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Development of a life-cycle cost analysis tool for improved maintenance and management of bridges

Andrew Mock
Iowa State University

Development of a life-cycle cost analysis tool for improved maintenance and management of bridges

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Andrew Mock

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Behrouz Shafei, Co-major Professor
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The student author, whose presentation of the scholarship herein was approved by the program of study committee, is solely responsible for the content of this thesis. The Graduate College will ensure this thesis is globally accessible and will not permit alterations after a degree is conferred.

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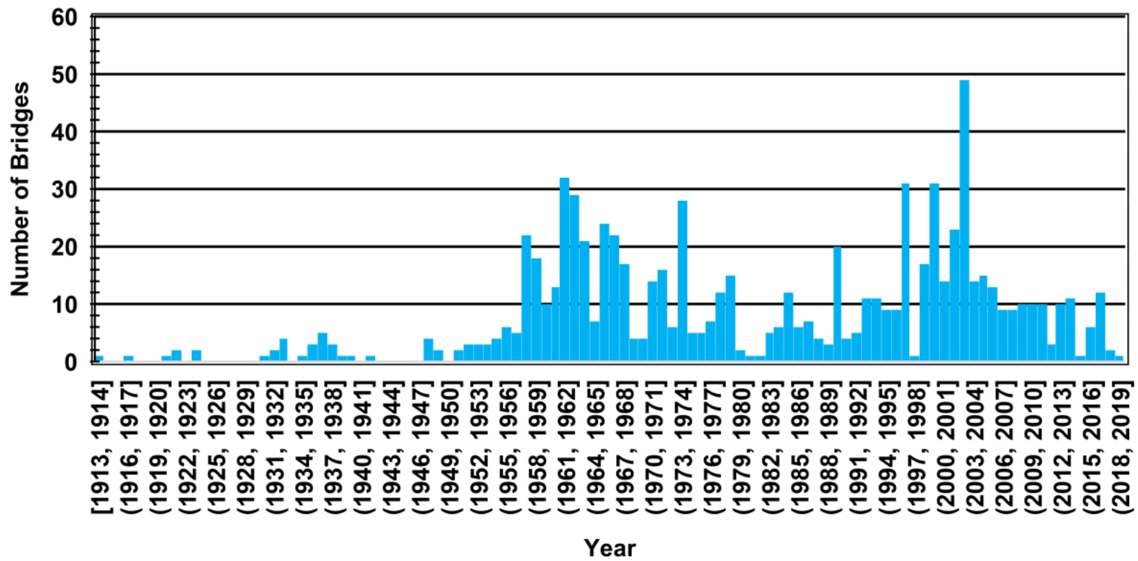
ABSTRACT

The Moving Ahead for Progress in the 21st Century Act (MAP-21) of 2012 requires states to develop and implement a transportation asset management plan (TAMP) for their National Highway System (NHS). Life-cycle cost and risk management analyses are the main analyses expected to be included in a state's TAMP. The life-cycle cost analysis (LCCA) can be defined as "a process for evaluating the total economic worth of a usable project segment by analyzing initial costs and discounted future costs, such as maintenance, user costs, reconstruction, rehabilitation, restoring, and resurfacing costs, over the life of the project segment" (TEA 21-1998). The proposed tool is expected to integrate the data from different sources, assign different confidence levels based on their accuracy, and use them as an input for LCCA. It will be an effective tool to compare the total user and agency cost of competing project implementation alternatives. With this, transportation investment decisions can consider all the costs incurred during the period over which the alternatives are being compared rather than just looking into the initial costs and create efficient maintenance strategies over the service life of a bridge.

The main objective of this research project is to include risk management analysis into the TAMP through the development of a LCCA tool. Such a tool is expected to cover the most common types of bridges in Iowa, while integrating the available historical data from maintenance crews, contractors, and past inspections to the predictive models that take into account the cost of maintenance and repair during the service life, and provide a manageable approach to include indirect costs in the analysis.

