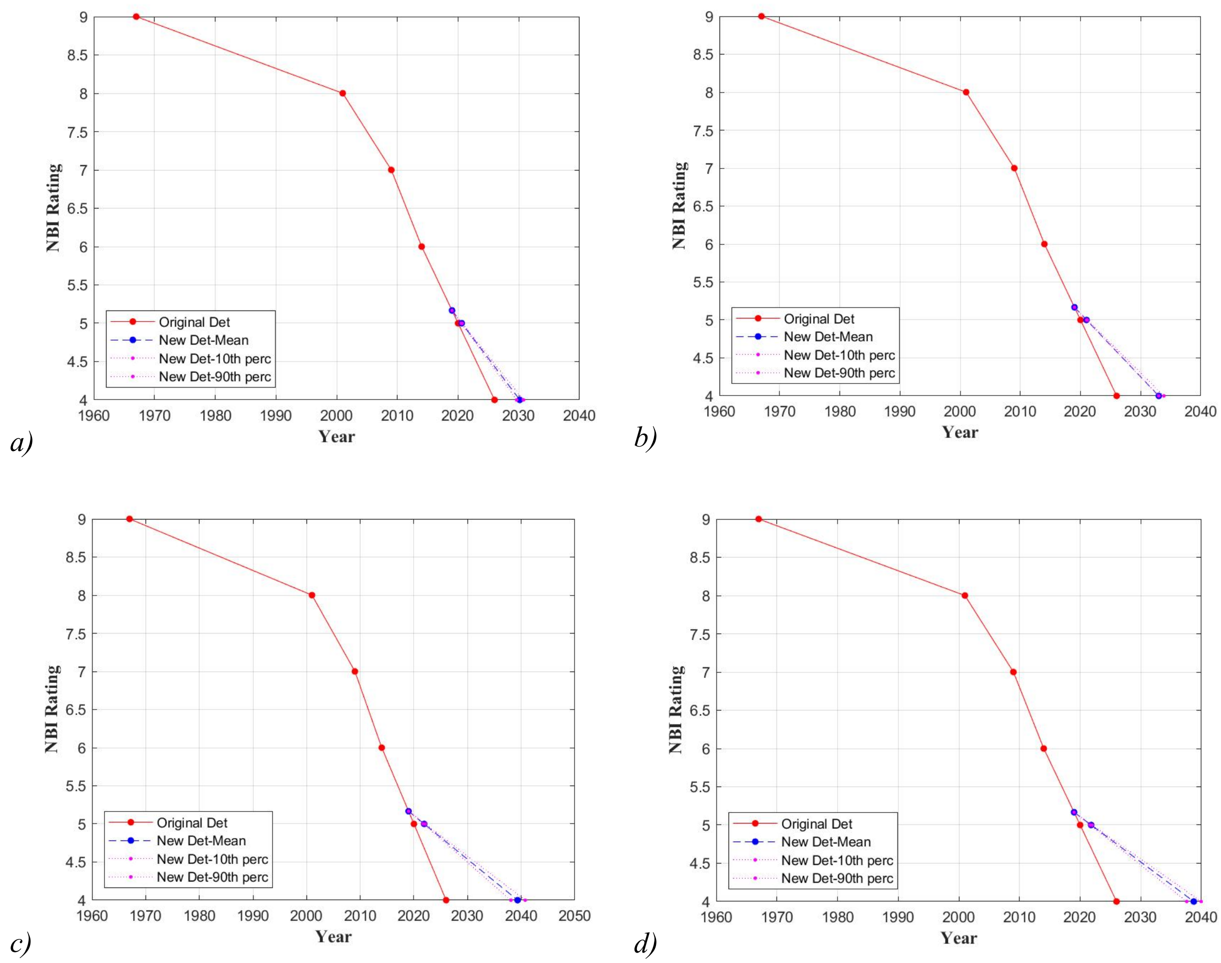


Figure 4.7. Deterioration model for bridge 08347A (OR) considering a) Healer-Sealer, b) HMA Overlay with Membrane, c) PCC or HPC Overlay, d) Thick Polymer Concrete Overlay.

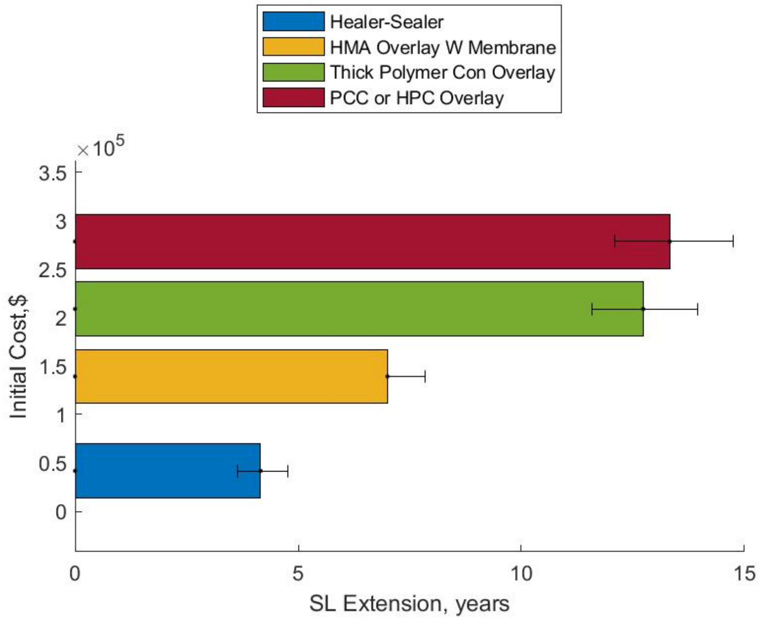


Figure 4.8. Initial cost versus service life extension for each of the investigated maintenance actions, bridge 08347A (OR).

Table 4.11. Tabular summary of the algorithm modules results for bridge 08347A (OR).

Variable	Do Nothing	Healer-Sealer	HMA Overlay with Membrane	PCC or HPC Overlay	Thick Polymer Concrete Overlay
	Deterministic	50th Percentile	50th Percentile	50th Percentile	50th Percentile
Undiscounted Sum, $	1,535,091	1,508,185	1,558,672	1,593,454	1,533,618
Present Value (PV), $	805,059	723,049	746,654	748,013	689,919
Improved NBI	5.2	5.9	6.4	7.4	7.3
RSL, years	7.0	11.2	14.0	20.3	19.7
SL Extension, years	0.0	4.2	7.0	13.3	12.7
Initial Cost, $	0	41,738	139,125	278,250	208,688

Table 4.12. Normalized agency LCC and remaining service life, bridge 08347A (OR).

Variable	Do Nothing	Healer-Sealer	HMA Overlay with Membrane	PCC or HPC Overlay	Thick Polymer Concrete Overlay
PV	0.86	0.95	0.92	0.92	1
RSL	0.34	0.55	0.69	1	0.97

Table 4.13. Optimization values for the maintenance actions, bridge 08347A (OR).

Variable	Do Nothing	Healer-Sealer	HMA Overlay with Membrane	PCC or HPC Overlay	Thick Polymer Concrete Overlay
	Deterministic	50th Percentile	50th Percentile	50th Percentile	50th Percentile
Equal Weight factors	0.6	0.75	0.81	0.96	0.99
Priority to PV (0.75*PV+0.25*RSL)	0.73	0.85	0.86	0.94	0.99
Priority to RSL (0.25*PV+0.75*RSL	0.47	0.65	0.75	0.98	0.98

4.3 Iowa DOT Bridge: ID 36281

4.3.1 Inputs

This bridge is relatively new, only nine years old, located in Mills County in Iowa and passes over Pony Creek. The structure number is 36281. Last inspection was performed in 2018 which indicated deck rating of 8 - Very Good Condition. The primary source of chlorides was considered to be the deicing salts. The climate historic data for that region, from 1980 to 2017, shows freeze thaw cycles ranging between 73 to 125 cycles per year and number of snowfalls between 29 to 102 days per year, as shown in Figure 4.9. Freeze thaw cycles and number of snowfalls per year at the location of bridge 36281 (IA). As for the previous examples, we assume that the number of snowfalls is equivalent to the number of deicing events although additional icing events will warrant more frequent deicer applications. This implies exposure classes of High for both freeze thaw chloride exposure as shown in Table 4.14. The ADTT for this bridge is 1877, which is classified as Medium. For this example, it was assumed that the contractor is experienced with the healer-sealer and PCC or HPC overlay. Low contractor experience was assumed for HMA overlay with membrane and the thick polymer concrete overlay, as shown in Table 4.15. The deck deterioration model described by the time at which the deck general NBI ratings are expected to decrease were extracted from the LTBP portal as shown in

Table 4.16.

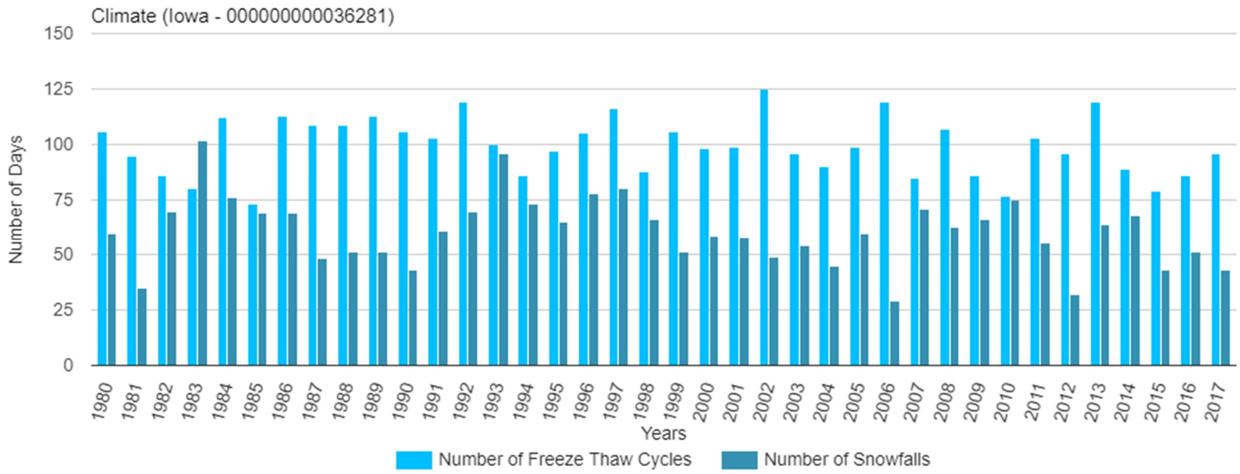


Figure 4.9. Freeze thaw cycles and number of snowfalls per year at the location of bridge 36281 (IA).

Table 4.14. BDPP inputs for bridge 36281 (IA).

	Variable	Value
Physical Description	Year constructed (27)	2010
	Deck structure type (107)	Concrete CIP
	Wearing surface type (108A)	Monolithic concrete
	Length (ft) (49)	154.8
	Width (ft) (52)	40
Exposure Conditions	Primary Chloride Source	Deicing Salt
	Chloride Exposure	High
	F/T exposure	High
	ADT (29)	6950
	%ADTT (109)	27

Table 4.15 Contractor experience assumed for bridge 36281 (IA).

Maintenance Actions	Contractor Experience Risk
Healer-Sealer	Low
HMA Overlay with Membrane	High
PCC or HPC Overlay	Low
Thick Polymer Concrete Overlay	High

Table 4.16. Deterioration model collected from LTBP portal for bridge 36281 (IA).

Deterioration Model	
NBI	**Year**
9	2010
8	2038
7	2045
6	2050
5	2055
4	2059

4.3.2 Outputs

The service life extension was estimated assuming the previously described exposure conditions and contractor experience. The slower deterioration rates due to the application of each of the maintenance actions were estimated, as shown in Figure 4.10. The initial cost versus the estimated service life extension is shown in Figure 4.11. The figure demonstrate the amount of increase in the service life extension as the initial cost increases. Summary of the results of SLEE and LCCA modules for each of the investigated actions is shown in Table 4.17. The lowest present value is estimated to be achieved with the healer sealer and the greatest service life extension to be achieved with the PCC or HPC overlay. Since the bridge is assumed to be at a general NBI rating higher than 8, based on the assumed deterioration model, the improved condition rating is greater than 9 for some the maintenance actions. It is noted that the highest NBI rating is 9, however values for improved conditions represent theoretical ratings to aid in the selection of actions by the user.

The optimization results considering sole priorities to each of the PV and RSL independently, as well as weighed priorities of the two parameters are presented in Table 4.18 and Table 4.19, respectively. The optimum alternative would be yielding a value of one. If the user is prioritizing the PV or assigning equal priorities to the PV and RSL, the healer-sealer would be ranked first. If the user has higher priority to the RSL, either the PCC or HPC overlay and thick polymer concrete overlay would be proposed by the portal.

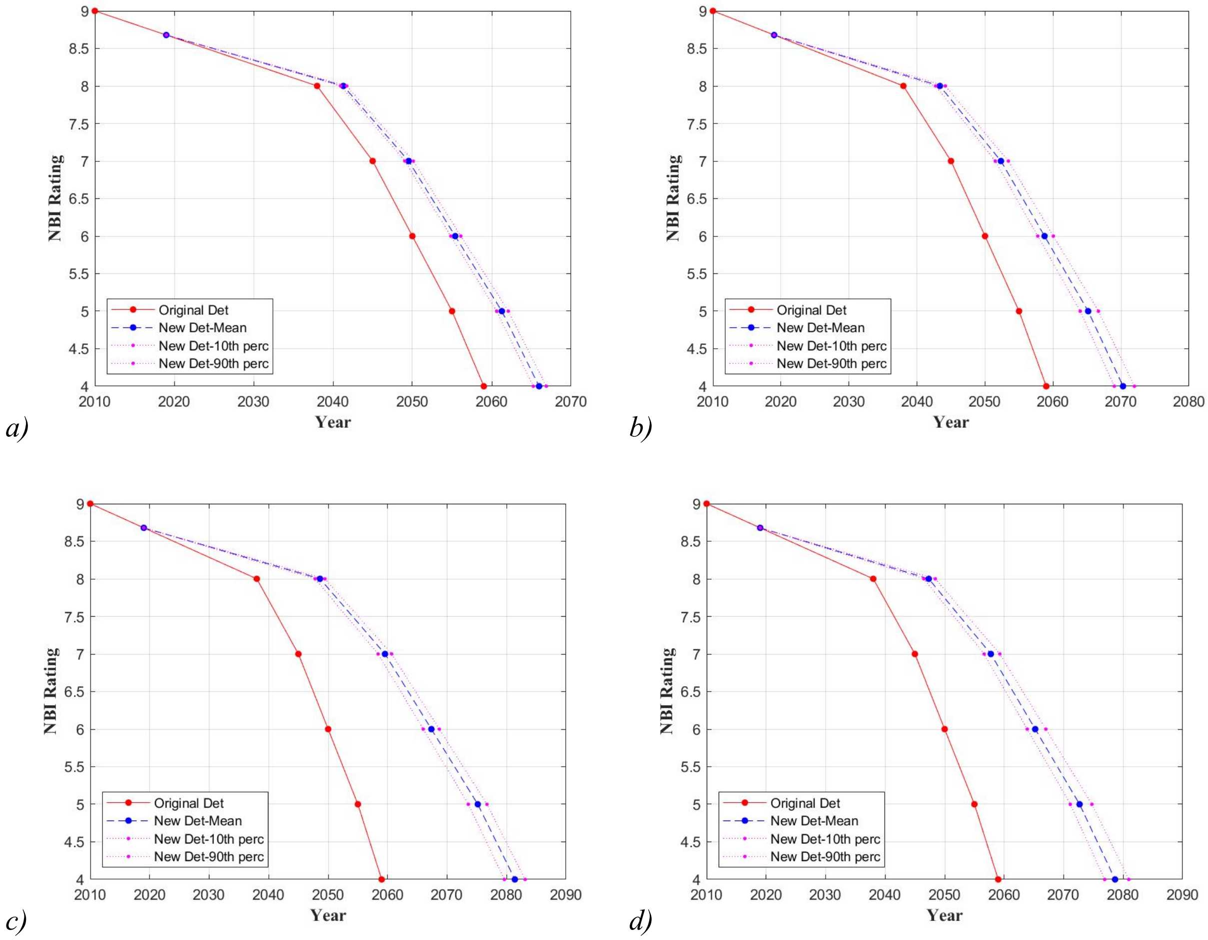


Figure 4.10. Deterioration model for bridge 36281 (IA) considering a) Healer-Sealer, b) HMA Overlay with Membrane, c) PCC or HPC Overlay, d) Thick Polymer Concrete Overlay.

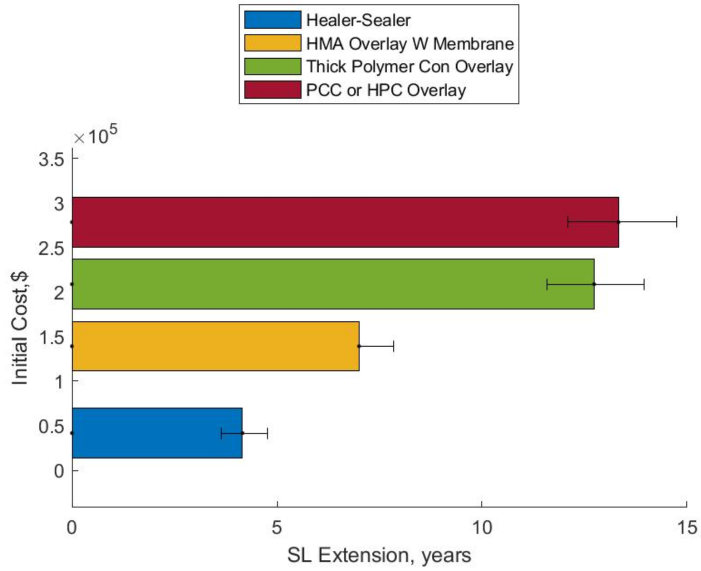


Figure 4.11. Initial cost versus service life extension for each of the investigated maintenance actions, bridge 36281 (IA).

Table 4.17. Tabular summary of the algorithm modules results for bridge 36281 (IA).

Variable	Do Nothing	Healer-Sealer	HMA Overlay with Membrane	PCC or HPC Overlay	Thick Polymer Concrete Overlay
	Deterministic	50th Percentile	50th Percentile	50th Percentile	50th Percentile
Undiscounted Sum, $	530,743	487,732	500,226	561,852	530,892
Present Value (PV), $	96,837	89,463	120,190	161,616	134,948
Improved NBI	8.7	8.9	9.1	9.5	9.4
RSL, years	40.0	47.0	51.3	62.4	59.6
SL Extension, years	0.0	7.0	11.3	22.4	19.6
Initial Cost, $	0	18,576	61,920	123,840	92,880

Table 4.18. Normalized agency LCC and remaining service life, bridge 36281 (IA).

Variable	Do Nothing	Healer-Sealer	HMA Overlay with Membrane	PCC or HPC Overlay	Thick Polymer Concrete Overlay
PV	0.92	1	0.74	0.55	0.66
RSL	0.64	0.75	0.82	1	0.96

Table 4.19. Optimization values for the maintenance actions, bridge 36281 (IA).

Variable	Do Nothing	Healer-Sealer	HMA Overlay with Membrane	PCC or HPC Overlay	Thick Polymer Concrete Overlay
	Deterministic	50th Percentile	50th Percentile	50th Percentile	50th Percentile
Equal Weight factors	0.78	0.88	0.78	0.78	0.81
Priority to PV (0.75*PV+0.25*RSL)	0.85	0.94	0.76	0.66	0.74
Priority to RSL (0.25*PV+0.75*RSL	0.71	0.81	0.80	0.89	0.89

4.3.3 Discussion

To demonstrate the effect of the condition of the bridge deck at the time of the maintenance action application, the results assuming different initial NBI ratings of the deck were investigated. This was explored by considering the same deterioration model presented in Table 4.16, but with the assumption that the "current" year is the year when the condition has dropped to a lower rating. It should be noted that this is not equivalent to the process of optimizing the time for applying the maintenance action, since in the following examples, the present values are obtained by converting future cost to their values at the year of the maintenance application, not the true current year.

The deterioration model shown in Table 4.16 implies a current general NBI rating for the deck (year 2019) of approximately 8.7. To investigate the portal results for a current condition of NBI ratings of 8, 7, 6, and 5, the "current" year is assumed to be 2038, 2045, 2050, and 2055, respectively. Figure 4.12 and Figure 4.13 show the effect of the current condition on the service life extension, where lower service life extension is expected for poorer deck conditions. This is mainly attributed to the incorporated pre-existing NBI condition reduction factor as well as the reduced service life extension lower bound considered for decks in fair o poor conditions as described in Chapter 3. The initial cost (at the "current" year when the action is assumed to be applied) versus the service life extension is shown in Figure 4.13. Note that inflation was not included in the cost analysis in the examples.

A summary of the present values and remaining service life results assuming different values for the current deck NBI ratings is shown in Table 4.20 and Table 4.21, respectively. When the analysis was performed assuming very good bridge conditions (deck NBI rating of 8 or higher), the healer-sealer yielded the lowest estimated present value. For lower condition rating, the thick polymer concrete overlay yielded the lowest agency LCC (present value). The PCC or HPC overlay alternative, based on the adopted assumptions, yielded the greatest remaining service life regardless of the assumed current condition. It is worth noting that some of the considered maintenance actions such as the healer-sealer are typically applied at regular intervals and the analysis of a single application might not be representative of such maintenance plans.

The optimization module was utilized to rank the maintenance actions based on a three different priority configurations regarding the agency cost and remaining service life. As discussed earlier, with a current estimated deck NBI rating of 8.7, the healer-sealer was ranked highest in the cases of equal priorities to the PV and RSL or higher priority to the PV. When higher priority was assigned to the RSL, both PCC or HPC overlay and the thick polymer concrete overlay were ranked first. For deck general NBI condition rating of 8 or lower, the portal ranked either the PCC or HPC overlay or the thick polymer concrete overlay first depending on the user priorities, as shown in Table 4.22.

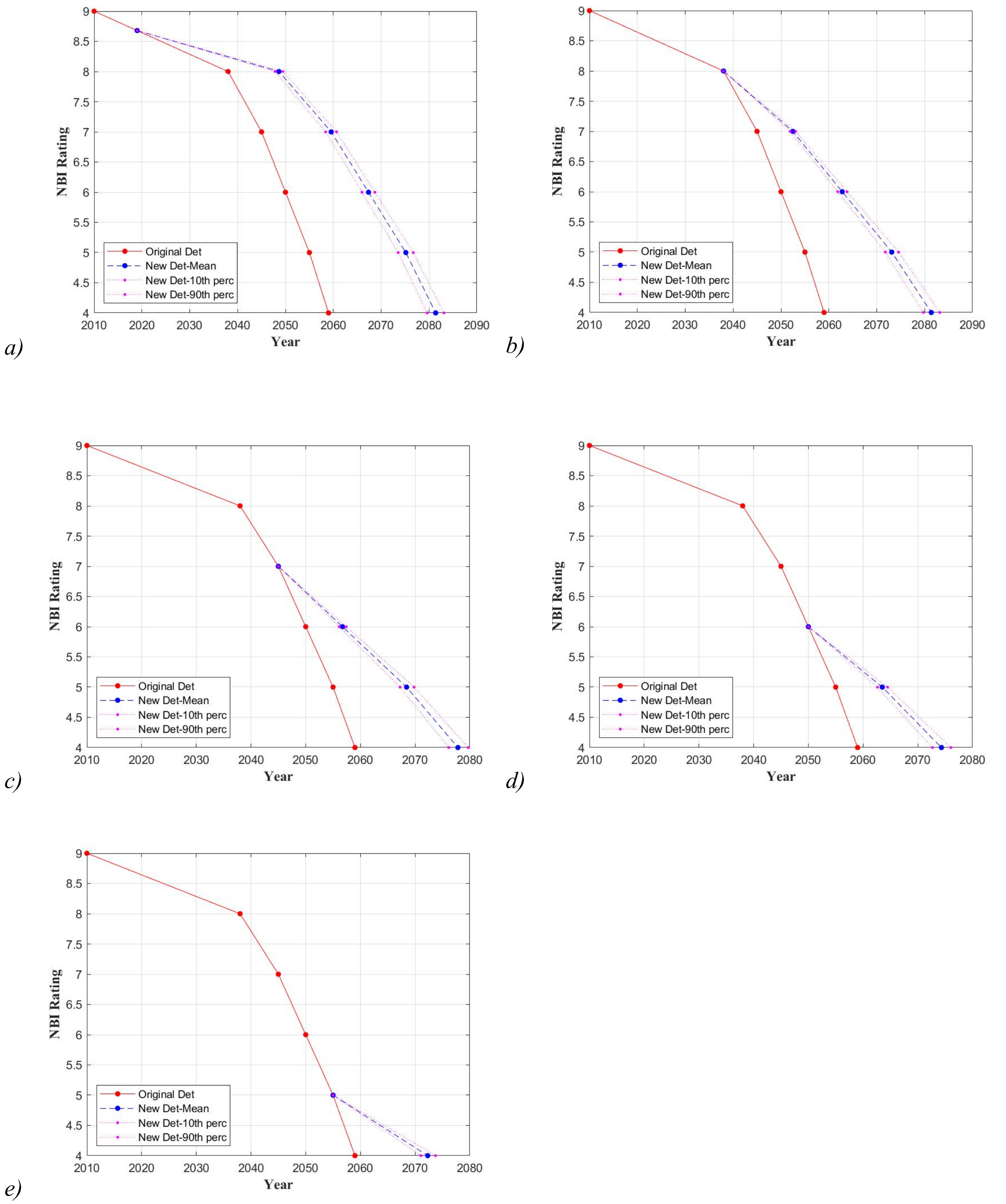
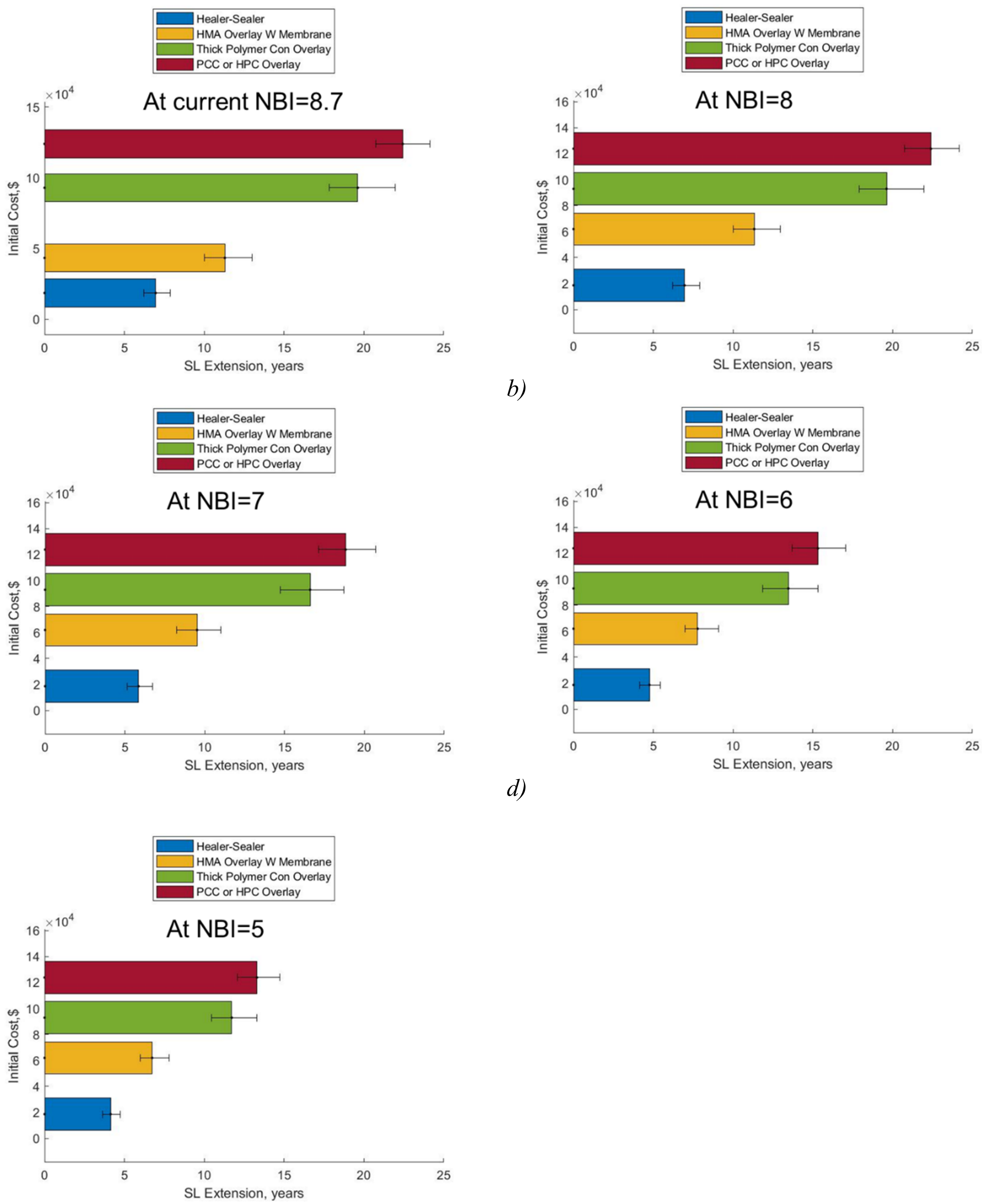


Figure 4.12. Deterioration models for bridge 36281 (IA) assuming PCC or HPC overlay and a current condition of the deck of a) NBI rating of 8.7, b) NBI rating of 8, c) NBI rating of 7, d) NBI rating of 6, and e)NBI rating of 5.



a) b) c) d) e)

Figure 4.13. Initial cost versus service life extension for bridge 36281 (IA) assuming a current condition of the deck of a) NBI rating of 8.7, b) NBI rating of 8, c) NBI rating of 7, d) NBI rating of 6, and e)NBI rating of 5.

Table 4.20. Summary of the present value (agency LCC) results for bridge 36281 (IA) assuming different current conditions.

Variable	Do Nothing	Healer-Sealer	HMA Overlay with Membrane	PCC or HPC Overlay	Thick Polymer Concrete Overlay
	Deterministic	50th Percentile	50th Percentile	50th Percentile	50th Percentile
NBI 8.7 - Present Value	96,837	89,463	120,190	161,616	134,948
NBI 8 - Present Value	214,716	179,972	196,451	207,169	187,093
NBI 7 - Present Value	284,828	243,514	255,674	255,569	237,491
NBI 6 - Present Value	347,868	306,145	316,617	311,353	295,154
NBI 5 - Present Value	424,376	378,603	386,476	373,258	358,638

Table 4.21. Summary of the remaining service life results for bridge 36281 (IA) assuming different current conditions.

Variable	Do Nothing	Healer-Sealer	HMA Overlay with Membrane	PCC or HPC Overlay	Thick Polymer Concrete Overlay
	Deterministic	50th Percentile	50th Percentile	50th Percentile	50th Percentile
NBI 8.7 - Remaining SL	40.0	47.0	51.3	62.4	59.6
NBI 8 - Remaining SL	21.0	28.0	32.3	43.4	40.6
NBI 7 - Remaining SL	14.0	19.9	23.5	32.8	30.6
NBI 6 - Remaining SL	9.0	13.8	16.8	24.3	22.5
NBI 5 - Remaining SL	4.0	8.1	10.7	17.3	15.7

Table 4.22. Optimization module results for bridge 36281 (IA) assuming different current conditions.

Optimization Function (Current NBI - 8.7)					
Variable	Do Nothing	Healer-Sealer	HMA Overlay with Membrane	PCC or HPC Overlay	Thick Polymer Concrete Overlay
Equal Weight factors	0.78	0.88	0.78	0.78	0.81
Priority to PV	0.85	0.94	0.76	0.66	0.74
Priority to RSL	0.71	0.81	0.80	0.89	0.89
Optimization Function (NBI - 8)					
Equal Weight factors	0.66	0.82	0.83	0.94	0.95
Priority to PV	0.75	0.91	0.88	0.90	0.96
Priority to RSL	0.57	0.73	0.79	0.97	0.95
Optimization Function (NBI - 7)					
Equal Weight factors	0.63	0.79	0.83	0.97	0.97
Priority to PV	0.73	0.89	0.88	0.95	0.98
Priority to RSL	0.53	0.70	0.77	0.98	0.95
Optimization Function (NBI - 6)					
Equal Weight factors	0.61	0.77	0.81	0.98	0.96
Priority to PV	0.73	0.86	0.87	0.96	0.98
Priority to RSL	0.49	0.67	0.75	0.99	0.94
Optimization Function (NBI - 5)					
Equal Weight factors	0.54	0.71	0.78	0.98	0.96
Priority to PV	0.70	0.83	0.85	0.97	0.98
Priority to RSL	0.39	0.59	0.70	0.99	0.93

4.4 Summary

This section serves to illustrate the approach presented in Chapter 3. The reported recommendations regarding the selection of maintenance actions are highly dependent on the assumed inputs. Accurate outputs would require accurate and representative inputs. The developed preliminary tool was capable of running different cases efficiently for proof of concept examples. The output of these examples suggest successful implementation of the framework. The algorithms tool is currently limited to single application of maintenance actions at the current year of the analysis. The approach for analyzing multiple applications of a set of maintenance actions is defined as part of the framework in Section 3.3.3, Maintenance Activity Plan. A validation of that approach could be performed pending further development of the analysis. Parametric study is needed to optimize and validate some of the parameters such as the classification thresholds and distribution parameters for reduction factors.

The current deck condition rating employed in the analysis is based on the deterioration models extracted from the LTBP portal as this information was not yet a part of the InfoBridge portal at the time of the report. These models are developed based on deterioration rates estimated for the overall bridge and not for the deck specifically. It is also worth mentioning that these deterioration models do not necessarily match the deck ratings listed in the latest inspection reports. The BDPP does not account for model updating based on recent inspections. In addition, previous repairs or rehabilitation are assumed to be accounted for by the deterioration model entered as an input to the analysis. It is our understanding that the newly developed InfoBridge portal is periodically updated based on recent inspection results, traffic volumes, and local climate changes.

5 NEXT STEPS FOR THE BRIDGE DECK PRESERVATION PORTAL

This report presents a framework for the BDPP to be a tool that aids decision-makers in selecting optimum maintenance actions for bridge decks by analyzing life cycle cost, service life improvement, and the inherent risk of possible maintenance actions.

As conceptualized herein, the BDPP relies on user input regarding the deck configuration, deck condition, and exposure conditions. Additional information on locally-observed costs and service life is also desirable to improve the analysis. The framework uses an automated process to select appropriate maintenance actions, predict how they will benefit service life, and estimate their costs. However, the user is given control over the decisions and output of the portal throughout the process such that the portal can be tailored to better address user needs. The framework ranks potential maintenance action plans that are generated and presents the supporting data to the user for use when deciding between different maintenance options. Chapter 3 discussed how the framework logic works and the assumptions embedded in the portal in detail. Chapter 4 provided preliminary examples demonstrating the functionality and feasibility of the proposed logic. The content in both referred to a maintenance actions database, for which a draft is presented in Appendix B.

5.1 RFP for Tool Development

The BDPP was intended to be a web-based portal. However, a MATLAB-based tool and a Microsoft Excel-based tool are alternative options. A limited MATLAB tool that can complete the SLEE, LCCA, and Optimization modules was already developed to conduct the preliminary examples in Chapter 4.

A web-based portal is desirable because it would be easily accessible to users across the states and do not require re-distribution of software when new software updates are completed. The webpage design may be tailored so that the interface is easy to understand without compromising the power needed for the calculations. The web-based portal could also communicate with other websites such as the InfoBridge and NOAA, as stated in Chapter 3, to automatically obtain deck condition and exposure condition inputs. However, developing a web-based portal is relatively expensive.

An Excel tool is an alternative option. Microsoft Excel is widely-used by the intended audience for this portal, which is desirable because this familiarity facilitates interaction between the portal and the user as well as transparency. However, due to the required user interaction, the portal would be relatively difficult to navigate in Excel. Additionally, calculation capabilities of Excel are relatively limited and complex Monte Carlo analysis and optimization may need to be simplified if an Excel tool is chosen.

The third option considered is a MATLAB tool. MATLAB is capable of more powerful analysis than Excel and better suited to the logic of the portal framework. Few agencies use MATLAB, but because the program can accept and output Excel spreadsheets, knowledge of MATLAB would not be required by the tool. Because the input/output and the calculating program are separate, this may make a MATLAB tool appear to be a black box but this may be overcome by incorporating instructions and controls in the Excel sheet. The MATLAB tool would simplify the Excel workbook and improve the interface between the portal and the user.

Based on discussion with TAC, it was determined that the MATLAB tool is the preferred approach. A list of tasks for a MATLAB-based tool and a web-based tool are presented in the following sections.

5.1.1 MATLAB-based Tool

During the current effort, WJE developed a preliminary version of a MATLAB-based program that could be used to complete the analyses proposed in the BDPP. The preliminary tool only considers single application of maintenance actions and can only be used for degradation-controlled service life. Additionally, the tool cannot perform several aspects of the framework including: filtering and selecting of maintenance actions, deferred maintenance, changing analysis time frame, and development of automatically-generated maintenance activity plans.

The tasks required to develop the tool to analyze multiple maintenance action plans and complete the described analyses by the proposed framework are as follows:

Task 1. **Develop the Input and Output Forms**
The forms must be easy to understand and navigate. Input variables, their units, and status as required or optional must be clearly identified.