CHAPTER 1. INTRODUCTION

America’s bridges are rapidly reaching the end of their original service lives. Forty-two percent of bridges in America are reaching ages of 50 years or more (FHWA 2019). In the state of Iowa, 35% of bridges are over 50 years old (Figure 1.1).



(Iowa DOT SIIMS) Figure 1.1. Year built distribution for bridges in Iowa

The graph shows a spike in bridge construction around the Baby Boom era (end of the 1950s and beginning of the 1960s). Therefore, many of the state’s bridges are reaching their initial intended service lives. This emphasizes the need to establish efficient maintenance, repair, and rehabilitation (MR&R) strategies. Budgets, however, remain tight and limited in their ability to cover bridge maintenance needs. Currently, on average 20% to 50% of infrastructure costs in multiple countries are associated with maintenance (Mao and Huang 2015). As populations continue to grow and the demand placed on aging infrastructure increases, the need to prolong the lifespan of existing structures given limited budgets requires that the life-cycle costs (LCC) of bridges and their components be strategically planned using LCCA (Ertekin et al. 2008).

The main objective of this research project was to develop a user friendly LCCA tool for Iowa's bridges based on survival analysis of bridge condition ratings. The tool was designed to cover the most common types of bridges in Iowa while integrating historical data from various sources into the predictive models that account for the cost of maintenance and repair activities during a bridge's service life.

This report provides background information on LCCA and bridge asset management practices and describes the development and implementation of the LCCA tool for bridges in Iowa resulting from this research.

1.1. Requirements of MAP-21

In 2012, the Moving Ahead for Progress in the 21st Century (MAP-21) Act was signed into law. MAP-21 requires states to develop and implement a transportation asset management plan (TAMP) for their respective portions of the National Highway System (NHS) as part of the National Highway Performance Program. MAP-21 defines asset management as "a strategic and systematic process of operating, maintaining, and improving physical assets, with a focus on both engineering and economic analysis based upon quality information, to identify a structured sequence of maintenance, preservation, repair, rehabilitation, and replacement actions that will achieve and sustain a desired state of good repair over the life-cycle of the assets at minimum practicable cost."

This federal-level push for LCCA originated in the 1980s with the development of Pontis, an early bridge management system (BMS) funded by the Federal Highway Administration (FHWA). The FHWA first started to encourage the use of LCCA in 1990, prior to making LCCA mandatory in all states for projects greater than or equal to $25 million in value (Goh and Yang 2014). Pontis, now known as AASHTOWare Bridge Management software (BrM), gives agencies the ability to record bridge data, suggest maintenance actions for various condition states, and provide suggestions on allocating resources network wide. AASHTOWare and similar BMS may use some historical data to formulate decisions but generally do not incorporate risk into the decision-making process (Khatami et al. 2016).

The current MAP-21 legislation has recognized the need to transition from deterministic estimations to stochastic modeling for the LCCA process. The legislation includes detailed expectations and all actions necessary to fulfill the FHWA's requirements for the NHS in terms of the agency's initiative to improve or preserve the condition of assets and the performance of the system. The states' TAMPs are expected to cover LCC and apply risk management to the analysis. Risk management identifies risks imposed by uncertainties and communicates this risk to the agency (FHWA 2012).

To help states comply with risk management requirements, there is a need for data collection, maintenance, and integration and the cost associated with creating and maintaining the necessary software for implementing risk-based and performance-based asset management (MAP-21). This report further covers risk-based management in Chapter 4. MAP-21 specifically mentions the requirement for LCCA in Section 1106 of the National Highway Performance Program in a list of the minimum plan requirements.

1.2. Definition of LCCA

The Transportation Equity Act for the 21st Century (TEA-21) defined LCCA as "a process for evaluating the total economic worth of a usable project segment by analyzing initial costs and discounted future costs, such as maintenance, user costs, reconstruction, rehabilitation, restoring, and resurfacing costs, over the life of the project segment."

LCCA can create the opportunity for infrastructure agencies to choose the "most economical design and repair decisions" (Mahmoud et al. 2018) while catering to the unique situation of each bridge project and introducing efficiency throughout the lifespan of the bridge. The increase in efficiency can then lead to a functioning system with minimal user delays and maximized use of strategic maintenance, repair, and replacement projects over the lifetime of a new or existing structure. In order to accomplish such goals, LCCA requires a multitude of data sets, especially if it is to be implemented at the state level. These data must be collected over a series of years, then properly stored and managed so that they are easily accessible for analysis and application to future decision making.

LCCA can aid in decision making because it offers a cost-centric approach while also featuring performance-based inputs. LCCA can compare all future costs in terms of present values, incorporating the total user and agency costs of competing project implementation alternatives. This ability allows the owner or those in charge of maintenance decisions to select the most cost-effective alternative to complete a preselected project at a desired level of benefit.

In contrast to LCCA, the current state of the practice is to develop alternative design strategies for a bridge and choose the one that meets the budgetary constraints of the project. In this approach, the initial costs weigh heavily in the selection process, and the long-term implications of the selected design are not accounted for. This decision-making process can result in larger accrued costs over the lifespans of bridges because some construction approaches have been shown to lead to faster deterioration and, despite their lower initial costs, result in higher maintenance and repair costs. In short, initial costs do not necessarily reflect the costs accrued over the lifespan of a project and basing decision decisions on lower initial costs creates the potential for costly maintenance and repair in the future.

The purpose of LCCA is to predict all potential future investments necessary over the assumed lifespan of the bridge in order to effectively compare all alternatives based on their LCCs rather than solely on their initial costs. LCCA therefore supports the choice of the most economically effective design in the long term, even if its initial cost is high (Hatami and Morcous 2013). The most economically effective choice does not have to have the longest service life or the lowest initial cost. Analyzing LCCs allows future budgets to be planned accordingly, timing projects and maintenance on a system-level scale as opposed to for a singular bridge. Project scaling is discussed further in Chapter 6.

The cost components of LCCA are as follows: initial, inspection, maintenance and repair, and user costs. Some studies have included additional costs such as salvage value and unexpected extreme events, but these will not be considered in this study. In order to plan for the individual cost components, LCCA requires a large amount of data and data analysis to understand trends in bridge performance at multiple scales. Bridges need to be studied at a large scale, focusing on major structural components, and at a more detailed scale, focusing on the individual elements of the bridge. Data gathering is discussed in Chapter 3. Once all costs have been identified, they are referenced to a set point in time and the LCC is calculated as the total cost, which is then used compare the LCCs of project alternatives.

The initial date of the conceptualization of LCCA for infrastructure projects is difficult to determine. As noted above, some initial efforts toward LCCA were seen in the late 1980s and mid-1990s. Early forms of LCCA were basic and involved few variables. These analyses were applied to pavement projects because little changed between projects; following basic road preparation work, pavement installation, repair, and revetment practices were repetitive and limited in complexity and therefore a viable subject for implementation of LCCA. In 1995's

National Highway System Designation Act, LCCA was expected of states conducting NHS projects greater than or equal to $25 million; this act was then followed by further details in a 1996 memorandum from the FHWA Executive Director (Walls and Smith 1998). Both documents were vague in comparison to current expectations specified by more recent legislation such as MAP-21.