Task 2. **Develop the Database**
The database is to contain the list of maintenance actions presented in Chapter 3. The database will attach a series of filters and thresholds, an upper bound for service life, a set of condition-dependent lower bounds for service life, and a cost distribution to each maintenance action. It will also define which reduction factors apply to the maintenance action and define the remaining factors a value of 1. This information is available in Appendix B. This task will include refining the assumed values as well as adding them as default values in the program. The task will also include decision matrices for using non-destructive evaluation data.

Task 3. **Develop the Filters & Thresholds Module**
This module will accept the information from the input form and evaluate which actions from the database are recommended based on the filters and thresholds associated with each bridge.

Task 4. **Reduction Factors**
This task will include reviewing the reduction factors and associated probability distributions. All the factors will be programmed in the code.

Task 5. **Deferred Maintenance**
This task will include modifying user input to permit user to choose the number of years initial maintenance is deferred. This will allow the user to optimize installation of preservation actions on bridge decks that are in good condition.

Task 6. **Develop the Automatically-Generated Maintenance Activity Plans and Timing Optimization Module**
This task will include development of the algorithm to automatically develop maintenance plans based on the bridge condition. This will include performing several re-runs of the Filters & Thresholds and SLEE modules to automatically build and evaluate life cycle maintenance activity plans at the request of the user.

As the framework stands now, it does not include an automated efficient optimization procedure to determine the optimal maintenance action plan. The time of maintenance is pre-determined by assuming that maintenance will be conducted in the current year and that further maintenance will be conducted in the year that the service life of the previous maintenance action ends. It is proposed that the tool may include this optimization capability by permitting both the type and the timing of the maintenance to be chosen freely without the limitations built into the Filters and Thresholds and the SLEE modules of the current framework. Using one of the algorithms described in Chapter 2, or an alternative optimization technique, the portal would be able to provide the estimated optimal maintenance action plan. This option is included in Task 6. If not desired, the effort associated with this task can be decreased.

Task 7. <u>Example Bridges and Quality Control</u>
Once written, the tool is to be troubleshot by running examples from start to finish without interruption including typical user input and interaction. The tool will be distributed to the TAC committee for evaluation and revisions will be made according to feedback received.

Task 8. <u>Bridge Deck Preservation Tool Manual</u>
A user's manual will be written in order to provide clear direction to the user regarding how to input data and interact with the portal, and to aid the user in troubleshooting issues. The manual is intended to be concise; while it will briefly describe the portal's applicability, it will not go into the detailed recount of assumptions as was provided in Chapter 3.

Task 9. <u>Distribute the Tool and Manual</u>
At the end of the project, the tool and manual will be made available to bridge owners. In addition, the contractor will offer a webinar based training at the same time to familiarize the primary users with the developed tool. The webinar should be made available on a website or cloud storage so that future users can benefit from the same training. It is envisioned that the training will include a description of all the modules included in the tool as well as few example bridges.

Optional Tasks

Task A.1. <u>Parametric Study to Validate Reduction Factors and Estimated Service Life.</u>
The proposed framework requires validation. It relies on Eq. 3-1, which states that the service life of the maintenance actions may be interpolated between the lower and upper bounds found in literature based on reduction factors that represent different exposure and bridge specific conditions. Values and distributions for the reduction factors were decided based on the experience of WJE's experts and conditions found across the states. However, there is no empirical basis for these parameters, or for their combination as described by Eq. 3.1. The reduction factors and form of the equation should be confirmed by conducting a parametric study of different scenarios found across the states. The results of the study will help in assessing whether the tool will yield reasonable results or if revisions are required.

Task A.2. <u>Graphical User Interface.</u>
The proposed tool will rely on excel based input sheets. A user friendly graphical interface can be developed for the tool where users can choose maintenance options and view results. Although not necessary for functionality, a user friendly graphical user interface can make the tool easier to use and improve the experience of the users.

5.1.2 Web-based Portal

This section discusses the tasks associated with developing a web-based portal based on the framework proposed in this report. Some of the tasks discussed above may be added to the scope of work below as needed.

Task 1. Kick Off Meeting

The developer will be required to attend a kick-off meeting with the Technical Advisory Committee to discuss the proposed processes and deliverables. The meeting can be through video conference or in person.

Task 2. Portal Framework Review

The Portal Framework will be provided to the developer. The framework outlines the background calculations necessary to determine the appropriate bridge deck rehabilitation process and life cycle. The developer will review the framework and provide comments on how the framework will incorporated into the proposed web tool.

Task 3. User Interface Review

After the framework is approved, the developer will create mock-up user interface (UI) exhibits to demonstrate how a user will input and output data from the portal. The UI mock-up will require explanations of how bridge data is input into the portal, how the information will be retrieved for editing, how user preferences will be saved, and how input and output data is documented for review.

During the user interface review, the developer will be required to demonstrate how data may be shared though out a jurisdiction, and how scenarios will be saved and managed.

Task 4. Background Calculations

The developer will be required to submit verification of the background calculations for review. The review will consist of verification that the results of completing analysis with the Bridge Deck Preservation Portal is validated to the intent of the information provided in the framework analysis.

Task 5. Beta Test Period

When the web portal is complete, the developer will provide the participating jurisdictions with a beta version. The participating jurisdictions will have a 60 day period to test the software, analyze bridges, and provide comments back to the developer.

Task 6. Documentation

When the final portal is provided, documentation of the code shall be submitted to the technical committee.

Task 7. Prepare a User Manual

The developer will prepare a user manual for the portal. The user manual should provide sufficient information on the inputs and the background calculations to allow engineers to understand the implications of the outputs from the portal. Specific engineering information will be provided to the developer in the Portal Framework.

5.2 Discussion and Next Steps

A framework for the bridge deck preservation tool was developed to aid state bridge preservation engineers in decision making regarding selecting maintenance actions for bridge decks. The developed framework is a project-level optimization tool, rather than a network level optimization tool, and currently focuses on optimizing maintenance actions for bridge decks. WJE developed a MATLAB-based tool to conduct the probabilistic analysis as shown in the examples. The current MATLAB-based tool could be used to check the results of a future web-based tool or it can be further developed as PC-based program to conduct all the analyses proposed in the framework. A summary of tasks for development of a MATLAB-based tool or a web-based portal was also developed.

The framework presented in this study is scalable and could be adopted for other bridge elements including superstructure and substructures. These parts of the bridge structure would require separate databases and different Filters and Thresholds modules, as they are not subjected to deck overlays and are better suited to maintenance actions such as installing coating systems, which are rarely used on decks. However, the general framework is expected to be translatable to these structures and the portal could be expanded such that it could analyze decks, superstructures, and substructures independently.

Once analyses for the superstructures and substructures are developed, the deck and the super- and substructures may be considered holistically such that the effect of maintenance on one area of the bridge may be included in analysis on the remaining parts of the bridge. For example, if the superstructure is expected to fall into poor condition, then the deck may be replaced with the superstructure and further preservation may be unnecessary. By conducting a holistic analysis, the portal would recognize interdependencies that it is not capable of considering currently, which would result in better optimization of the maintenance action plans for bridges.

The tasks in Section 5.1, *RFP for Tool Development*, are limited to development of the framework presented in Chapter 3. However, additional capabilities beyond the proposed framework have been identified as desirable. In addition, several assumptions were made to increase the practicality of the proposed tool including the use of deterioration models from available sources such as InfoBridge. A summary of potential additional capabilities and areas of research are identified below for future consideration.

- *Conduct long-term studies to monitor and evaluate how maintenance effectiveness decreases with time and continued bridge deck deterioration.*
  The SLEE and DM algorithms rely on the assumption that the maintenance action is effective for its expected service life, and then the maintenance action or repair loses its functionality at the end of its life. This is an approximation, as was discussed in Chapter 3, and may result in optimistic estimates. To combat it, the lower bounds found in literature were decreased based on experience. As for the reduction factors, there is limited empirical basis for these and studies of how effectiveness of the maintenance decreases with time should be conducted. These studies would have the additional benefit of improving the accuracy of the assumed deterioration curve after the maintenance. While not critical to further analysis in the portal now, a more accurate curve can aid the portal in developing more appropriate long-term maintenance action plans.

- *Use of accurate cost estimates.*
  The Filters and Thresholds, SLEE, and LCCA modules rely heavily on the maintenance actions database to generate cost and service life estimates. During the preliminary examples, it was

found that the ranking is particularly sensitive to the costs assumed for the maintenance actions. A preliminary literature review was conducted to provide reasonable cost estimates for the common maintenance actions and the resulting draft database is provided in Appendix B. The default values found during the preliminary literature review should be further researched and refined to ensure accurate portal output, especially if it is anticipated that users will not have service life and cost estimates of their own available for use. Alternatively, accurate cost estimates can be provided by the users which is anticipated to change between different states.

- *Implement a system in the database that permits users to input service life and cost data such that the database will update its default values accordingly.*
  Dynamic default values may be used instead of static values. Rather than conducting literature reviews at regular intervals to maintain the accuracy of the database, the database may become a data repository or work with agency data repositories to update its default costs and service life bounds automatically as new data is generated each year. While a review of existing literature would be required to firmly establish the database and there would be a higher initial investment to develop the capability, this method would require less maintenance long-term.

- *Add other types of deterioration not covered by the current framework.*
  While the current portal covers typical degradation mechanisms that can affect the service life of concrete, steel and timber decks, additional mechanisms such as fatigue of steel could be added to future versions of the tool. Deterioration curves will need to be established for such mechanisms to be allow for prediction of remaining service life.

- *Update InfoBridge deterioration models based on current conditions.*
  The examples presented in Chapter 4 used inspection data provided by states and deterioration curves from LTBP web-portal. In some cases, discrepancies were found in terms of the bridge deck condition, where the inspection report shows a different condition than the estimated in the deterioration curve. In its current form, the developed framework will rely on the deterioration curve condition rate. In addition, improved condition from recent repairs are typically not accounted for in the deterioration curves. A model updating module could be developed in the future to account for such cases and provide a more realistic deterioration curve and remaining service life expectancy. Alternatively, state engineers can use in-house deterioration curves for bridge decks if available.

- *Work towards implementation of artificial intelligence platform to provide more accurate service life and cost estimates.*
  Incorporating AI in the framework for this project was not pursued because the best practices for bridge deck maintenance are widely known and accepted throughout industry, and the development of an AI platform would take resources and experimentation that could delay the prompt deployment of a functional tool. However, an AI system should be considered long-term because it would be able to improve the accuracy of service life and cost estimates conducted by the BDPP algorithms and because implementation of AI is becoming easier and more widely accepted. An AI platform would require implementation and maintenance of a data repository, which requires more upfront effort from the agency but would help individual portal users. A repository would also permit performance tracking and retention of experience-based estimates despite changes in personnel. The data repository would need to be synced to the BDPP algorithms to provide service life and cost estimates, and the framework would

eventually need to be reconsidered to shift from the algorithms defined in Chapter 3 to more refined algorithms developed by the AI platform.

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APPENDIX A. EXAMPLES OF DECISION MATRICES USED IN STATE PRACTICE

CONDITION CATEGORY	**PERCENT OF UNSOUND DECK AREA**	**WORK TYPE OPTIONS** Traffic Volume (current ADT)		
		< 2,000	2,000 to 10,000	> 10,000 and Interstates
I Slight Deterioration	0 to 2% SIMS deck condition state 2	**Priority 11** Do Nothing or Spot Repairs	**Priority 9** Do Nothing or Spot Repairs	**Priority 8** Do Nothing or Spot Repairs
II Moderate Deterioration	2% to 10% SIMS deck condition state 3	**Priority 10** Mill And Patch	**Priority 7** Mill And Patch	**Priority 6** Mill And Patch or Re-Overlay
III Severe Deterioration	10% to 25% SIMS deck condition state 4	**Priority 5** Deck Repairs, 100% Scarify And Add Overlay	**Priority 4** Deck Repairs, 100% Scarify And Add Overlay	**Priority 3** Deck Repairs, 100% Scarify And Add Overlay
IV Critical Deterioration	> 25% SIMS deck condition state 5	**Priority 4** *Deck Repairs, 100% Scarify And Add Overlay	**Priority 2** **Schedule New Deck	**Priority 1** **Schedule New Deck

* Priority 4 decks should be overlayed only if a thorough evaluation indicates that minimal unsound concrete extends below the top of rebars. If extensive areas of unsound concrete exist below the top of rebars, patch and repair and maintain the deck in accordance with the guidelines until the end of its useful life.

**When the useful service life of the deck has ended, a bituminous overlay may be required to maintain ride ability. A limited service concrete overlay may be economical to extend the useful life of the deck.

Figure A.1. A bridge deck preservation matrix published in the Fiscal Year 2016 through 2020 Bridge Preservation and Improvement Guidelines, from the Minnesota Department of Transportation (Bridge Office, 2015).

BRIDGE DECK PRESERVATION MATRIX – DECKS WITH UNCOATED "BLACK" REBAR

DECK CONDITION STATE				REPAIR OPTIONS	POTENTIAL RESULT TO DECK BSIR		ANTICIPATED FIX LIFE
Top Surface		Bottom Surface					
BSIR #58a	Deficiencies % (a)	BSIR #58b	Deficiencies % (b)		Top Surface BSIR #58a	Bottom Surface BSIR #58b	
≥ 5	N/A	N/A	N/A	Hold (c) / Seal Cracks	No Change	No Change	N/A
				Silane			5 years
				Healer Sealer (d)			8 to 10 years
	≤ 10%	≥ 6	≤ 2%	Epoxy Overlay (f)	8, 9	No Change	15 to 20 years
	≤ 10%	≥ 4	≤ 25%	Deck Patch (e, j)	6, 7, 8	No Change	5 to 10 years
4 or 5	10% to 25%	≥ 5	≤ 10%	Deep Concrete Overlay (h, j)	8, 9	No Change	25 to 30 years
		4	10% to 25%	Shallow Concrete Overlay (h, i, j)	8, 9	No Change	20 to 25 years
				HMA Overlay with water-proofing membrane (f, i)	8, 9	No Change	8 to 10 years
		2 or 3	> 25%	HMA Cap (g, i)	8, 9	No Change	2 to 4 years
≤ 3	>25%	≥ 6	< 2%	Deep Concrete Overlay (h, j)	8, 9	No Change	20 to 25 years
		4 or 5	2% to 25%	Shallow Concrete Overlay (h, i, j)	8, 9	No Change	10 years
				HMA Overlay with water-proofing membrane (f, i)	8, 9	No Change	5 to 7 years
		2 or 3	>25%	HMA Cap (g, i)	8, 9	No Change	1 to 3 years
				Replacement with Epoxy Coated or Stainless Rebar Deck	9	9	60+ years

(a) Percent of deck surface area that is spalled, delaminated, or patched with temporary patch material. Top surface decision making based on concrete surface, not the condition of thin epoxy overlays or other wearing surfaces.
(b) Percent of deck underside area that is spalled, delaminated or map cracked.
(c) The "Hold" option implies that there is on-going maintenance to sustain current ratings.
(d) Seal cracks when cracks are easily visible and minimal map cracking. Apply healer sealer when crack density is too great to seal individually by hand. Sustains the current condition longer.
(e) Crack sealing must also be used to seal the perimeter of deck patches and joint replacements.
(f) Deck patching required prior to placement of epoxy overlay or waterproofing membrane.
(g) Hot Mix Asphalt cap without waterproofing membrane for ride quality improvement. Deck should be scheduled for replacement in the 5 year plan.
(h) If bridge crosses over traveled lanes and the deck contains slag aggregate, do deck replacement.
(i) When deck bottom surface is rated poor (or worse) and may have loose or delaminated concrete over traveled lanes, sidewalks or non-motorized paths, an in-depth inspection should be scheduled. Any loose or delaminated concrete should be scaled off and false decking should be placed over traveled lanes where there is potential for additional concrete to become loose.
(j) Some full depth repairs should be expected where top surface deficiencies align with bottom surface deficiencies.

Bridge Deck Preservation Matrix **July, 2017 Rev.**

Figure A.2. One of the bridge deck preservation matrices published by the Michigan Department of Transportation.

APPENDIX B. MAINTENANCE ACTIONS SERVICE LIFE BENEFIT AND COST

This appendix provides profiles for the maintenance actions currently considered in the proposed framework for the BDPP as well as a few supplementary profiles that should be considered in future iterations. The maintenance action is first defined and introduced. A description of the procedure and/or material is included as well as advantages and disadvantages of the action. Three subsections identify appropriate times of implementation, cost, and service life. The references used to build the profile are listed at the end of each action.

The maintenance actions currently included are the following:

1. Roughening the Wearing Surface
2. Crack Sealing of Concrete
3. Applying a Penetrating Sealer
4. Applying a Healer-Sealer
5. Placing a Polymer Chip Seal
6. Crack Sealing of Asphalt
7. Repairing Asphalt Pavement
8. Applying a Bituminous Surface Treatment
9. Installing Studs
10. Painting a Steel Deck (Underside)
11. Metallizing a Steel Deck
12. Replacing Grid Plates
13. Applying a Surface Preservative Treatment
14. Installing a Fumigant or Preservative
15. Stress-Laminating Timber Decks
16. Replacing Timber Planks or Runners
17. Placing a HMA Overlay
18. Placing a Modified Asphalt Overlay
19. Placing a HMA Overlay with a Waterproofing Membrane
20. Placing a PCC/HPC Overlay
21. Placing a SFC Overlay
22. Placing an UHPC Overlay
23. Placing a LMC/PMC Overlay
24. Placing a LMCVE Overlay
25. Placing a Thick Polymer Concrete Overlay
26. Placing a Thin Polymer Overlay
27. Concrete Partial-Depth Repair (supplemental)

1. Roughening the Wearing Surface

Concrete and asphalt pavements experience abrasion due to tire treads and will lose their skid resistance over time. Pavements with aggregates that are less abrasion-resistant become polished more quickly. For bridge decks with concrete wearing surfaces, this is not a large concern in dry areas because there is sufficient friction between the concrete and the tire. But in wet conditions, loss of texture can cause hydroplaning and increases the number of safety accidents. Asphalt pavements are particularly susceptible to decreased skid resistance under conditions that encourage bleeding of the slippery asphalt binder to the top of the surface. This can be caused by excess binder in the mixture design, high temperatures, or a combination of the two.

In areas of high risk, concrete pavements are often "tined" or "grooved." Evenly-spaced grooves may also be cut into existing pavements to improve safety. This is achieved by channeling water away, which decreases the chance of hydroplaning, and introduces macrotexture, which improves skid resistance. Roughening the wearing surface may also be achieved by diamond grinding instead of grooving. Grinding the surface primarily improves skid resistance by introducing micro-texture. Grinding the surface may also be used to improve skid resistance.

The general procedure for roughening a bridge deck's wearing surface assumed by the BDPP is as follows:

1. Measure the current profile of the wearing surface.
2. Groove the surface in the direction desired.
3. Grind areas to provide a smooth profile between grooved and non-grooved areas as necessary.
4. Re-measure the profile to verify new texture.

Cost

The unit cost for roughening the wearing surface will be assumed to be $4.25/sq ft.

Thresholds

Roughening the wearing surface is only considered feasible for concrete and asphalt wearing surfaces. It should only be done when the purpose of the maintenance action is to restore skid resistance or improve ride quality. As such, the deck should be in good condition (NBI deck condition rating of 7 or higher) and the element-level distress identified should be for abrasion/wear. Table B.1 shows the entries for which roughening the wearing surface by grinding or grooving will be removed from consideration in the BDPP.

Table B.1. User entries that cause roughening the wearing surface to be omitted from consideration.

User Input Variable	***Entry***
Wearing surface	Wood or timber
	Gravel
	Other
NBI deck condition rating	≤ 6
Abrasion/wear CS1	> 95%
Primary purpose of maintenance strategy	Extended service life

Service Life

The service life of this repair is controlled by abrasion. Newly-roughened wearing surfaces generally have a high initial friction that drops quickly within the first few months of re-opening to traffic. After this period, the skid resistance decreases relatively slowly. The long-term performance of diamond grinding with regards to friction and associated "texture life" has limited literature. Pavement studies indicate that grinding can extend pavement service life by about 8 to 15 years, on average. However, these pavements have generally been ground to alleviate poor ride quality and the failure mode is not loss of skid resistance, but faulting and poor ride quality again. Therefore, 8 years is considered the minimum expected abrasion-controlled service life of a roughened wearing surface. A service life of 25 years is chosen as the maximum expected abrasion-controlled service life of a roughened wearing surface.

The abrasion-controlled service life of the roughened wearing surface is assumed to fall between 8 and 25 years and is dependent on the following external factors:

- ADTT,
- Number of freeze-thaw cycles, and
- Contractor experience

It is also dependent on the material properties of the concrete and has often been correlated to concrete strength and aggregate abrasion resistance. However, the BDPP only considers environmental or load-related factors.

Roughening the wearing surface offers no service life extension to degradation-controlled service life.

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2. Crack Sealing of Concrete

Cracks in concrete compromise the concrete cover and provide an easy path for chloride ions and moisture to reach the reinforcing steel. As a result, crack sealing is an important maintenance action, particularly for bridges that are exposed to deicing salts. For the BDPP, crack sealing is assumed to be "crack chasing," in which discrete cracks are filled individually with an epoxy resin or other material as described in the following procedure:

1. The area around the crack is lightly sandblasted and cleaned to remove contamination.
2. The crack is blown clean with compressed air.
3. The epoxy resin or other gravity-fill polymer is applied to the crack according to the manufacturer's instructions.

Note that this procedure is followed for relatively wide surface cracks with a low crack density. The cracks may be filled by hand or pressure injected. Pressure injection is typically used for full-depth cracks and is more expensive. Alternatively, cracks may be sealed with a "healer-sealer," which is applied as a flood coat and spread over an area with a high crack density. Because the procedure and full effects are more similar to a deck sealant, healer-sealers are categorized separately.

Cost

The unit cost assumed for crack sealing of concrete is $5.00/linear foot.

Thresholds

This maintenance activity is considered appropriate only for decks with concrete or thick polymer wearing surfaces. Cracking must be present for crack sealing to be considered and the deck should be in good condition. If the deck is in fair condition, then this indicates that an alternative maintenance activity is required to address distress. The primary purpose of crack sealing is to extend service life and this action does not improve skid resistance or ride quality. As such, the primary purpose of the maintenance strategy should be to extend service life. These thresholds are summarized in Table B.2.

Table B.2. User entries that cause crack sealing of concrete to be omitted from consideration.

User Input Variable	***Entry***
Wearing surface type	Epoxy overlay
	Bituminous overlay
	Wood or timber
	Gravel
	Other
NBI deck condition rating	≤ 6
Cracking CS2	> 0%
Primary purpose of maintenance strategy	Improved skid resistance
	Improved ride quality

Hearn (2019) provides guidance for when crack sealing should be considered for bridge decks. The recommended limits associated with each distress type are provided in Table B.3.

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Table B.3. Ranges of element-level condition data for the deck for which crack sealing is considered appropriate, based on Hearn (2019). '-' means no limit.

Distress Type	Quantities			
	CS1	CS2	CS3	CS4
Delamination/spall/patched area	-	< 10%	0%	0%
Exposed rebar	-	0%	0%	0%
Exposed prestressing	-	0%	0%	0%
Cracking (PSC)	< 20%	< 10%	< 5%	0%
Efflorescence/rust staining	-	< 10%	0%	0%
Cracking (RC and other)	< 40%	< 20%	< 10%	0%
Abrasion/wear (PSC/RC)	-	< 10%	0%	0%

Service Life

The life of crack chasing repairs can vary from 1 year to over 10 years. They tend to fail at the interface between the concrete substrate and the polymeric fill, or the fill may crack such that some polymer is left on each side of the original crack in the concrete. It is assumed that these cracks are dormant cracks and all crack movement is caused by thermal stresses. Therefore, the maximum service life expected for this repair is 10 years while the minimum service life is shown in Table B.4 as a function of the current deck NBI condition. The factors affecting the life are:

- Pre-existing condition,
- Number of freeze-thaw cycles, and
- Contractor experience.

Table B.4. Minimum service life extension provided by crack sealing of concrete as a function of NBI deck condition rating.

NBI deck rating	Min. life extension (years)
NBI > 7	5
7 ≥ NBI > 6	3

The above discussion applies to degradation-controlled service life of the bridge deck. Crack sealing of concrete has no effect on the abrasion-controlled service life.

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3. Applying a Penetrating Sealer

Concrete deck sealing is performed to prevent chloride and moisture ingress. There is a wide variety of sealers on the market, with silane-based or siloxane-based penetrating sealers the most common. These products penetrate into the concrete and prevent moisture and chloride ingress by making the surfaces of the concrete pores hydrophobic, by blocking the pores due to their solid contents, or a combination of the two.

Penetrating sealers that protect the concrete by blocking the pores are also called "film formers" and are more commonly used as healer-sealers that also seal fine cracks. These are regarded separately and for this section, it is assume that a silane- or siloxane-based sealer is used.

The general procedures for deck sealing include:

1. Clean and dry the deck.
2. Apply the sealer at the recommended rate.
3. Allow the sealer time to penetrate.

Cost

The cost assumed to seal a concrete deck is $1.35/sq ft.

Thresholds

This maintenance action is only suitable for decks with concrete wearing surfaces and bridges that have chloride exposure due to deicing salts or a marine location. Penetrating sealers are most effective when applied early in the life of the structure; when there is very little distress and the NBI condition rating is high. Penetrating sealers are only used to extend service life of the deck and offer no benefit for ride quality or skid resistance.

The entries input by the user at the start of using the BDPP for which deck sealing will be removed from consideration are listed in Table B.5.

Table B.6 shows the ranges for CS1, CS2, CS3, and CS4 for which deck sealing is appropriate according to Hearn (2019). If the element-level condition data for the deck (or its wearing surface if a non-monolithic wearing surface is present) lays outside of these bounds, then deck sealing will also be not be recommended from consideration.

Table B.5. User entries that cause deck sealing with a penetrating sealer to be omitted from consideration.

User Input Variable	***Entry***
Wearing surface	Latex concrete
	Epoxy overlay
	Bituminous overlay
	Wood or timber
	Gravel
Primary chloride source	None
NBI deck condition rating	≤ 6
Primary purpose of maintenance strategy	Improved skid resistance
	Improved ride quality

Table B.6. Ranges of element-level condition data for the deck for which deck sealing is considered appropriate (Hearn, 2019). '-' means no limit.

Distress Type	Quantities			
	CS1	CS2	CS3	CS4
Delamination/spall/patch	-	< 10%	0%	0%
Efflorescence/rust staining	-	< 10%	0%	0%
Cracking (RC)	< 10%	< 10%	0%	0%
Cracking (PS)	< 10%	0%	0%	0%
Abrasion/wear	-	< 10%	0%	0%
Exposed PS	-	0%	0%	0%
Exposed rebar	-	0%	0%	0%

Service Life

Silane and siloxane penetrating sealers generally have a service life of 3 to 6 years. The service life depends primarily on the material and the pore structure of the concrete rather than the exposure conditions and as such, no reduction factors are considered. For the BDPP, the maximum service life expected for this repair is 6 years while the minimum service life is shown in Table B.7 as a function of the current deck NBI condition. The service life depend on the following factors:

- ADTT,
- Pre-existing condition, and
- Contractor experience.

Table B.7. Minimum service life extension provided by applying a penetrating sealer as a function of NBI deck condition rating.

NBI deck rating	Min. life extension (years)
NBI > 7	3
7 ≥ NBI > 6	2

The above discussion is for degradation-controlled service life. Penetrating sealers offer no benefit for abrasion-controlled service life.

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Morse, K. L. (2009). *Effectiveness of Concrete Deck Sealers and Laminates for Chloride Protection of New and In Situ Reinforced Bridge Decks in Illinois.* Springfield, IL: Illinois Department of Transportation.

Sanders, D., & Mostafa, K. (2018). *Improving the Long-Term Performance of Concrete Bridge Deck using Deck and Crack Sealers.* Carson City, NV: Nevada Department of Transportation.

4. Applying a Healer-Sealer

Like penetrating sealers, healer-sealers are intended to prevent chloride and moisture ingress. However, they are also intended to seal widespread, fine cracking and have a limited ability to seal the pores at the concrete surface. Rather than penetrating the pores, these sealers form a film over the concrete surface. As a result, they require fine aggregates to be overlaid on the binder for skid resistance. The binders are typically high molecular weight methacrylate (HMWM), thin epoxy, or polyurethane.

The general procedures for applying a healer-sealer include:

1. Clean and dry the deck.
2. Apply the sealer at the recommended rate.
3. If the sealer is HMWM, epoxy, or polyurethane (non-penetrating), then apply fine aggregates to the surface.
4. Allow the sealer time to cure, as applicable.

Cost

The cost assumed to apply a healer-sealer to a concrete deck is \$3.00/sq ft.

Thresholds

This maintenance action is only suitable for decks with concrete wearing surfaces and bridges that have chloride exposure due to deicing salts or a marine location. The deck should be in good condition since a fair condition indicates that more extensive maintenance is required. Healer sealers are effective for fine cracks less than 0.010 inches and are often used to address shrinkage, map, and other types of cracking that occur early in the life of the structure. They are only applied in order to extend service life by preventing chlorides and moisture from reaching the steel reinforcement through the cracks. Table B.8 summarizes the user entries for which healer-sealers will be removed from consideration.

Table B.9 shows the ranges for CS1, CS2, CS3, and CS4 for which deck sealing is appropriate according to Hearn (2019). If the element-level condition data for the deck (or its wearing surface if a non-monolithic wearing surface is present) lays outside of these bounds, then deck sealing will also be not be recommended from consideration.

Table B.8. User entries that cause deck sealing with a healer-sealer to be omitted from consideration.

User Input Variable	*Entry*
Wearing surface	Latex concrete
	Epoxy overlay
	Bituminous overlay
	Wood or timber
	Gravel
Primary chloride source	None
NBI deck condition rating	≤ 6
Crack width (in), avg.	> 0.010
Chloride concentration at rebar	> 0.9*(Ct)
Primary purpose of maintenance strategy	Improved skid resistance
	Improved ride quality

Table B.9. Ranges of element-level condition data for the deck for which deck sealing is considered appropriate, based on Hearn (2019). '-' means no limit.

Distress Type	Quantities			
	CS1	CS2	CS3	CS4
Delamination/spall/patch	-	< 10%	0%	0%
Efflorescence/rust staining	-	< 10%	0%	0%
Cracking (RC)	< 40%	< 20%	< 10%	0%
Cracking (PS)	< 20%	< 10%	< 5%	0%
Abrasion/wear	-	< 10%	0%	0%
Exposed PS	-	0%	0%	0%
Exposed rebar	-	0%	0%	0%

Service Life

The service life of deck sealers and healer-sealers generally ranges from 5 years to 10 years. With time, they become less effective at blocking chloride ingress and lose skid resistance relatively quickly. Aggregates that are less resistant will wear away faster and the polymer matrix left behind will quickly become polished. As the aggregates become ripped out, they will leave cracks and holes in the matrix, permitting chlorides and moisture to penetrate. The maximum service life extension assumed to be feasible for the healer-sealer is 10 years. The minimum service life extension is described in Table B.10 as a function of the current NBI deck condition rating. It is assumed that the life of the healer-sealer will depend on the following factors:

- ADTT,
- Pre-existing condition,
- Number of freeze-thaw cycles, and
- Contractor experience.

Table B.10. Minimum service life extension provided by a healer-sealer as a function of NBI deck condition rating.

NBI deck rating	Min. life extension (years)
NBI > 7	5
7 ≥ NBI > 6	3

It is assumed that a healer-sealer is applied in order to extend the degradation-controlled service life of a bridge deck, and it is unrelated to the abrasion-controlled service life.

References

DeRuyver, J., & Schiefer, P. (2016). *Thin Epoxy Overlay/Healer Sealer Treatments on Bridge Decks.* Lansing, MI: MDOT Region Bridge Support Unit Bridge Field Services.

Florida Department of Transportation. (n.d.). Chapter 7 - Maintenance and Preservation Techniques for Bridge Decks and Slabs. In *Bridge Maintenance Course Series, Reference Manual.*

Hearn, G. (2019). *Proposed AASHTO Guide to Bridge Preservation Actions, Project NCHRP 14-36.* National Cooperative Highway Research Program.

5. Placing a Polymer Chip Seal

A polymer chip seal is very similar to the aggregate chip seal described under *Applying a Bituminous Surface Treatment* and the maintenance activity *Placing a Thin Polymer Overlay*. It is similar to a bituminous chip seal in that it consists of laying a bonding agent and then an aggregate. The bonding agent is typically epoxy, which makes it similar to a thin polymer overlay. However, because a polymer chip seal only consists of one layer, it is much less effective at sealing the concrete surface and protecting the deck from chloride and moisture intrusion. Polymer chip seals are applied to improve skid resistance on concrete decks. The general procedures for placing a polymer chip seal are as follows:

1. Clean and dry the wearing surface.
2. Apply the epoxy resin to the surface.
3. Cover the epoxy with a layer of aggregate.
4. Allow the chip seal time to cure.
5. Remove excess aggregate.

Cost

The cost assumed for a polymer chip seal is $4/sq ft.

Thresholds

Polymer chip seals should only be applied on decks with a concrete wearing surface. As with thin polymer overlays, polymer chip seals should be applied when the deck is in good condition. Chip seals are only capable of improving skid resistance and should not be considered if the primary purpose of the maintenance action is improving the ride quality or extending the service life. These conditions are presented in Table B.11. The element-level thresholds for which thin polymer overlays are assumed to be appropriate, as recommended by Hearn (2019) in Table B.40, are assumed to apply for polymer chip seals as well.

Table B.11. User entries that cause polymer chip seals to be omitted from consideration.

User Input Variable	***Entry***
Wearing surface	Bituminous overlay
	Wood or timber
	Gravel
	Other
NBI deck condition rating	≤ 6
Primary purpose of maintenance	Improving ride quality
	Extending service life

Service Life

A polymer chip seal is assumed to only extend the abrasion-controlled service life, and it is assumed to have the same abrasion-controlled service life as a thin polymer overlay. The possible range is then 7 to 25 years and the ADTT factor and the contractor experience controls the precise value.

References

DeRuyver, J., & Schiefer, P. (2016). *Thin Epoxy Overlay/Healer Sealer Treatments on Bridge Decks.* Lansing, MI: MDOT Region Bridge Support Unit Bridge Field Services.

Hopwood, T., Meade, B. W., Fairchild, J., & Palle, S. (2015). *Preventive Maintenance Program for Bridges.* Lexington, KY: Kentucky Transportation Cabinet.

Soriano, A. (2003). *Alternative Sealants for Bridge Decks.* Pierre, SD: South Dakota Department of Transportation.

6. Crack Sealing of Asphalt

Asphalt pavements experience cracking due to thermal stresses or other causes of volume change and fatigue. Cracks due to volume change typically occur early in the life of the pavement and are longitudinal or transverse cracks. Cracks due to fatigue occur when the pavement cannot support the loads it is subjected to and typically occur late in the life of the pavement. Early-age cracks permit moisture ingress and debris, which accelerate deterioration of the pavement. As a result, cracks in asphalt pavements should be addressed early. Because fatigue cracking is due to deterioration that will continue whether the cracks are sealed or not, sealing these late-life cracks will have minimal to no effect.

There are a variety of materials and methods that may be used to seal cracks in asphalt pavements. The materials are categorized as cold pour and hot pour materials. Cold pour sealants such as emulsified asphalt binder may be poured at ambient temperatures and cure as the water fraction that lends its fluidity evaporates. Because of this, they take a relatively long time to cure. Hot pour sealants such as rubberized asphalt or asphalt binder with other modifiers must be heated and set as they cool, giving them a relatively short curing time. The sealant may be applied using different configurations. For inactive cracks, the crack is cleaned and dried and the sealant is poured in such that it is flush with the pavement (flush fill) or a wide band with a small thickness bridges the gap (overband). If the crack is active, routing is recommended. Routing consists of cutting a small, rectangular reservoir into the crack and filling the reservoir with sealant. The general procedure for crack sealing of asphalt pavements is as follows:

1. Cut a uniform rectangular reservoir into the crack if it is to be routed (optional).
2. Clean and dry the crack.
3. Immediately after drying the crack, place the sealant.
4. Allow sealant to cure fully before reopening to traffic.

Cost
The unit cost assumed for crack sealing of asphalt is $3.50/linear foot. This is highly dependent on the material used.

Thresholds
Crack sealing of asphalt may only be used when the wearing surface is bituminous. For pavements, it is typically only executed when the crack widths exceed 0.20 inches but the element-level condition states for cracks in the wearing surfaces classifies cracks between 0.012 and 0.05 inches as CS2 and cracks greater than 0.05 in width as CS3. This is because 0.012 is a typical crack limit for concrete and cracks of this width and greater are known to let deicing chlorides penetrate easily. Therefore crack sealing of asphalt is only removed from consideration if CS2 and CS3 are 0. Finally, crack sealing of asphalt is not considered if the primary purpose of the maintenance is to improve skid resistance or ride quality. The primary purpose of sealing a crack in an asphalt pavement on a bridge deck is to prevent moisture and chlorides from reaching the underlying deck and thereby lengthen its life. This activity also protects any underlying waterproofing membrane from damage as well. Table B.12 summarizes the entries for which crack sealing of asphalt will be removed from consideration.

Table B.12. User entries that cause crack sealing of asphalt to be omitted from consideration.

User Input Variable	*Entry*
Wearing surface type	Monolithic concrete
	Integral concrete
	Latex concrete
	Low slump concrete
	Epoxy overlay
	Wood or timber
	Gravel
	Other
Crack (wearing surface) [CS2 + CS3]	0
Primary purpose of maintenance strategy	Improved skid resistance

Hearn (2019) suggests the thresholds presented in Table B.13 as the maximum amount of distress below which asphalt repair should be considered.

Table B.13. Ranges of element-level condition data for the deck for which crack sealing of asphalt is considered appropriate, based on Hearn (2019). '-' means no limit.