Bridge data are more difficult to assess due to the greater number of variables deriving from the increased complexity caused by the large number of components in a bridge, the variety of environments in which bridges are built, and the biases inevitably involved in human input. The compilation and analysis of necessarily large data sets may have seemed too daunting for early implementation of LCCA by state departments of transportation (DOTs). Recording systems and databases, along with condition appraisal systems, have come and gone over the years as federal laws and expectations have changed. As understanding of the importance of condition assessment and the diligence required of inspectors has progressed, so has the training inspectors receive, leading to additional information being recorded during inspections, forming databases and the data required for potential LCCA. BMS have recently become more popular and may have led to the assumption that these BMS are separate from LCCA (Safi et al. 2015). However, the data input into a BMS could have a large influence on the accuracy of LCCA (Mahmoud et al. 2018, Hegazy et al. 2004). DOTs that are completely reliant on BMS may fail to understand the power and benefits associated with implementing a risk based LCCA tool into their decision-making systems. They may see the potential for larger initial costs without 100% confidence in the calculated future costs and be unwilling to take the risk of trusting a LCCA (Mahmoud et al. 2018). However, through MAP-21 the federal government is now emphasizing the need for LCCA and is encouraging more states to implement the analysis into their bridge-related decision-making processes.

1.3. Existing LCCA Frameworks

For the design and maintenance of both new and existing bridges, it is critical for agencies to conduct proper LCCAs if they are to keep up with their deteriorating and increasingly strained infrastructure while adhering to a financial plan. LCCA has multiple variations that range in complexity and data requirements. There are a multitude of ways to compute LCCA, in part due to the large number of factors affecting LCC. While the two main types of LCCA focused on in the literature and in practice are deterministic and probabilistic (Mahmoud et al. 2018), there are three different types of LCCA models, deterministic, rational, and probabilistic, as seen in Table 1.1.

Table 1.1. Comparison of the three types of LCCA models

Deterministic Models	Rational Models	Probabilistic Models
1. Discrete costs	1. Discrete costs	1. Cost probability
2. Estimated average	2. Historical data	2. Historical data
3. Acceptable LCC range	3. Matrices	3. Probability of component variability
4. Neglects uncertainties	4. Risk analysis	4. Includes uncertainties
		5. Accounts for inflation

Source: Mahmoud et al. 2018

The first and simplest type of LCCA model is the deterministic models. These models consider all actions and their consequences as deterministic and do not account for the uncertain nature of the events or parameters affecting them. For this type of model, all costs and intervals for them are predetermined, producing a final LCC that lacks detail and individualization but provides an “acceptable range” for the user (Basim and Estekanchi 2015). Each cost type, cost, and number of occurrences of each cost over a bridge’s lifetime are summed for the final discrete

LCC. These values are fixed; they are based on estimations but rarely use existing data and do not consider any degrees of variability nor the uncertainty of input values (Azizinamini et al. 2014, Reigle and Zaniewski 2002). Additionally, this method does not account for unexpected events that may occur during the bridge's lifespan.

Unfortunately, failing to include uncertainties in a deterministic LCCA model can skew the final results. The results can even be invalidated due to unexpected future costs, changes in costs due to variables such as the materials used in or the locations of bridges, and differences in types of environment. Attempting to utilize the average of each cost component limits the strength and versatility of this type of model. If there is a complete lack of historical data and the model must rely on expert judgement, then estimations of yearly maintenance costs may be the only option, but these estimations cannot be expected to be highly accurate. Finally, if costs are difficult to determine or estimate, they are often ignored. For example, depending on the level of detail, user costs can be incredibly difficult to quantify (Kang et al. 2007).

The deterministic method is similar to type of LCCA currently used by the Iowa DOT, initially referred to as Whole Life Cost Analysis. For this analysis, the Iowa DOT Office of Bridges and Structures has accumulated a list of 10 typical maintenance activities routinely performed over the life-cycle of Iowa's bridges. Included with each activity is the expected number of occurrences of that activity over a bridge's lifespan. Similar to a rational LCCA model, the Iowa DOT's method also includes expected maintenance and repair activities for the three most common bridge types in Iowa, prestressed (PS) girder, steel girder (SG), and reinforced concrete (RC) slab, and for the prestressed and steel girder bridges the model specifies the abutment types as either integral or stub abutments. These activities are tabulated by bridge type and have fixed costs and fixed iterations. The attempt to calculate LCC for three specific types of bridges using data from similar bridge types brings this method close to a rational approach, but the method is fundamentally a deterministic approach (Neubauer 2018). Table 1.2, adapted from data provided by the Iowa DOT, depicts the activities and cost information used for LCCA.