Distress Type (Wearing Surface)	**Quantities**			
	CS1	**CS2**	**CS3**	**CS4**
Delamination/patch/pothole	-	< 20%	< 10%	< 10%
Crack	-	< 20%	< 10%	< 10%
Effectiveness	-	< 20%	< 10%	< 10%
Distress Type (Deck)	**Quantities**			
	CS1	**CS2**	**CS3**	**CS4**
Delamination/spall/patch	-	< 10%	0%	0%
Exposed rebar	-	0%	0%	0%
Exposed prestressing	-	0%	0%	0%
Cracking (RC and other)	< 10%	0%	0%	0%
Cracking (PSC)	-	< 10%	0%	0%
Efflorescence/rust staining	< 10%	< 10%	0%	0%
Abrasion/wear	-	< 10%	0%	0%

Service Life

Service life of asphalt sealants range from 2 to 10 years, although lives up to 15 years have been reported. On average, the life varies from 3 to 7 years and this range is assumed by the BDPP. The sealant typically fails due to loss of bond between the sealant and the asphalt (adhesion loss), cracking within the sealant or in the substrate adjacent (cohesion loss), pull-out of the material, and the presence of secondary cracks below the sealant. The time of failure is controlled by the following factors:

- ADTT,
- Pre-existing condition,
- Number of freeze-thaw cycles, and
- Contractor experience.

Crack sealing of asphalt has no effect on the abrasion-controlled service life of the bridge deck. The above applies to the corrosion-controlled service life of the deck.

References

ERES Consultants, Inc. (1999). *Sealing and Filling Cracks in Asphalt Pavements.* Champaign, IL: Federal Highway Administration.

Hearn, G. (2019). *Proposed AASHTO Guide to Bridge Preservation Actions, Project NCHRP 14-36.* National Cooperative Highway Research Program.

Truschke, C., Peshkin, D., Smith, K. L., & Smith, K. D. (2014). *Colorado Deparment of Transportation Hot-Mix Asphalt: Crack Sealing and Filling Best Practices Guidelines.* Denver, CO: Colorado Department of Transportation.

USDA Forest Service Northern Region Engineering. (2017). *Cost Estimating Guide for Road Construction.* USDA Forest Service Northern Region Engineering.

Yildirim, Y., Qatan, A., & Prozzi, J. (2006). *Field Manual for Crack Sealing in Asphalt Pavements.* Austin, TX: Texas Department of Transportation.

7. Repairing Asphalt Pavement

Fatigue cracking and potholes in asphalt pavements typically indicate that patch repair is needed. The repair is intended to restore the ride quality and material integrity of the pavement. Repairs should be done as quickly as possible to prevent accelerated deterioration of the surrounding pavement due to exposure to moisture. If the flaw is a pothole, then it may be filled in with cold patch. Cold patch repair is convenient because it is readily available and easy to install, but the material tends to deteriorate relatively quickly. Permanent patches generally use hot-mixed asphalt (HMA) as the patching material. The success of the patches depends significantly on the quality of the compaction and whether or not adjacent asphalt contaminated with moisture, ions, and debris is removed or not. The general procedure is as follows:

1. Remove defective asphalt to the depth of the original deck or a depth where the pavement is in sound condition. Additionally, remove asphalt pavement adjacent to the defect.
2. If necessary, repair any unsound areas in the underlying deck.
3. Prepare the hole by squaring off the edge vertically, drying the hole, and tacking the surfaces.
4. Place the asphalt mix.
5. Compact the mix into the hole.

Cost
The cost assumed for repairing an asphalt wearing surface is $10.50/sq ft.

Thresholds
This maintenance action is only feasible if the wearing surface is bituminous. It would be applicable to a bridge deck in fair condition, but may be completed regardless of the NBI deck condition rating. Patch repairs are conducted primarily to improve ride quality and do not provide enough protection to extend the service life of the bridge deck. This results in the filters listed in Table B.14.

Table B.14. User entries that cause asphalt patch repair to be omitted from consideration.

User Input Variable	***Entry***
Wearing surface	Monolithic concrete
	Integral concrete
	Latex concrete
	Low slump concrete
	Epoxy overlay
	Wood or timber
	Gravel
	Other
Primary purpose of maintenance activity	Improving skid resistance
	Extending service life

Hearn (2019) does not distinguish between asphalt patching and crack sealing and recommends the same element-level thresholds described by Table B.13 for crack sealing of asphalt as for the general repair of an asphalt pavement.

Service Life
The service life of an asphaltic repair depends primarily on the conditions during installation and the quality of materials. For example, patches placed in the winter in Canada typically last less than one year while patches placed in the summer last from 1 to 7 years. Because of their short lifespan, patches are only placed

in the winter if absolutely required for safety and ride quality. The BDPP assumes patches are placed in the summer and that a service life of 1 to 5 years is feasible. The factors assumed to control the service life are the following:

- ADTT,
- Pre-existing condition,
- Number of freeze-thaw cycles, and
- Contractor experience.

Patch repairs primarily address cracked areas to improve ride quality. They are not used to provide skid resistance, and as such, asphalt repairs are assumed to have no benefit for the abrasion-controlled service life. The elimination of cracks does benefit the degradation-controlled service life, and therefore the above discussion applies for the degradation-controlled service life of the maintenance.

References

Ghosh, D., Turos, M., Hartman, M., Millavitz, R., Le, J.-L., & Marasteanu, M. (2018). *Pothole Prevention and Innovative Repair.* St. Paul, MN: Minnesota Department of Transportation.

Hearn, G. (2019). *Proposed AASHTO Guide to Bridge Preservation Actions, Project NCHRP 14-36.* National Cooperative Highway Research Program.

Smith, K., Harrington, D., Pierce, L., Ram, P., & Smith, K. (2014). *Second Edition Concrete Pavement Preservation Guide.* National Concrete Pavement Technology Center.

WSDOT. (2017). Chapter 3 - Pavement Patching and Repair. In *WSDOT Maintenance Manual M 51-01.06.* Washington State Department of Transportation.

8. Applying a Bituminous Surface Treatment

Bituminous surface treatments (BSTs) are used to renew skid resistance, seal small cracks, and extend time until rehabilitation is required for asphalt pavements. There are several different types of BSTs and the type is selected based on the extent of cracking or raveling of the asphalt and the need for improved skid resistance. Fog seals are used when there is minor distress and no skid resistance issues. They consist of applying a light application of diluted asphalt emulsion to the surface, which seals the surface. The maximum amount of emulsion to be placed depends on the minimum skid resistance required of the bridge deck. Because fog seals do not contain aggregates, they are relatively slippery. Sand seals and chip seals contain aggregates. They are used when cracking and raveling are more advanced, and consist of applying the emulsified asphalt and then placing a layer of fine aggregate on top of the bituminous layer. The aggregate improves the skid resistance dramatically. The procedures for a BST are as follows:

1. Clean and dry the surface of the pavement.
2. Apply the asphalt emulsion to the surface.
3. If the BST is a chip or sand seal, then apply a layer of aggregate on top.

Cost
The cost assumed for applying a BST is $1.0 /sq ft.

Thresholds
BSTs are only used on bituminous wearing surfaces. They can extend the service life by sealing cracks and limiting moisture and chloride ingress to the underlying substrate, and if a seal with aggregates is used, then they can also be used to improve skid resistance. However, none of the treatments are capable of improving ride quality.

BSTs may be used regardless of the condition of the deck. They provide a benefit if the deck is in good condition with minor cracking and are a relatively inexpensive activity that may be completed when the deck is in fair condition to address abrasion. As a result, no filters are based on NBI condition of the deck. The entries that remove BSTs from consideration are provided in Table B.15. Hearn (2019) does not discuss bituminous surface treatments.

Table B.15. User entries that cause bituminous surface treatments to be omitted from consideration.

User Input Variable	***Entry***
Wearing surface	Monolithic concrete
	Integral concrete
	Latex concrete
	Low slump concrete
	Epoxy overlay
	Wood or timber
	Gravel
	Other
Primary purpose of maintenance activity	Improving ride quality

Service Life
BSTs generally last approximately 5 to 10 years. Service lives as short as 3 years have been reported for fog seals and as long as 15 years have been reported for chip or slurry seals. Due to the decreased skid

resistance of fog seals, it is assumed that the BST under consideration is a chip or slurry seal, which contains aggregates. For this portal, the maximum degradation-controlled service life is assumed to be 8 years. The minimum expected extension is described in Table B.16. The factors affecting the service life extension calculated by the portal include the following:

- ADTT
- Pre-existing condition, and
- Number of freeze-thaw cycles.

Table B.16. Minimum service life extension provided by a PCC/HPC overlay as a function of NBI deck condition rating.

NBI deck rating	Min. life extension (years)
NBI > 7	3
7 ≥ NBI > 6	3
6 ≥ NBI > 5	2
5 ≥ NBI	2

The abrasion-controlled service life range assumed is 7 to 15 years and depends only on the ADTT and contractor experience.

References

Ghosh, D., Turos, M., Hartman, M., Millavitz, R., Le, J.-L., & Marasteanu, M. (2018). *Pothole Prevention and Innovative Repair.* St. Paul, MN: Minnesota Department of Transportation.

Smith, K., Harrington, D., Pierce, L., Ram, P., & Smith, K. (2014). *Second Edition Concrete Pavement Preservation Guide.* National Concrete Pavement Technology Center.

Virginia Department of Transportation. (2018, January 24). Bid Tabulations. VDOT.

9. Installing Studs

The wearing surface on steel decks is the steel itself, which is typically serrated. Despite the abrasion resistance of steel, skid resistance will still decrease over time and the surface will become especially slippery when wet. In response to this, studs may be welded to the intersections of the grid to provide friction. They are typically about 5/16 inches in diameter and 3/8 inches in height.

The general procedure assumed for installing studs to improve skid resistance is as follows:

1. Clean and profile the surfaces of the grid that the studs are to be welded to by abrasive blasting.
2. Dry the surfaces.
3. Weld the studs as specified.

Cost

The unit cost to install studs on a deck for skid resistance is assumed to be $32.00/sq ft. Note that this cost is estimated from a single project, James River Bridge in Virginia.

Thresholds

Installing studs is only considered feasible for steel decks without any overlays. The deck should be in good condition. If the deck has an NBI deck condition rating of 5 or 6, this indicates areas of the grid need replacement or other more costly repairs that inherently improve skid resistance. In these instances, installing studs to address abrasion concerns is assumed to be an unnecessary expense. Any available element-level distress data should identify abrasion/wear as the distress type and the primary purpose of the repair should be to improve skid resistance. While roughening a concrete wearing surface by grinding can improve ride quality by smoothing the surface profile, installing studs can only improve skid resistance. These requirements are described in Table B.17.

Table B.17. User entries that cause installing studs to be omitted from consideration.

User Input Variable	*Entry*
Deck structure type	CIP concrete
	Precast concrete panels
	Timber
	Other
Wearing surface type	Monolithic concrete
	Integral concrete
	Latex concrete
	Low slump concrete
	Epoxy overlay
	Bituminous overlay
	Wood or timber
	Gravel
NBI deck condition rating	≤ 6
Abrasion/wear CS1	> 95%
Primary purpose of maintenance strategy	Extended service life
	Improved ride quality

Service Life
There is very little literature regarding studs applied to bridge decks for skid resistance. Their life is assumed to be governed by the welds, which are the common failure point in welded steel decks. Welds are susceptible to fatigue cracking and their performance depends heavily on the surface preparation, welding parameters, and general quality of the operation. Because welds have rough surfaces, they are also relatively susceptible to corrosion when chlorides are present. Therefore the service life factors affecting the life of the installed studs are:

- ADTT,
- Chloride exposure, and
- Contractor experience.

Due to the limited literature available for this repair, no service life range has been established in the portal and user input will be required. The studs have no effect on the degradation-controlled service life of the deck.

References
Connolly, G. (2013, October 17). VDOT: James River Bridge Stud Installation Complete. *Williamsburg Yorktown Daily*.

Florida Department of Transportation. (n.d.). Chapter 7 - Maintenance and Preservation Techniques for Bridge Decks and Slabs. In *Bridge Maintenance Course Series, Reference Manual.*

10. Painting a Steel Deck (Underside)

When corrosion of a steel deck is a concern, the deck may be painted. The most common painting system is a three-coat system. The first coat is a zinc-rich primer. The zinc in this layer helps protect the steel from corrosion if any chlorides or moisture penetrates the system by corroding preferentially to the steel. The second coat is a midcoat, and the third is the topcoat. The coats are typically made of polyurethane or epoxy. Acrylic topcoats have been used as well. This system may be used for bridges that have not been painted or whose paint has deteriorated such that it is no longer performing adequately. In the second case, the deteriorated paint must be removed prior to application of the new, three-coat system. Alternatively, the life of existing, deteriorated paint layers may be extended by overcoating. Overcoating consists of applying a coat that is intended to act as a barrier or inhibitive layer without removing the existing coating system. Materials used for overcoats include epoxies, polyurethanes, acrylics, and calcium-sulfonate modified or low-VOC alkyds. Zinc is not used in overcoats because it must be in contact with the steel to provide corrosion protection. If the bridge requires spot painting due to some select areas with exposed steel, then overcoats or three-coat systems are considered appropriate. Finally, ultra-weathering paints have been introduced to the market recently. Examples of materials that may be used in ultra-weathering paints include fluoropolymers, microcapsules, and corrosion inhibitors. These paints are considered to be very durable, but because no historic data is available and laboratory testing is limited, and because the three-coat system performs satisfactorily, they are less commonly used.

Paint application requires good surface preparation to provide the paint system with a clean and profiled surface to bond. Cleaning is typically done by abrasive blasting, unless containment requirements make other methods more practical and/or cost-effective. Abrasive blasting is also not done if an overcoat is being applied as this would strip the steel of the existing paint. In these cases, deteriorated paint and rust are removed by hand or with power tools, but this is very labor-intensive. Alternative chemical and electrical methods may be required. Once the surface is prepared, the paint layers are typically applied using an airless spray although rolling and brushing are alternative application methods. Recently, topcoats have been applied by hand at specific locations that are difficult to paint with an airless spray. Painting by hand at edges and other spots that are difficult to access provides a better quality coating and therefore a longer-lasting paint.

The general procedure assumed for painting by the BDPP is as follows:

1. If applying a three-coat system, remove deteriorated paint and rust by abrasive blasting.
2. If applying an overcoat, or if abrasive blasting did not fully clean and profile the surface, clean with hand and power tools.
3. Apply the paint using an airless spray.
4. Hand paint with a brush any edges or areas that were difficult to access with the spraying equipment.

Cost

The full cost for repainting a steel bridge deck, assuming full removal of the existing paint system and application of a three-coat system, is approximately $33.0/sq ft.

Thresholds

Painting is only feasible for steel decks. The type of wearing surface does not matter since the paint would only be applied to the underside of the deck. Because painting is expensive, the deck should have a condition rating of 6 or higher; if the condition rating is 5, then it is assumed that replacement is as economical as repainting. The primary purpose of the maintenance should be extension of service life. These requirements are summarized in Table B.18.

Table B.18. User entries that cause painting to be omitted from consideration.

User Input Variable	*Entry*
Deck structure type	CIP concrete
	Precast concrete panels
	Timber
NBI deck condition rating	≤ 5
Primary purpose of maintenance	Improving ride quality
	Improving skid resistance

Hearn (2019) offers guidance on when to consider painting a full bridge based on the condition of the bridge, but does not provide specifics for the deck.

Service Life

The service life of a three-coat system is typically between 15 and 30 years, regardless of whether the system is new or a replacement. Coatings generally degrade due to ultraviolet light exposure. The UV radiation breaks down the polymer chains, resulting in a more permeable and brittle coating. The increased permeability permits moisture and contaminating ions such as sulfates and chlorides to reach the steel substrate, resulting in corrosion. The corrosion products cause blistering and delamination of the coating, ending its service life. Thermal stresses due to temperature cycling also affect the service life of the coating, especially as the paint becomes more brittle.

The life of the coating is assumed to depend on the following factors. UV radiation is considered synonymous to average temperature and heat, and the number of freeze-thaw cycles is assumed to correlate with the severity of temperature cycling.

- Chloride exposure,
- Number of freeze-thaw cycles,
- Average temperature,
- Average relative humidity, and
- Contractor experience.

The above applies for the degradation-controlled service life. Painting a steel deck does not affect the abrasion-controlled service life of the deck.

References

Corrpro Companies Inc. (2001). *Cost Effective Alternative Methods for Steel Bridge Paint System Maintenance Report IX: Field Metallizing Highway Bridges.* FHWA.

Hearn, G. (2019). *Proposed AASHTO Guide to Bridge Preservation Actions, Project NCHRP 14-36.* National Cooperative Highway Research Program.

Klaiber, F. W., Wipf, T. J., & Russo, F. M. (2004). *Synthesis 327: Cost-Effective Practices for Off-System and Local Bridges.* Washington D.C.: NCHRP.

Vinik, P., Bottenberg, R., Brown, C., Ocel, J., Schwerdt, T., Todsen, M., & Palle, S. (2016). *Scan 15-03: Successful Preservation Practices for Steel Bridge Coatings.* Lawrenceville, NJ: NCHRP.

11. Metallizing a Steel Deck

Metallizing consists of placing a sacrificial zinc coating on bare steel. The zinc acts as a barrier preventing chlorides and moisture from reaching and corroding the steel. Once the zinc has corroded such that the steel is partly exposed, the remaining zinc continues to corrode preferentially to the steel and sacrifice itself. Historically, metallizing has been cost-prohibitive and painting has been the much more common alternative. However, some states have found metallizing to be a reliable way to extend service life of steel.

The general procedure assumed for metallizing is as follows:

1. Clean and profile the surface by abrasive blasting.
2. Continue cleaning by hand or with power tools if necessary.
3. Apply the zinc layer as a thermal spray.

Cost

The cost assumed for this maintenance is $22.0/sq ft.

Thresholds

Metallizing is considered synonymous to painting, and as such, similar threshold values apply. The deck must be steel and the wearing surface type does not matter since metallizing would only be conducted on the underside. Due to the expense of metallizing, the deck should have a NBI condition rating of 6 or higher and the purpose of the maintenance should be to extend the degradation-controlled service life of the deck. These limits are shown in Table B.18. Additionally, metallizing should only be considered for bare steel. Since painted decks are rare and a painted coating is not considered a protection system option on the federal SA&I datasheet, it is assumed that the deck is bare steel and no filter is applied based on this requirement. If this assumption is not true, then the user should remove this option from consideration.

Service Life

The service life of metallized steel is similar to the service life of a three-coat paint system. As such, a service life range of 15 to 30 years is assumed. The factors controlling the service life are similar to those of the paint system as well. The service life of the zinc layer depends on the corrosion rate, which is controlled by the ambient temperature, the amount of moisture, and the amount of chlorides present. Therefore the factors are assumed to be the following:

- Chloride exposure,
- Average temperature,
- Average relative humidity, and
- Contractor experience.