Table 1.2. Iowa DOT expected LCCs and iterations of common maintenance activities

	Deck Patching	**Joint Sealing or Repair/ Replacement**	**Approach Pavement Repair**	**Berm/Slope Protection Repair**	**Abutment Erosion Repair**	**Deck Overlay**
PS Girder w/ Integral Abutments	5% of deck area	5 times	2 times	1 time	1 time	1 time
	$100/square foot	$15/foot of joint	$100,000/ repair	$36,000	$5,000	$50/square foot
PS Girder w/ Stub Abutments	5% of deck area	2 times	2 times	1 time	1 time	1 time
	$100/square foot	$1,000/foot of joint	$100,000/ repair	$36,000	$5,000	$50/square foot
Steel Girder w/ Integral Abutments	5% of deck area	5 times	2 times	1 time	1 time	1 time
	$100/square foot	$15/foot of joint	$100,000/ repair	$36,000	$5,000	$50/square foot
Steel Girder w/ Stub Abutments	5% of deck area	2 times	2 times	1 time	1 time	1 time
	$100/square foot	$1,000/foot of joint	$100,000/ repair	$36,000	$5,000	$50/square foot
Concrete Slab	5% of deck area	5 times	2 times	1 time	1 time	1 time
	$100/square foot	$15/foot of joint	$100,000/ repair	$36,000	$5,000	$50/square foot

Source: (Neubauer 2018)

The second type of LCCA model is the rational model. This model combines the features of deterministic LCCA with risk analysis. Similar to a deterministic model, the LCC is the sum of fixed costs but these costs are based on the frequency of a certain cost affecting bridges in similar situations to the one being analyzed (Mahmoud et al. 2018). However, the incorporation of new variables can create a more realistic estimation of the LCC. Rational models are not common within the literature, and therefore an example in practice is not available. These models are generally “in-between” models, in that they represent an attempt to transition from a deterministic approach to a stochastic approach. These models demonstrate an effort to analyze historical data rather than rely on estimations of current experts in bridge maintenance. There is also some consideration of risks in project alternatives, and a limited recognition of the variability of model inputs (Hawk 2003).

The third and most recent type of LCCA model is the probabilistic model, a risk-based methodology that heavily relies on the probabilities of the various costs occurring and the potential variability in those costs. These variabilities, referred to as uncertainties, are estimated through diligent data analysis of existing and historic structures. The confidence of the estimations is based upon the calculated probability distributions of each variable that is included in the model. Uncertainties can be accounted for in many of the input variables, including material costs, environmental conditions, construction methods, construction time, and design variations (Hawk 2003). This provides a more realistic understanding of the necessary maintenance and the ways different strategies may affect bridges.

As these brief descriptions show, each of the three types of LCCA methods has its strengths and weaknesses. The usefulness of any LCCA model depends on the skill set of the user, the bridge under consideration, and the availability of satisfactory data. These are explained in further detail in the discussion of risk based LCCA in Chapter 4.

A common gateway into LCCA for bridges is the method called Bridge Life-Cycle Cost Analysis (BLCCA), which was proposed in National Cooperative Highway Research Program (NCHRP) Report 483, *Bridge Life-Cycle Cost Analysis* (Hawk 2003). The method was created under NCHRP Project 12-43. The purpose was to develop a LCCA procedure and lay the groundwork for states interested in implementing LCCA at a time when many states did not have the necessary data to implement a more detailed analysis. Some of the goals of BLCCA stated in the report show that it was intended to be a versatile method that would yield accurate results without requiring a large data source to start, allowing for growth with new data (Hawk 2003).