References

Corrpro Companies Inc. (2001). *Cost Effective Alternative Methods for Steel Bridge Paint System Maintenance Report IX: Field Metallizing Highway Bridges.* FHWA.

Vinik, P., Bottenberg, R., Brown, C., Ocel, J., Schwerdt, T., Todsen, M., & Palle, S. (2016). *Scan 15-03: Successful Preservation Practices for Steel Bridge Coatings.* Lawrenceville, NJ: NCHRP.

12. Replacing Grid Plates

Open-grid decks are flexible and contain many connections, and as such are susceptible to fatigue. The connections are typically rivets or welds, but some designs have removed rivets and welds altogether by containing keys and keyholes such that the plates lock into place. Welds are particularly subject to fatigue cracking. In these cases, the weld is typically ground until the crack is no longer present. If the crack is deep enough, then the weld may need to be replaced. Broken rivets are replaced by installing high-strength bolts at the broken connections and then replacing the bolts with rivets one at a time. This procedure is carried out in order to ensure structural integrity during repair. Both methods can be costly, and as such, rather than repairing the connections, the damaged area of the plate is more often cut out and replaced.

The general procedure assumed for grid plate replacement is as follows:

1. Cut and remove damaged grid areas.
2. Grind off any remaining welds on the support beams.
3. Cut and place replacement decking.
4. Weld new decking into place.
5. Check for loose decking and weld as needed.

Cost

The cost for replacing grid plates is project dependent and, therefore, the portal does not assume cost for this repair. Note that the cost for one project to replace grid plates in Iowa was $190/sq ft.

Thresholds

This maintenance activity is only considered for open-grid steel decks. It is considered regardless of the NBI deck condition rating and is only conducted to extend the service life of the deck. The filters are shown in Table B.19. Hearn (2019) recommends that replacing grid plates be considered for the distress levels presented in Table B.20.

Table B.19. User entries that cause replacing grid plates to be omitted from consideration.

User Input Variable	*Entry*
Deck structure type	CIP concrete
	Precast concrete panels
	Closed steel grating
	Steel plates
	Timber
	Other
Primary purpose of maintenance	Improving ride quality
	Improving skid resistance

Table B.20. Ranges of element-level condition data for the deck for replacing grid plates is considered appropriate, based on Hearn (2019). '-' means no limit.

Distress Type (Deck)	Quantities			
	CS1	CS2	CS3	CS4
Corrosion	-	< 20%	< 10%	0%
Fatigue crack (steel/other)	-	< 20%	< 10%	0%
Connection	-	< 20%	< 10%	0%

Service Life

There is little information available regarding the service life of this repair, partly because steel decks are rare and open grid steel decks are generally limited to moveable bridges. According to Hearn (2019), grid plates should be replaced at a frequency of about 24 years. The new grid plate would be expected to have a service life similar to the area of the steel deck that it replaced. Therefore, the service life range assumed is 18 to 30 years. The factors controlling this are:

- ADTT,
- Chloride exposure,
- Average temperature,
- Average relative humidity, and
- Contractor experience.

All of the above contribute to corrosion and fatigue-related distress in steel. This repair is for the degradation-controlled service life of the deck and does not provide any benefit to the abrasion-controlled service life.

References

Florida Department of Transportation. (n.d.). Chapter 7 - Maintenance and Preservation Techniques for Bridge Decks and Slabs. In *Bridge Maintenance Course Series, Reference Manual.*

Hearn, G. (2019). *Proposed AASHTO Guide to Bridge Preservation Actions, Project NCHRP 14-36.* National Cooperative Highway Research Program.

13. Applying a Surface Preservative Treatment

Preservatives are used to protect timber from decay. Most timber is preserved using a pressure process prior to construction, but while the original preservative treatment penetrates relatively far into the timber member, cuts and holes made during construction and cracks or splits due to deterioration will expose untreated wood. In-place surface treatments are often applied to these exposed areas. They form a toxic barrier to decay agents and do not penetrate far into the wood. As a result they are most effective when applied prior to the start of decay and need to be applied at regular intervals. Preservatives used in surface treatments include copper naphthenate (CuNap) in solution and borate solutions, as well as pastes. Pastes are better for use on vertical surfaces or on the undersides of members. The general procedure for applying a preservative using a surface treatment is as follows:

1. Clean and dry the timber to be preserved.
2. Brush, squirt, or spray-flood the wood surface as appropriate until the surface is saturated, taking care not to spill or have too much excess preservative.

Cost

The cost assumed by the BDPP for applying a surface preservative treatment is $0.40/sq ft.

Thresholds

In-place surface preservative treatments can only be done on timber decks. They should be applied prior to any decay and, therefore, the NBI deck condition rating is required to be 8 or 9. Preservative treatments extend service life and have no effect on ride quality or skid resistance. These filters are summarized in Table B.21.

Table B.21. User entries that cause surface preservative treatments to be omitted from consideration.

User Input Variable	***Entry***
Deck structure type	CIP concrete
	Precast concrete panels
	Open steel grating
	Closed steel grating
	Steel plates
	Other
NBI deck condition	≤ 7
Primary purpose of maintenance	Improving ride quality
	Improving skid resistance

Service Life

The service life of a surface preservative treatment is assumed to be 3 to 5 years. Preservative treatments are prone to leaching out of the wood due to wetting and drying cycles and constant exposure to moisture. Therefore the amount of rainfall and relative humidity is assumed to control the service life.

This maintenance relates to the decay-controlled service life of the timber deck, which is assumed to be synonymous to the corrosion-controlled service life of a steel or concrete deck. Therefore, the above is categorized under degradation-controlled service life and has no effect on the abrasion-controlled service life.

References

Bigelow, J., Lebow, S., Calusen, C. A., Greimann, L., & Wipf, T. J. (2009). Preservation Treatment for Wood Bridge Application. *Transportation Research Record: Journal of the Transportation Research Board*, 77-85.

MNDOT. (n.d.). Chapter 14 Maintenance and Rehabilitation of Timber Bridges.

14. Installing a Fumigant or Preservative

Preservatives and fumigants may also be applied by drilling into the timber member, injecting or placing the agent, and then sealing the hole with a plug. The number of holes and their spacing depends on the ability of the preservative or fumigant to penetrate through the wood. The preservatives used are similar to those used for surface treatments, but may be in solid capsules. Solid capsules do not penetrate as deeply as solutions and pastes because moisture is required for diffusion into the wood, but they are considered safer because they are less likely to leak. Fumigants are typically made of chloropicrin, methylisothiocyanate, metham sodium, or granular dazoment. These may also be in liquid or solid form and volatize into a gas that travels through the wood. Preservatives and fumigants are useful when decay or biological attack has already begun because they may be placed at strategic locations on the interior of the timber. They should be placed in sound wood to prevent the toxins from diffusing out of the wood and escaping, which decreases their effectiveness and longevity. The general procedure for installing a fumigant or preservative is as follows:

1. Bore holes into the timber at the required distances.
2. Inject the liquid fumigant or place the solid fumigant capsules in the bored holes.
3. Seal the holes with plugs made of treated wood or plastic.

Note that this technique may be more suitable for sub- and super-structure elements.

Cost

Cost information for this type of maintenance is not commonly available and, therefore, the portal does not assume cost for this repair.

Thresholds

Like surface preservative treatments, fumigant and preservative installations can only be done on timber decks. They will extend service life but will not affect the ride quality or skid resistance. Unlike surface treatments, these treatments target internal decay and so would be applied when the deck is in fair condition. The filters are summarized in Table B.22.

Table B.22. User entries that cause installing fumigants or preservatives to be omitted from consideration.

User Input Variable	*Entry*
Deck structure type	CIP concrete
	Precast concrete panels
	Open steel grating
	Closed steel grating
	Steel plates
	Other
NBI deck condition	> 6
Primary purpose of maintenance	Improving ride quality
	Improving skid resistance

Service Life

These treatments reportedly last from 10 to 15 years and depends on the type of material used; therefore, no value is assumed by the portal and this will be a user input. The service life of this option is assumed to be controlled by the following factors:

- Pre-existing condition.
- Scheffer index, and
- Contractor experience.

This is categorized under degradation-controlled service life for the same reason as surface preservatives. Installing fumigants or preservatives is irrelevant to abrasion.

References

Bigelow, J., Lebow, S., Calusen, C. A., Greimann, L., & Wipf, T. J. (2009). Preservation Treatment for Wood Bridge Application. *Transportation Research Record: Journal of the Transportation Research Board*, 77-85.

MNDOT. (n.d.). Chapter 14 Maintenance and Rehabilitation of Timber Bridges.

15. Stress-Laminating Timber Decks

Nail-laminated decks are prone to deterioration due to cyclic loading. The repeated dynamic traffic loads cause the nails to loosen and the boards to delaminate with time. The delamination causes deterioration of any wearing surface above, water penetration, and an increased rate of deterioration. Stress-lamination connects the planks again such that they distribute dynamic loads more effectively and seals them. The general procedure for stress-laminating nail-laminated decks is as follows:

1. Install high-strength steel rods transverse to the laminations along the ends of the planks.
2. Stress the steel rods as specified.
3. Add planks at the edges of the deck as needed to offset narrowing due to the stressing.

Cost

Cost records for stress-laminating timber decks are difficult to find and, therefore, the portal does not assume cost for this repair.

Thresholds

This maintenance activity is only feasible for timber decks, and specifically for nail-laminated timber decks, or glue-laminated decks. Specific types of timber decks are not distinguished in the SA&I submittal and as a result the user will need to remove this maintenance activity if the deck cannot be stress-laminated. The deck may be in good or fair condition since deteriorated planks may be replaced during this procedure. Stress-laminating a deck is primarily done to extend the service life by limiting moisture exposure and improve the ride quality. It is not considered an option if the primary purpose is to improve the skid resistance. These filters are summarized in Table B.23.

Table B.23. User entries that cause stress-laminating a timber deck to be omitted from consideration.

User Input Variable	***Entry***
Deck structure type	CIP concrete
	Precast concrete panels
	Open steel grating
	Closed steel grating
	Steel plates
	Other
Primary purpose of maintenance	Improving the skid resistance

Service Life

Provided that the steel rods and connections do not degrade significantly before the wooden planks, the service life of this repair is controlled by decay of the timber. Decreasing moisture exposure slows this significantly, but the effectiveness of this repair is not reported in literature. Therefore, the BDPP will not assume a service life for this action. The factors controlling the life are:

- ADTT,
- Pre-existing condition,
- Scheffer index, and
- Contractor experience.

References

Florida Department of Transportation. (n.d.). Chapter 7 - Maintenance and Preservation Techniques for Bridge Decks and Slabs. In *Bridge Maintenance Course Series, Reference Manual.*

MNDOT. (n.d.). Chapter 14 Maintenance and Rehabilitation of Timber Bridges.

16. Replacing Timber Planks or Runners

Because timber decks are comprised of individual planks, when the deck begins to show signs of decay, splitting, abrasion, or other deterioration, repairs may be limited only to the affected planks or runners. This is easiest for plank decks, wherein the planks lay alongside each other. Replacing planks is more difficult but still feasible for laminated decks, in which adjacent planks are nailed, glued, or post-tensioned such that they act together. Runners, which run longitudinally along the deck over the planks, are designed so they may be easily replaced when they have become worn. Replacing planks requires access to the planks, and as such it is important to consider the condition of the planks prior to placing an asphalt or other bonded overlay which will limit access. Gravel overlays may be easily swept aside.

The general procedure for replacing planks or runners is assumed to be as follows:

1. Remove any gravel and deck-mounted elements such as curbs, parapets, and railings for access to the planks.
2. Remove the deteriorated planks and their fasteners.
3. Clean the newly-exposed stringers.
4. Apply the chosen preservative treatment to the stringers (opt'l).
5. Place and fasten the new planks to the existing stringers.

Cost

The cost assumed by the BDPP for replacing timber planks or runners is $12/sq ft.

Thresholds

This maintenance action is only applicable to timber bridge decks. If the planks or runners have decayed or abraded to the point of needing replacement, then the deck is in fair condition. Replacing the planks or runners will both extend the service life of the deck and improve the ride quality and the skid resistance of the wearing surface. As a result the primary purpose of the maintenance of the activity is not considered a filter. Table B.24 provides the filters for replacing planks or runners. The distress thresholds below which Hearn (2019) recommends replacing timber planks or runners be considered are presented in Table B.25.

Table B.24. User entries that cause replacing timber planks or runners to be omitted from consideration.

User Input Variable	***Entry***
Deck structure type	CIP concrete
	Precast concrete panels
	Open steel grating
	Closed steel grating
	Steel plates
	Other
NBI deck condition rating	≤ 6

Table B.25. Ranges of element-level condition data for the deck for which replacing timber planks or runners is considered appropriate, based on Hearn (2019). '-' means no limit.

Distress Type (Deck)	Quantities			
	CS1	CS2	CS3	CS4
Decay/section loss	-	< 20%	< 10%	0%
Check/shake	-	< 20%	< 10%	0%
Crack	-	< 20%	< 10%	0%
Split/delamination	-	< 20%	< 10%	0%
Abrasion/wear	-	< 20%	< 10%	0%

Service Life

As with grid plates for steel, timber planks or runners will likely have a lifespan similar to the timber elements they replaced, assuming the construction and preservative treatments are the same. Hearn (2019) considers plank replacement to be a condition-driven maintenance activity but suggests an interval of 18 years. Many timber elements are capable of having much longer service lives, provided they receive good preservative treatments prior to construction. Non-preserved timber may have a life as short as 2 years before requiring replacement due to decay, although this has been reported in relatively aggressive environments when the timber is buried in soil or in a marine environment.

Based on the above information, an abrasion-controlled service life of 10 to 20 years is assumed and the only factor controlling the specific value is the ADTT. A degradation-controlled service life of 15 to 30 years is assumed and this value is controlled by the following factors:

- Scheffer index, and
- Contractor experience.

References

Florida Department of Transportation. (n.d.). Chapter 7 - Maintenance and Preservation Techniques for Bridge Decks and Slabs. In *Bridge Maintenance Course Series, Reference Manual.*

Hearn, G. (2019). *Proposed AASHTO Guide to Bridge Preservation Actions, Project NCHRP 14-36.* National Cooperative Highway Research Program.

NHDOT Bridge Management Committee. (2018). *NHDOT Bridge Program Recommended Investment Strategy.* New Hampshire Department of Transportation.

17. Placing a HMA Overlay

There are several different types of asphalt overlays and systems that can be used on bridge decks. The most common overlay uses a typical hot-mixed asphalt (HMA) mixture comprised of about 5% asphalt binder and 95% aggregate. Thicknesses are generally on the order of 1 to 2 inches. This type of overlay is easy and quick to install, has a low cost, and provides a smooth wearing surface for motorists. However, it typically experiences reflective cracking caused by corrosion of reinforcing steel within an underlying concrete deck or differential movement of timber panels in an underlying timber deck. Additionally, these mixtures are prone to fatigue cracking on steel and timber decks due to the decks' flexibility. HMA can also trap moisture and deicing salts, furthering deterioration of underlying concrete.

Regarding concrete bridge decks, HMA overlays are most suitable for application near end-of-life to prolong ride quality until replacement. Due to cracking issues, non-modified HMA pavements are rarely used on steel decks and poorly suited to glue-laminated timber decks. Regarding steel and timber decks, a waterproofing membrane is often part of the pavement system. Because asphalt overlays with waterproofing membranes are considered separately from asphalt overlays with regard to concrete decks, these actions are handled separately in the BDPP and HMA overlays with waterproofing membranes are discussed in another section.

The general procedures for placing a HMA overlay are as follows:

1. Remove the current wearing surface to desired depth. This may consist of removing a previous overlay.
2. Repair unsound concrete.
3. Apply an asphalt tack coat to the surface.
4. Place and compact asphalt overlay.

Cost

The cost assumed for applying a HMA overlay is $2.0/sq ft.

Thresholds

HMA overlays can be useful under a variety of conditions. While modified asphalt overlays and HMA overlays with waterproofing membranes are much more common for steel and timber decks, the BDPP assumes an HMA overlay may be applied to any structure type. HMA overlays offer relatively little protection from deicing chemicals and moisture ingress, but are good for improving ride quality and skid resistance. These overlays also may be applied when the structure is in good or fair condition. As a result HMA overlays will only be removed from consideration when the primary purpose of the maintenance is to extend service life, as shown in Table B.26.

Table B.26. User entries that cause HMA overlays to be omitted from consideration.

User Input Variable	*Entry*
Deck structure type	Open steel grating
Primary purpose of maintenance strategy	Extended service life

Hearn (2019) recommends that an asphalt overlay be considered under the conditions presented in Table B.27.

Table B.27. Ranges of element-level condition data for the wearing surface and the deck for which HMA overlays are considered appropriate, based on Hearn (2019). '-' means no limit.

Distress Type (Wearing Surface)	Quantities			
	CS1	CS2	CS3	CS4
Delamination/patch/pothole	-	< 20%	< 10%	0%
Crack	-	< 20%	< 10%	0%
Effectiveness	-	< 20%	< 10%	0%
Distress Type (Deck)	**Quantities**			
	CS1	**CS2**	**CS3**	**CS4**
Delamination/spall/patch	-	< 10%	0%	0%
Exposed rebar	-	0%	0%	0%
Exposed prestressing	-	0%	0%	0%
Cracking (RC and other)	< 10%	0%	0%	0%
Cracking (PSC)	< 10%	< 10%	0%	0%
Efflorescence/rust staining	-	< 10%	0%	0%
Abrasion/wear	-	< 10%	0%	0%

Service Life

Service lives between 5 and 20 years have been reported by the states (Krauss et al. 2009). The Wisconsin DOT and Minnesota DOT cite service lives of 3 to 7 years and less than 5 years, respectively. The mean service life is 8 to 15 years.

The service life of the HMA depends strongly on the failure mechanism it will experience. Asphalt pavements are susceptible to cracking for a variety of reasons. The first is reflective cracking and is caused by cracks in the underlying concrete. In this scenario, the life of the asphalt depends entirely on the condition of the underlying concrete and its corroding reinforcing steel. Other types of cracking include alligator and block cracking, which are caused primarily by fatigue and age. Sources of fatigue include temperature cycling and traffic volumes. Asphalt becomes more brittle with age and subsequently loses its ability to accommodate these loads and cracks. Alligator and block cracking typically occur later in the life of the asphalt. Finally, raveling may also be a concern due to abrasion from traffic and snowplows. This distress also typically occurs later in the life of the asphalt.

Based on the above discussion, a HMA overlay may fail due to abrasion or degradation in the underlying deck. The service life extension offered by HMA overlay is assumed to be between up to 15 years. The minimum expected extension is described in Table B.28. The abrasion-controlled service life is expected to depend on the following factors:

- ADTT,
- Chloride exposure
- Number of freeze-thaw cycles, and
- Contractor experience.

Table B.28. Minimum service life extension provided by a HMA overlay as a function of NBI deck condition rating.

NBI deck rating	Min. life extension (years)
NBI > 7	5
7 ≥ NBI > 6	4
6 ≥ NBI > 5	3
5 ≥ NBI	2

In truth, chloride exposure is not a direct factor, but is expected to correlate with the number of snowplows the asphalt will be exposed to. The traffic and freeze-thaw cycles affect ride quality rather than abrasion, but because these pavement characteristics both deal with the riding surface, they are both considered under the abrasion-controlled service life.

The degradation-controlled service life is expected to depend on the following factors:

- Chloride exposure,
- Pre-existing condition and
- Contractor experience.

References

Eriksson, M., Wheeler, H., & Kosmalski, S. (2012). *Asphalt Paving of Treated Timber Bridge Decks.* Missoula, MT: USDA Forest Service.

Hearn, G. (2019). *Proposed AASHTO Guide to Bridge Preservation Actions, Project NCHRP 14-36.* National Cooperative Highway Research Program.

Krauss, P. D., Lawler, J. S., & Steiner, K. A. (2009). *Guidelines for Selection of Bridge Deck Overlays, Sealers and Treatments, Project 20-07.* Northbrook: National Cooperative Highway Research Program, Transportation Research Board.

Wisconsin Department of Transportation. (2019). Chapter 40 - Bridge Rehabilitation. In *WisDOT Bridge Manual.* WisDOT.

18. Placing a Modified Asphalt Overlay

There are several types of asphalt that may be used instead of a typical HMA mixture to overcome durability concerns. Polymer-modified asphalt (PMA) mixtures incorporate styrene-butadiene-styrene (SBS) or other polymers to improve their resistance to permanent deformation. Mastic asphalts (MA) contain a relatively high amount of asphalt binder such that the aggregates have little to no contact with each other. The additional binder makes them impermeable to moisture, but more prone to permanent deformation. Rosphalt contains both more asphalt binder (about 7% to 10%) and a polymer modifier.

PMA and Rosphalt overlays are still considered relatively experimental regarding concrete decks, and have been used sparingly due to their high expense and lack of proven performance. However, PMA and MA pavements are commonly used on steel decks due to their ability to accommodate more deformation.

The procedures for placing a modified asphalt overlay are similar to the procedures for placing a HMA overlay.

Thresholds
While modified asphalt overlays are more established for steel decks, they are considered feasible for all deck structure types. Unlike typical HMA overlays, mastic asphalts and Rosphalt can extend service life by protecting the underlying deck from chlorides and moisture ingress. As a result, modified asphalt overlays are always considered a feasible option. Hearn (2019) does not distinguish between HMA overlays and modified asphalt overlays and as such the recommended distress thresholds shown in Table B.27 for HMA overlays apply for modified asphalt overlays as well.

Cost
Modified asphalt overlays are significantly more expensive than typical HMA overlays. As an example, the material cost of Rosphalt is 9 to 10 times the material cost of typical HMA mixtures according to bid prices recorded by the New Jersey Turnpike Authority. Similarly, the Wisconsin DOT estimates that the material cost of a PMA overlay is 10 to 11 times the material cost of a typical HMA overlay. For the BDPP, a cost of $15.0/sq ft. is assumed for modified asphalt overlays.

Service Life
The range of service lives (5 to 20 years) reported to Krauss et al. (2009) applied to a miscellaneous set of asphalt overlays, including typical HMA mixtures and modified mixtures. The Wisconsin DOT (2019) expects a service life of approximately 10 to 15 years from a PMA overlay, which is higher than its estimate of 3 to 7 years for a typical HMA overlay. However, due to the fact that these overlays are not widely used for concrete decks, there is substantially more literature on the installation than the longevity of these overlays.

Modified asphalt overlays are generally susceptible to the same distresses as typical HMA overlays. While modified asphalt overlays have improved resistance to fatigue, they are also often exposed to larger cyclic stresses due to the higher flexibility of steel and timber decks. Their smaller permeability helps reduce the risk of reflective cracking, but if the overlay cracks, then this low permeability is compromised and moisture and chlorides may reach the deck and cause degradation.

Therefore, the factors controlling the service life of a modified asphalt overlay are assumed to be the same as the factors controlling the service life of a HMA overlay, for both abrasion- and degradation-controlled distress. The more durable properties of the modified asphalt overlays will be represented by assuming a higher minimum service life range compared to HMA overlay as shown in Table B.29.

Table B.29. Minimum service life extension provided by a modified asphalt overlay as a function of NBI deck condition rating.

NBI deck rating	Min. life extension (years)
NBI > 7	10
7 ≥ NBI > 6	8
6 ≥ NBI > 5	7
5 ≥ NBI	6

References

Hearn, G. (2019). *Proposed AASHTO Guide to Bridge Preservation Actions, Project NCHRP 14-36.* National Cooperative Highway Research Program.

Hunsucker, D. Q., Ashurst, K. H., Rister, B. W., Allen, D. L., & Grady, E. (2018). *Longer Lasting Bridge Deck Overlays.* Lexington, KY: Kentucky Transportation Center.

Krauss, P. D., Lawler, J. S., & Steiner, K. A. (2009). *Guidelines for Selection of Bridge Deck Overlays, Sealers and Treatments, Project 20-07.* Northbrook: National Cooperative Highway Research Program, Transportation Research Board.

Russell, M., Uhlmeyer, J. S., Anderson, K., & Weston, J. (2008). *Evaluation of Trinidad Lake Asphalt Overlay Performance.* Olympia, Washington: Washington State Department of Transportation.

Sprinkel, M. M., & Apeagyei, A. K. (2013). *Evaluation of the Installation and Initial Condition of Rosphalt Ovelrays on Bridge Decks.* Charlottesville, VA: Virginia Center for Transportation Innovation and Research.

Wisconsin Department of Transportation. (2019). Chapter 40 - Bridge Rehabilitation. In *WisDOT Bridge Manual.* WisDOT.

19. Placing a HMA Overlay with a Waterproofing Membrane

Waterproofing membranes are used to protect the underlying deck from chloride and moisture intrusion. There are two primary types: constructed-in-place, also called liquid, membrane systems, and preformed membrane systems. Liquid membranes can be further subdivided into bituminous and resinous membranes while preformed membranes may be asphalt-impregnated fabric, asphalt-laminated board, polymer, or elastomer systems. The entire HMA overlay and waterproofing membrane system, abbreviated as HMAWM, consists of a primer at the bottom, followed by the membrane, a tack coat, and then the asphaltic concrete. The primer aids the bond between the substrate) and the membrane while the tack coat helps bond the membrane with the asphalt. A protective board is sometimes placed between the membrane and the tack coat.

HMAWM systems may be used on new and existing concrete decks. The majority of states use them on existing decks to prolong service life; however, some use them on new decks as protective systems as well. HMAWM systems are generally not used in states along the south coast because of the lack of deicing salts. Benefits and disadvantages of these systems vary widely across the states. Some have experienced cost-effective benefits when HMAWM systems have been used both in early life and late life. Others do not use HMAWM systems due to poor performance during experimental projects.

HMAWM systems are typically used on steel and timber decks due to the concern that moisture within the asphalt pavement will cause deterioration of underlying timber or corrosion of underlying steel. However, timber decks treated with an oil-based preservative have compatibility issues with most waterproofing membranes. The problem is double-fold. First, the preserved wood does not absorb the asphalt-based primer coat well and as a result, a slippery layer of asphalt binder lays between the timber and the membrane during installation. This causes the membrane to fold and bunch during installation. And second, oil-based preservatives dissolve asphalt binder, resulting in leakage and dripping underneath the deck, rutting, bleeding, and general deterioration of the asphalt pavement. Water-based preservatives have not demonstrated these issues in the field. It is recommended that oil-based preservatives be given several years for the residue to evaporate prior to application of waterproofing membranes.

The procedures for placing a HMA overlay with a waterproofing membrane are similar to the procedures for placing a HMA overlay. The waterproofing membrane is placed after applying the primer for good adhesion. A second coat may be applied between the membrane and the HMA pavement to facilitate a better bond as well.

Cost
The cost assumed by the BDPP is $10.0/sq ft.

Thresholds
As discussed above, HMAWM systems are widely applicable, much like HMA and modified asphalt overlays. They may be used on concrete, steel, and timber decks. Due to the nature of the membrane, HMAWM systems are considered infeasible if the structure is an open-grated steel deck. Based on best practice, a HMAWM will be omitted from analysis if a timber deck is under 2 years of age. This is shown as a complex user input variable and entry in Table B.30 and assumes the timber has an oil-based preservative treatment, which is common and conservative. The action may be overwritten by the user as desired if these assumptions are untrue.

HMAWM systems are only considered if deicing chlorides are used on the bridge, in alignment with general state practices.

While it is generally agreed upon that systems using waterproofing membranes are poor choices for bridge decks with high amounts of truck traffic, no threshold regarding ADTT was selected. This is because a hard threshold value would be difficult to define. The effect of high ADT and %ADTT is expected to be captured by the analytical algorithms in the portal such that if a HMAWM overlay system has a non-competitive service life extension and life cycle cost, then the HMAWM system will have a low ranking and be omitted from consideration in the final optimization stage instead of this initial filtering stage.

Table B.30. User entries that cause HMAWM overlay systems to be omitted from consideration.

User Input Variable	***Entry***
Deck structure type	Open steel grating
Deck structure type and age	Timber
	≤ 2 years
Primary chloride source	None
	Marine coast

Assuming the needed partial and full-depth repairs are completed prior to installation, HMAWM systems can be advantageous almost regardless of pre-existing condition, provided the installation is of good quality. Hearn (2019) suggests the limits presented in Table B.31. The conditions of both the wearing surface and the structural deck are considered and much more damage is considered acceptable for a non-structural wearing surface than for a structural surface.

Table B.31. Suggested limits below which a HMAWM system is recommended according to Hearn (2019). '-' means no limit.

Distress Type (Wearing Surface)	**Quantities**			
	CS1	**CS2**	**CS3**	**CS4**
Delamination/patch/pothole	-	< 40%	< 20%	< 10%
Crack	-	< 40%	< 20%	< 10%
Effectiveness	-	< 40%	< 20%	< 10%
Distress Type (Deck)	**Quantities**			
	CS1	**CS2**	**CS3**	**CS4**
Delamination/spall/patch	-	< 10%	0%	0%
Exposed rebar	-	0%	0%	0%
Exposed prestressing	-	0%	0%	0%
Cracking (RC and other)	< 10%	0%	0%	0%
Cracking (PSC)	-	< 10%	0%	0%
Efflorescence/rust staining	< 10%	< 10%	0%	0%
Abrasion/wear	-	< 10%	0%	0%

Service Life

The HMAWM system is intended to extend service life by preventing moisture from entering the deck, which is required for corrosion of the rebar and subsequent spalling. Only the waterproofing membrane provides this benefit; the permeable asphalt overlay is present to provide a good riding surface and protect the membrane from traffic loads. Under ideal conditions, the HMAWM system can provide long-term service, but it is difficult to construct and prone to debonding, and as a result tends to have a short life. As an example, service lives of 3 to 40 years were reported to Krauss et al. (2009) and there is general agreement in literature that a typical life is 10 to 20 years (Balakumaran et al. 2017, Krauss et al. 2009, Xi et al. 2018). The HMAWM system tends to fail at the bond between the membrane and the deck substrate underneath, primarily due to poor quality construction or traffic loads. The deck condition prior to the placement of the membrane can also affect the life of the system and moisture or chlorides may become trapped under the membrane if the installation is poor, which permits continued corrosion of the underlying deck. If the asphalt overlay reaches end-of-life prior to the membrane, the overlay can be removed and reapplied and the membrane left in place, provided it is not damaged. This would be considered an HMA overlay installation.

While a HMA overlay re-installation may be required, for simplicity the BDPP considers the waterproofing membrane and asphalt riding surface to be one unit and does not consider their service lives separately. From the perspective of the degradation-controlled service life, this is reasonable since the waterproofing membrane protects the asphalt pavement from reflective cracking. From the perspective of the abrasion-controlled service life, this is not entirely accurate. However, since high traffic volume is both the primary factor affecting abrasion-controlled service life and the primary cause of failure of the waterproofing membrane, it is still reasonable to represent the asphalt overlay and membrane as one unit. This portal only considers the HMAWM system for degradation-controlled decks.

For this portal, the service life extension offered by a HMAWM is assumed to be up to 20 years. The minimum expected extension is described in Table B.32. The factors affecting the service life extension calculated by the portal include the following:

- ADTT,
- Chloride exposure,
- Pre-existing condition of the deck, and
- Contractor experience.

Table B.32. Minimum service life extension provided by a HMAWM system as a function of NBI deck condition rating.

NBI deck rating	Min. life extension (years)
NBI > 7	10
7 ≥ NBI > 6	8
6 ≥ NBI > 5	7
5 ≥ NBI	6

References

Battaglia, I., & Peters, J. (2012). *An Evaluation of Concrete Bridge Deck Overlays and HMA Bridge Deck Overlays with Waterproof Membrnaes.* Madison, WI: Wisconsin Department of Transportation.

Eriksson, M., Wheeler, H., & Kosmalski, S. (2012). *Asphalt Paving of Treated Timber Bridge Decks.* Missoula, MT: USDA Forest Service.

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Russell, M., Uhlmeyer, J. S., Anderson, K., & Weston, J. (2008). *Evaluation of Trinidad Lake Asphalt Overlay Performance.* Olympia, Washington: Washington State Department of Transportation.

Sprinkel, M. M., & Apeagyei, A. K. (2013). *Evaluation of the Installation and Initial Condition of Rosphalt Ovelrays on Bridge Decks.* Charlottesville, VA: Virginia Center for Transportation Innovation and Research.

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20. Placing a PCC/HPC Overlay

Portland cement concrete (PCC) or high-performance concrete (HPC) overlays used on bridge decks are diverse but all have the same purpose of limiting the deck's exposure to moisture and chloride ions and providing a better riding surface. As a result, mixtures are designed to minimize permeability and cracking. Low-slump dense concrete (LSDC) or superplasticized dense concrete (SDC) overlays are the most common types and meet this objective by using low w/c ratios. This decreases the amount of capillary pores, which limits moisture intrusion, but it also decreases the workability of the concrete.

Because of the high paste content and low w/c ratio, LSDC overlays have a tendency to experience shrinkage cracking and require proper curing. As a result, many states have experimented with fiber-reinforced concrete (FRC) to limit crack frequency and widths. FRC typically has dosages of 3 to 8 lb/yd^3 if using polyolefin fibers and 20 to 90 lb/yd^3 if using steel fibers. While studies show that fibers can decrease cracking; fiber balling and workability issues have been reported. If fibers are not practical, shrinkage-reducing admixtures or expansive cements such as Type K may be used.

Other types of PCC overlays use high amounts of supplementary cementitious materials (SCMs) such as fly ash or high-reactivity metakaolin to further decrease permeability. SCMs achieve this by hydrating within the capillary pores left behind by the primary hydration of the cement. The secondary hydration products from SCMs fill and block the pores. By this definition, silica fume concrete (SFC), otherwise known as microsilica concrete (MSC), may also be categorized as a PCC overlay. However, SFC overlays are considered distinct from typical concrete overlays and have sufficient data and literature to be categorized separately. As a result they have their own subsection in the BDPP.

The general procedures for placing a PCC/HPC overlay are as follows:

1. Remove the current wearing surface to desired depth. This may consist of removing a previous overlay.
2. Repair unsound concrete.
3. Install the overlay.
4. Cure the overlay.
5. Apply a surface friction treatment as necessary.

Cost

For the BDPP, a cost of $20.00/sq ft. is assumed.

Thresholds

PCC/HPC overlays can be beneficial in many situations. If applied early in the life of a concrete deck prior to substantial chloride contamination, then they effectively increase the cover above the rebar and extend the time to corrosion initiation. If applied later in the life of the deck when corrosion damage is present, then the distress is repaired, improving the condition of the deck, and the overlay will provide a new wearing surface with good ride quality and non-chloride-contaminated concrete cover. PCC/HPC overlays are generally not used on timber decks. As a result, PCC/HPC overlays will only be omitted from further analysis if the bridge deck is steel or timber, as shown in Table B.33.

Hearn (2019) treats a concrete or modified concrete deck overlay similarly to a HMAWM system and suggests the same condition state limits as in Table B.34.

Table B.33. User entries that cause PCC and HPC overlays to be omitted from consideration.

User Input Variable	*Entry*
Deck structure type	Timber
	Steel
	Other

Table B.34. Ranges of element-level condition data for the deck for which a PCC/HPC overlay is considered appropriate, based on Hearn (2019). '-' means no limit.

Distress Type (Wearing Surface)	Quantities			
	CS1	CS2	CS3	CS4
Delamination/patch/pothole	-	< 40%	< 20%	< 10%
Crack	-	< 40%	< 20%	< 10%
Effectiveness	-	< 40%	< 20%	< 10%
Distress Type (Deck)	**Quantities**			
	CS1	**CS2**	**CS3**	**CS4**
Delamination/spall/patch	-	< 10%	0%	0%
Exposed rebar	-	0%	0%	0%
Exposed prestressing	-	0%	0%	0%
Cracking (RC and other)	< 10%	0%	0%	0%
Cracking (PSC)	-	< 10%	0%	0%
Efflorescence/rust staining	< 10%	< 10%	0%	0%
Abrasion/wear	-	< 10%	0%	0%

Service Life

The service life of a PCC/HPC overlay can be between 10 and 45 years but most states report expected service lives between 15 and 30 years, which falls in line with the average and median service life reported to Krauss et al. (2009). There is very little discussion on the service life of concrete pavements with regards to abrasion, and as a result, degradation of the underlying concrete deck is assumed to be the only failure mode of concern for these overlays in the BDPP.

The degradation-controlled service life of these overlays depends on the pre-existing condition of the deck. If placed early in the life of the structure such that chloride levels have not built up enough to initiate corrosion of the rebar, then they function as additional cover and can extend the time of corrosion, and subsequently the life of the structure, very effectively. If the overlay is placed after corrosion-related damage is present, then the service life depends heavily on the installation procedures. Longer service lives will be achieved if more chloride-contaminated concrete is removed, which will prevent continued corrosion of the rebar and subsequent delaminations and spalls. This has the disadvantage of increasing the time of construction and cost of the overlay substantially, as accounted for in the previous section.

A service life range of up to 30 years is assumed by the BDPP. The minimum service life extension assumed is described in Table B.35. The factors affecting the service life extension provided by the overlays include the following:

- Chloride exposure,
- Pre-existing condition, and
- Contractor experience.

Table B.35. Minimum service life extension provided by a PCC/HPC overlay as a function of NBI deck condition rating.

NBI deck rating	Min. life extension (years)
NBI > 7	15
7 ≥ NBI > 6	10
6 ≥ NBI > 5	8
5 ≥ NBI	7

References

Amirkhanian, A., & Roesler, J. (2019). *Overview of Fiber-Reinforced Concrete Bridge Decks.* Ames, IA: Iowa Department of Transportation.

Balakumaran, S. S., Weyers, R. E., & Brown, M. C. (2017). *Performance of Bridge Deck Overlays in Virginia: Phase I: State of Overlays.* Richmond, VA: Virginia Department of Transportation.