The BLCCA model acknowledges that life-cycle costing needs to include an analysis of risk, which can introduce economic vulnerabilities for bridge agencies. Hawk (2003) believes that a realistic approach to LCCA is to include risks and uncertainties. The report states that the risks imposed on bridges stem from uncertainties in the effects of load capacity based on condition ratings, cost of activities, effects of traffic, seismic vulnerability, deterioration caused by the surrounding environment, as well as other hazards (Hawk 2003). Additionally, the model uses statistical regression to predict the deterioration of bridges. This allows for the opportunity to determine and understand the relationships between condition states and parameters that would be expected to affect the condition state (Ertekin et al. 2008).

BLCCA is versatile and can be applied to either deterministic or stochastic (probabilistic) scenarios. The deterministic approach utilizes one-time estimates of costs, ignoring any potential for variability in the inputs, whereas the probability distributions of each cost serve as the inputs for a probabilistic BLCCA model. Similarly, deterministic models have single values for deterioration rates, whereas the stochastic model includes uncertainties and other relevant criteria to adjust deterioration rates for each situation and as the condition of the bridge changes over its lifespan. The end results of the two models are therefore different, in that the former produces a singular estimate of the LCC and the latter produces a distribution curve of results with defined confidence levels. A sensitivity analysis can be performed to evaluate the effects of cost estimates in the deterministic model and can be expanded to other input variables for the stochastic model (Hawk 2003).

NCHRP Report 483 has had a large influence on much subsequent work on LCCA. Some examples are as follows. Helmerich et al. (2008) recognized the importance of the report in their work on BMS for effective management of bridges. Safi et al. (2015) regularly referenced Hawk's (2003) work in their discussion of the necessity to integrate complementary BMS and LCCA efforts. The Colorado DOT, in its efforts to consolidate cost data for LCCA, referenced NCHRP Report 483 when determining what data to collect and how to analyze it (Hearn 2012). Ertekin et al. (2008) referenced NCHRP Report 483 when considering the number of elements to study in order to accurately portray the health of a bridge in LCCA, acknowledging that other studies were limited in their scope. In their review of existing tools, Hatami and Morcous (2013) discussed BLCCA's ability to determine the net present value of agency and user costs due to maintenance activities, taking into account uncertainties in costs and timing for each alternative within the user-defined sequence of maintenance and repair events.

Within the last decade, LCCA methods for bridges have advanced as more agencies have taken steps towards using these methods for maintenance and repair decision making. Researchers have applied statistical models to simulate real-world conditions and accurately capture deterioration, considering environmental and use factors, to optimize maintenance strategies. Monte Carlo simulations to account for uncertainty and variability in deterioration model inputs have been used in a multitude of works (Ertekin et al. 2008, Walls and Smith 1998, Basim and Estekanchi 2015, Liu and Frangopol 2004, Bucher and Frangopol 2006, Osman 2005, Saassouh and Lounis 2012, Alipour 2010, Alipour et al. 2010 and 2013, Shafei et al. 2012 and 2013, Shafei and Alipour 2015a and b, and Cui and Alipour 2018). This technique is widely used due to its robustness and its versatility. Other models found in the literature employ the genetic algorithm (GA) for optimization and deterioration models (Morcous and Lounis 2005, Furuta et al. 2005, Liu et al. 1997), though these will not be discussed in this report. Additionally, Markov chains are commonly used in maintenance decision research as a strategy to optimize maintenance in pavements, bridge decks, superstructures, and bridges in general through the use of historical bridge data and transition probabilities between bridge condition states (Ertekin et al. 2008, Hatami and Morcous 2013, Ilg et al. 2017). Markov chains and Monte Carlo simulations are used in this research and are discussed in Chapter 4 of this report.

Existing LCCA tools are briefly reviewed in the remainder of this section. Many are competent models that have aided their developers in conducting LCCAs in their specific situations. Unfortunately, however, many models are custom tailored to their initial intended users. Implementation of LCCA in Iowa similarly requires customization to meet the state's needs as well as to use its existing data. Features of the following models and guidelines, as well as others, are incorporated into this work.