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21. Placing a SFC Overlay

Silica fume concrete (SFC) or microsilica concrete (MSC) overlays achieve low permeability by incorporating approximately 5% to 7% silica fume (by weight of cementitious materials). The silica fume packs into the pores and secondary hydration products and even unhydrated silica fume block the pores, preventing chloride ions from penetrating. Compared to the overlays that use polymers as part of the binding agent, SFC overlays are relatively easy to construct because they do not require special equipment. However, the high amount of silica fume can cause workability issues and these overlays tend to experience early-age cracking if cured improperly. SFC overlays may be used in the same manner as a PCC/HPC overlay. The general procedures for constructing SFC overlays are the same as for constructing PC/HPC overlays.

Thresholds

SFC overlays are synonymous to PCC/HPC overlays and subsequently have the same applications and thresholds as shown in Table B.33 and Table B.34.

Cost

The cost assumed in the BDPP for SFC overlays is $11.00/sq ft.

Service Life

The service life of a SFC overlay is comparable to that of a PCC/HPC overlay. States report expected service lives between 15 and 30 years. A service life range of up to 30 years is assumed by the BDPP. The minimum service life extension assumed is described in Table B.35. Again, since abrasion is not discussed in the literature, it is assumed that SFC overlays only fail due to corrosion. The factors controlling the service life estimate are the following:

- Chloride exposure,
- Pre-existing condition, , and
- Contractor experience.

References

Alhassan, M., & Ashur, S. (2014). Fibrous Latex-Modified Concrete Overlay for Bridge Decks: Installation and Life-Cycle Cost Analysis. *Journal of Advanced Science and Engineering Research, 4*(2), 74-87.

Balakumaran, S. S., Weyers, R. E., & Brown, M. C. (2017). *Performance of Bridge Deck Overlays in Virginia: Phase I: State of Overlays.* Richmond, VA: Virginia Department of Transportation.

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22. Placing an UHPC Overlay

Ultra-high performance concrete (UHPC) is known for high strengths of 18,000 ksi or greater and is considered impervious to all moisture-driven degradation mechanisms. This is because it has a very limited pore network. The primary constituents of UHPC are cement, silica fume, a very fine sand or fly ash, steel fibers, water, and a superplasticizer. The water-to-cement ratio is very low, typically less than 0.26, which prevents the formation of pores and the mixture of constituents has a gradation that encourages maximum particle packing. While the high strength and limited pore network are beneficial, UHPC can be difficult to place and cure. It is relatively sensitive to changes in the source materials and while it is a self-consolidating concrete, it has limited workability time due to the very high fines content.

UHPC is relatively new to the market and is currently an expensive proprietary material. Efforts to make it more available in construction industry are currently in progress, but the first bridge deck overlay in the states was not placed until 2016. Only a few states have begun to investigate the use of UHPC as an overlay material. The focus of these studies are the mixture design development and installation of UHPC. Because of this, long-term field performance data regarding the durability and, subsequently, the service life benefit of UHPC overlays is not available.

Cost

UHPC currently has a material cost over 10 times the material cost of conventional concrete. However, material reductions of about 30 to 75% may be realized when using UHPC instead of conventional concretes. Due to limited information in the literature, no cost is assumed for UHPC.

Thresholds

As for many of the previous overlays, UHPC overlays may be advantageous in most scenarios. While it is primarily being used on concrete decks, it is also considered a feasible wearing surface for steel decks. Similar to PCC/HPC and SFC overlays, UHPC overlays are not considered feasible for timber decks. Additionally, because UHPC overlays have a very high initial cost and are relatively thin, they are not considered an appropriate option to improve the riding quality of the deck. These limits are shown in Table B.36. Otherwise, UHPC overlays may be applied when the deck is in good or fair condition. Regarding condition limits recommended by Hearn (2019), UHPC overlays are considered to fall under the category of Modified Concrete Deck Overlays for which the recommended limits are shown in Table B.34.

Table B.36. User entries that cause UHPC overlays to be omitted from consideration.

User Input Variable	***Entry***
Deck structure type	Timber
	Other
Primary purpose of maintenance strategy	Improved riding quality

Service Life

UHPC is a relatively new technology and has not been used extensively, and most studies of UHPC overlays focus on the material development and installation procedure. No long-term field performance or follow-up studies have been conducted to date. As a result service life estimates for UHPC overlays have been based on laboratory testing and predicted performance.

In a study conducted by Khayat and Valipour (2018), an UHPC overlay was expected to have a service life approximately 40% to 60% longer than its conventional concrete (PCC/HPC overlay) counterpart. Based on this, a service life range of 22 to 45 years can be predicted. Given the enhanced durability of UHPC and the fact that conventional concrete overlays have demonstrated 45-year lives at their best, this appears to be a reasonable estimate. The BDPP does not assume a service life for UHPC overlays.

Because failure has not been demonstrated in the field, the failure mechanism of UHPC is unknown. UHPC demonstrates relatively excellent freeze-thaw durability and low chloride permeability because of its high unit weight. It additionally has very high abrasion resistance and as a result, it is assumed that the service life of the overlay is degradation-controlled. The performance of UHPC will strongly depend on crack management, which is primarily controlled by installation procedures. In the event that no cracks are present, only the pre-existing condition and contractor experience are expected to control the service life of an UHPC overlay.

References

Khayat, K. H., & Valipour, M. (2018). *Design and Performance of Cost-Effective Ultra High Performance Concrete for Bridge Deck Overlays.* Jefferson City, MO: Missouri Department of Transportation (SPR).

Munoz, J. F., De la Varga, I., & Graybeal, B. (2018). *TechNote: Ultra-High Performance Concrete for Bridge Deck Overlays.* McLean, VA: Federal Highway Administration.

Wibowo, H., & Sritharan, S. (2018). *Use of Ultra-High Performance Concrete for Bridge Deck Overlays.* Ames, IA: Iowa Deaprtment of Transportation.

23. Placing a LMC/PMC Overlay

Polymer-modified concrete (PMC) overlays differ from PCC overlays in that part of the mixing water is replaced with a polymer-based admixture. Latex-modified concrete (LMC) overlays are a specific and widespread subset of PMC overlays that replace about 60% of the mixing water with styrene-butadiene-latex. Because of the incorporation of a polymer, these overlays are relatively resistant to chloride penetration and have a higher strength than typical PCC. However, LMC overlays are relatively expensive and can take a long time to cure. They require specialized equipment and need to be mixed on site because they set quickly. Despite these special installation requirements, the procedures for placing a LMC/PMC overlay are generally similar to the procedures for placing a PCC/HPC overlay.

Thresholds

As for PCC/HPC and SFC overlays, LMC/PMC overlays will only be considered when the deck is made of concrete, as shown in Table B.33. LMC/PMC overlays are grouped with general concrete or modified concrete overlays by Hearn (2019) such that the recommended limits for condition data in Table B.34 apply.

Cost

The cost assumed for LMC/PMC overlays is $16.0/sq ft.

Service Life

Service lives of 10 to 50 years have been reported (Krauss et al. 2009). Most states expect a service life of at least 20 years from a LMC overlay and service life caps range from 30 to 40 years in literature. A service life range of up to 30 years is assumed by the BDPP. The minimum service life extension assumed is described in Table B.35. The factors controlling where the service life falls in this range are the following:

- Chloride exposure,
- Pre-existing condition, and
- Contractor experience.

The above discussion applies to the degradation-controlled service life. LMC/PMC overlays tend to have good abrasion resistance and as a result, abrasion is not considered a failure mechanism for this maintenance action.

References

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24. Placing a LMCVE Overlay

Very early strength LMC (LMCVE) overlays are LMC overlays that use a rapid-setting cement. The primary reason for using the rapid-setting cement is to limit closure time; a typical LMC overlay would require several days of closure while a LMCVE overlay can be opened to traffic in about half a day. Additionally, LMCVE overlays are even less permeable to chloride ions than LMC overlays and shrink less than other overlays, which helps limit early-age cracking. However, they lose workability quickly and require the contractor to place the overlay very quickly due to their fast setting time, which can encourage early-age cracking.

The procedures for placing a LMCVE overlay are similar to the procedures for placing a PCC/HPC overlay.

It should be noted that the LMCVE overlay is almost identical to the LMC/PMC overlay in its purpose, cost, and service life. However, because the short construction time can decrease user costs substantially and user costs are an optional variable to consider in the optimization algorithm, the BDPP considers LMCVE overlays separately. Their relatively challenging construction currently makes them a riskier action than a more typical LMC/PMC overlay, but this is not captured in the uncertainties assumed by the model, but can be included in the contractor experience reduction factor. The user should use their own discretion to decide whether to consider LMCVE overlays or not.

Thresholds

As for LMC/PMC overlays, LMCVE overlays will be omitted from consideration if the bridge is made of steel or timber, as shown in Table B.33, and subject to the same set of recommended thresholds proposed by Hearn (2019) in Table B.34.

Cost

Based on a study conducted by Liang et al. (2010), LMCVE overlays are assumed to have a slightly higher material cost than LMC overlays. Therefore, a cost of $17.0 /sq ft. is assumed.

Service Life

The assumed service life range and controlling factors for LMCVE overlays are considered to be the same as for LMC/PMC overlays.

References

Balakumaran, S. S., Weyers, R. E., & Brown, M. C. (2017). *Performance of Bridge Deck Overlays in Virginia: Phase I: State of Overlays.* Richmond, VA: Virginia Department of Transportation.

Hearn, G. (2019). *Proposed AASHTO Guide to Bridge Preservation Actions, Project NCHRP 14-36.* National Cooperative Highway Research Program.

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25. Placing a Thick Polymer Concrete Overlay

Polymer concrete overlays are comprised of aggregates and a polymeric binding agent instead of a cementitious one. Not to be confused with thin polymer overlays, these overlays are approximately 0.75 inches to 1.0 inch thick or more. Their thickness makes them highly impermeable and resistant to chloride and moisture ingress, and the use of a polymeric binder minimizes the required closure time. Note that surface preparation and the pre-existing condition are of paramount importance for successful installation of thick polymer overlays. Restrictions regarding environmental conditions during placement, specific deck temperature range is recommended, and placement on wet or damp surfaces also exist.

The general procedures for installing a thick polymer concrete overlay are as follows:

1. Grind the existing surface to the desired profile.
2. Shotblast or sandblast the surfaces to be overlaid.
3. Clean the surface to be overlaid.
4. Apply a primer coat.
5. Install the premixed polymer concrete overlay.
6. Finish the surface and broadcast sand on the top for skid resistance.
7. Allow the overlay to cure.

Cost

The portal assumes a cost of $15.0/sq ft. This will change based on the thickness of the material to be placed and the contractor experience.

Thresholds

Polymer concretes are typically only used in rehabilitation because of their expense. However, because of the potential benefit of early-age application, they will be considered for all concrete and decks in the BDPP. Literature indicates that these systems could also be placed on steel decks as the primer will help in developing a bond between the overlay and underlying deck. Although tried on experimental basis, they will not be considered for timber decks as shown in Table B.37.

Table B.37. User entries that cause thick polymer overlays to be omitted from consideration.

User Input Variable	***Entry***
Deck structure type	Timber
	Other

Hearn (2019) provides guidance for when to apply thin polymer overlays, but does not distinguish between thin and thick polymer overlays. Thin polymer overlays are primarily intended for installation early in the life of the structure whereas the purpose of thick polymer overlays aligns more closely with the purpose of PCC/HPC overlays, although they also provide benefits when applied early in the life of the bridge deck. Therefore, the recommended thresholds shown in Table B.34 are assumed to apply for thick polymer concrete overlays.

Service Life

Expected service lives for polymer concrete overlays are between 20 and 40 years. These estimates likely only consider failure from chloride-induced corrosion. Therefore, the maximum service life extension assumed for the degradation-controlled service life is 25 years, the minimum extension assumed is shown in Table B.38, and the factors controlling the assumed life are as follows:

- Pre-existing condition, and
- Contractor experience.

Thick polymer overlays are expected to have the higher abrasion-controlled service life properties compared to thin polymer overlays, for which the service life range is assumed to be 7 to 25 years and the factors controlling the precise value are ADTT and contractor experience.

Table B.38. Minimum service life extension provided by a thick polymer overlay as a function of NBI deck condition rating.

NBI deck rating	Min. life extension (years)
NBI > 7	15
7 ≥ NBI > 6	10
6 ≥ NBI > 5	8
5 ≥ NBI	7

References

Anderson, K. W., Uhlmeyer, J. S., Russell, M., Simonson, C., Littleton, K., McKernan, D., & Weston, J. (2019). *Polyester Polymer Concrete Overlay Final Report.* Olympia, WA: Washington State Department of Transportation.

ElBatanouny, Mohamed K., Nadelman, Elizabeth I., Kurth, Jonah C., and Krauss, Paul D. (2017). *Use of Polymer Overlays or Sealers on New Bridges*. Iowa Highway Research Board TR-717. WJE report.

26. Placing a Thin Polymer Overlay

Thin polymer overlays are similar to polymer concrete overlays; however, their thicknesses range from 0.125 inches to 0.5 inches and they typically have thicknesses of 0.375 or 0.25 inches. The binder is typically either epoxy, polyester, or methyl methacrylate (MMA), although some states have used epoxy-urethane binders in the past. They may be typically constructed in multiple layers using the broom and seed method. Most states lay down two layers wherein the binder is applied to the prepared surface, then the aggregates are applied, and then the process repeated to build the second layer. The general procedures for placing a thin polymer overlay are assumed to be as follows for the BDPP:

1. Prepare the deck surface by roughening and cleaning the surface.
2. Place the first layer of polymer.
3. Place the aggregate over the polymer layer.
4. Place the second layer of polymer.
5. Place a second layer of aggregate over the second polymer layer.
6. Allow the overlay to cure.
7. Remove excess aggregates.

Thin polymer overlays are advantageous because they provide an impermeable layer that can resist chloride intrusion and because they can restore skid resistance. However, the popular multi-layer system cannot change the profile of the deck and, therefore, cannot be used to correct drainage patterns or improve the ride quality. They are also only effective if placed prior to chloride contamination of the deck, and tend to delaminate quickly if the reinforcing steel is corroding.

Cost

The cost assumed for a thin polymer overlay is $8/sq ft.

Thresholds

Thin polymer overlays are used exclusively on concrete decks. The decks should be in good condition with very little corrosion-related distress. Thin polymer overlays are commonly used to prevent chloride and moisture ingress but may also be applied if the primary purpose is to restore skid resistance. Because they are relatively thin, thin polymer overlays cannot be used to improve ride quality by improving the surface profile. The conditions under which thin polymer overlays are omitted from consideration are presented in Table B.39. The recommended thresholds below which Hearn (2019) recommends thin polymer overlays be considered are presented in Table B.40.

Table B.39. User entries that cause thin polymer overlays to be omitted from consideration.

User Input Variable	*Entry*
Deck structure type	Other
NBI deck condition rating	≤ 6
Primary purpose of maintenance	Improving ride quality

Table B.40. Ranges of element-level condition data for the deck for which a thin polymer overlay is considered appropriate, based on Hearn (2019). '-' means no limit.

Distress Type (Wearing Surface)	Quantities			
	CS1	CS2	CS3	CS4
Delamination/patch/pothole	-	< 40%	< 20%	< 10%
Crack	-	< 40%	< 20%	< 10%
Effectiveness	-	< 40%	< 20%	< 10%
Distress Type (Deck)	**Quantities**			
	CS1	**CS2**	**CS3**	**CS4**
Delamination/spall/patch	-	< 10%	0%	0%
Exposed rebar	-	0%	0%	0%
Exposed prestressing	-	0%	0%	0%
Cracking (RC and other)	< 10%	0%	0%	0%
Cracking (PSC)	-	< 10%	0%	0%
Efflorescence/rust staining	< 10%	< 10%	0%	0%
Abrasion/wear	-	< 10%	0%	0%

Service Life

Reported service life for thin polymer overlays varies widely from 5 to 30 years. The service life is typically controlled by the traffic volume. The skid resistance of the polymer overlay depends on the aggregates, but if the aggregates have relatively poor abrasion resistance or are not well-embedded in the polymer matrix, they may become polished or pop out. The polymer will also polish quickly, resulting in a short life under heavy traffic. When aggregates pop out, they leave behind cracks and holes in the overlay that chlorides and moisture may enter through, compromising the protective qualities of the overlay. Additionally, thin polymer overlays are prone to delamination, particularly if moisture is trapped in the concrete or the interface underneath.

Therefore, the maximum service life extension assumed for the degradation-controlled service life is 25 years, the minimum extension assumed is shown in Table B.38.

The maximum service life extension assumed by the BDPP for both abrasion-controlled and degradation-controlled service life is 15 years. The minimum extension assumed is shown in Table B.41. Only ADTT and contractor experience are assumed to affect the abrasion-controlled service life while factors controlling the assumed degradation-controlled life are as follows:

- ADTT
- Pre-existing condition, and
- Contractor experience

Table B.41. Minimum service life extension provided by a thick polymer overlay as a function of NBI deck condition rating.

NBI deck rating	Min. life extension (years)
NBI > 7	7
7 ≥ NBI > 6	6
6 ≥ NBI > 5	5

References

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27. Concrete Partial-Depth Repair (supplemental)

Partial-depth repairs are typically conducted when localized areas of the concrete wearing surface are deteriorated, often due to corrosion of the top mat of reinforcing steel. The expansive corrosion products cause cracking around the rebar, leading to delamination of the concrete above the rebar and unsound concrete below the rebar. This requires the unsound concrete to be removed, the reinforcing steel to be cleaned or replaced if corrosion has caused significant section loss, and the area to be filled with a patching material. Patching materials may be typical concrete mixes, rapid-setting and proprietary cementitious materials, or epoxy and polymer based repair materials depending on the required closure time.

Most states classify partial-depth repairs according to the depth of concrete that needs to be removed because the extent of surface preparation affects the construction duration and project cost significantly. Hearn (2019) defines two types of partial-depth repairs, Type I and Type II. Type I repairs are conducted when the depth of concrete removal does not extend past the top mat of reinforcing steel. Type II repairs are required when the depth of concrete removal extends to half the thickness of the deck or 1 inch below the top mat of reinforcing steel, whichever is greater. Using the depth of the reinforcing steel as the boundary between different partial-depth repair types is logical because it takes considerably more effort to remove concrete behind the rebar than above.

The BDPP assumes that all partial-depth concrete repairs extend at least to the depth of the rebar. The procedure assumed for partial-depth concrete repairs is as follows:

1. Identify and remove delaminated concrete and incipient spalls. If a patch with a longer service life is desired, remove all chloride-contaminated concrete as well.
2. Check for remaining unsound concrete at the edges and bottom of the delamination and remove as necessary.
3. Clean exposed reinforcing steel, or remove deteriorated reinforcing steel if necessary.
4. Clean the repair area by abrasive blast cleaning.
5. Replace any steel that was removed.
6. Place and cure concrete patch.

Some states also specify placement of sacrificial anodes within the repair area to mitigate corrosion related to ring anode effect.

References

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