As mentioned above, the FHWA has supported and encouraged the development of maintenance schemes and models to produce more cost-efficient asset management strategies. The Systematic Preventive Maintenance (SPM) plan was intended to create preventive maintenance schemes that are cost-effective and follow American Association of State Highway and Transportation Officials (AASHTO) guidelines. The Life-Cycle Cost Analysis Primer represents the steps for performing LCCA. The steps are as follows:

1. Define design alternatives
2. Determine the timing of activities
3. Estimate the agency and user costs
4. Calculate the life-cycle cost
5. Evaluate the results

These steps derive from those proposed in NCHRP Report 483, in which the BLCCA tool was developed, as discussed earlier in this chapter. They represent the steps necessary for either a deterministic or probabilistic approach to LCCA. The approach used depends on how costs and timing are input.

Another LCCA tool is Pontis, now referred to as AASHTOWare BrM. The Iowa DOT currently uses AASHTOWare BrM, and this LCCA tool is intended to work in conjunction with the program managing the maintenance decision process. Currently, the program can predict future condition states and can suggest maintenance actions but does not include the associated risks.

RealCost software was developed by the FHWA in 1998 to provide deterministic and probabilistic net present values for pavement projects. The program relies completely on a large amount of user inputs in order to calculate agency and user costs. It can use deterministic values and has the capability to use seven different probability distribution types as inputs. RealCost even uses Monte Carlo simulations to provide the probability distributions for the final LCC results (Hatami and Morcous 2013, Hawk 2003). The program's powerful computing capability gives it an advantage over other existing software. However, the program fails to incorporate historical data into its calculations. All data it requests must be input by the user, increasing the likelihood of inconsistency and user error.

The goal for Iowa is to create a probabilistic LCCA that encompasses risk management. Past literature, including NCHRP Report 483, provided guidance to help Iowa achieve its goal of a working model. Certain assumptions were made due to existing data restrictions. These are specified in Chapters 2 through 5. This project takes advantage of the available data and, in doing so, guides future data gathering efforts to create an accurate LCCA.

1.4. Iowa DOT Current Status and Goals

The Iowa DOT aims to transition to life-cycle cost analysis in hopes of better allocating its existing budget. Currently, Iowa bridges are inspected following the required maximum interval of every 24 months, as mandated by the FHWA. When necessary, bridges are inspected more frequently, usually for a more in-depth inspection preceding project decisions and after any concerning accidents. The data from these inspections are logged into Iowa's central inspection database, the Structure Inventory and Inspection Management System (SIIMS). All National Bridge Inventory (NBI) data required by the FHWA are recorded here, as well as any additional information Iowa chooses to log. This process is further explained in Chapter 3 of this report.

The data recorded are used by the Quality Control Team of the Iowa DOT's Office of Bridges and Structures to suggest maintenance and repair options to appropriate staff engineers, who then make the necessary decisions for programming. These decisions are ranked in terms of their priority according to their scale and necessity to the system. If a project is ranked as a 4, this generally means that the project can be held as a future candidate for the Five-Year Program, a budget system used to make large-scale project decisions. If a project is deemed a 1, then the Five-Year Program is to be adjusted in order to make room for the project as soon as it is feasible. Necessary adjustments are made at annual meetings between the six districts and the Iowa DOT's Office of Bridges and Structures; meetings allocate funding where it is absolutely necessary. This method relies on the expert judgement of the professionals in the Iowa DOT's Office of Bridges and Structures. These experts use the condition index of the bridges under investigation, a rating from 0 to 100 based on the collective NBI data retrieved through an inspection. As the current system stands, funding is generally broken down as follows: 70% is allocated for replacements, 23% for rehabilitation, and 7% for repair (Neubauer 2018).

The current Iowa method for project decisions falls short when it comes to predicting future maintenance and repair costs, particularly on smaller scale projects with lower expected costs and shorter planning times. However, changes in budget allocations have improved reaction times to critical problems, slowing the progress of deterioration through efforts including “deck patching, joint replacement or repair, and approach pavement repair” (Neubauer 2018). The expert judgement used in these decisions will be a valuable resource in the development of a LCCA program for the state of Iowa. Additionally, the current and future NBI data and element-level condition data will be vital in predicting future costs. Analysis of historical data will be used to create transition probability matrices that will dictate deterioration rates in deterioration models. More is explained in Chapter 4 about the implementation of Markov chains and Monte Carlo simulations to develop this stochastic approach.

The state of Iowa has started to develop its TAMP and introduce the concept of risk management analysis in its decision making. This new LCCA tool is designed to meet the following five criteria:

1. Address Iowa’s most common bridge types
2. Utilize and incorporate Iowa’s existing data from previous inspections to create predictive models
3. Gather and use cost data from maintenance and repair activities during a bridge’s service life
4. Provide a manageable approach to include indirect costs in the analysis
5. Deliver the capability of the new approach to pair with the AASHTOWare BrM and/or SIIMS

To meet these criteria, the LCCA tool will have to be able to integrate Iowa's available data and adapt as time progress and more data are added. As the database grows, so will the calculated confidence levels of the tool's output, directing Iowa DOT engineers to the most efficient alternatives.

1.5. Main Types of Bridges

This report will serve as a foundation for Iowa's next-generation LCCA tool. We will focus the initial efforts on the most common bridge types in the state. The three main types of bridge structures found in Iowa are steel girder, prestressed girder, and reinforced concrete slab. These bridges make up an average of 75% of all existing state-owned bridges in Iowa, and therefore the largest amount of data is available for these bridge types, allowing for greater accuracy with the various components of LCCA ((Neubauer 2018), (Iowa DOT SIIMS)). Tables 1.3 and 1.4 show the quantity and type of each of these bridges and the various deck types in each of the Iowa DOT's six districts.

Table 1.3. Distribution of main bridge types in Iowa

Element Number	Description	District 1	District 2	District 3	District 4	District 5	District 6	Total
38	Reinforced Concrete Slab	70	111	120	97	63	92	553
107	Steel Girder/Beam	209	115	100	164	115	193	896
109	PS Girder/Beam	404	264	202	258	323	361	1,812
	Total	683	490	422	519	501	646	
	Total state-owned bridges	838	649	625	686	623	911	
	Percentage	82%	76%	68%	76%	80%	71%	
	Average Percentage	**75%**						

Source: (Iowa DOT SIIMS)

Table 1.4. Distribution of deck types in Iowa

Element Number	Description	District 1	District 2	District 3	District 4	District 5	District 6	Total
12	RC Deck	610	374	299	420	433	552	2,688
13	PS Concrete Deck	0	0	0	1	0	0	1
15	PS Concrete Top Flange	0	0	0	0	0	0	0
16	RC Top Flange	1	1	5	1	3	1	12
28	Steel Open Grid Deck	0	0	0	0	0	0	0
31	Timber Deck	3	0	0	0	1	0	4
38	RC Slab	70	111	120	97	63	92	553
54	Timber Slab	0	0	0	0	1	0	1
	Totals	684	486	424	519	501	645	3,259
	Totals of 3 main bridge types	683	490	422	519	501	646	3,261

Source: (Iowa DOT SIIMS)

1.6. Bridge Elements and Focus of the Project

The goal of LCCA is to find the best design alternative considering the lifespan of the structure. The costs accrued throughout the life of the structure are divided into agency costs and user costs. Agency costs consist of MR&R. The routine maintenance efforts are normally performed by the agency's maintenance crews at the district level, while larger maintenance efforts are contracted out. A survey of six bridge and maintenance engineers and Iowa DOT personnel showed that most of the routine rehabilitation work involves the bridge decks. Based on discussions with this project's technical advisory committee, it was concluded that the best plan would be to focus the developmental efforts for the LCCA tool on bridge decks, with the possibility of potential extensions in the next implementation phases. Based on this, National Bridge Element (NBE) 12, Reinforced Concrete Deck, is the focus of this study. NBEs comprise the main structural components of the bridge and are explained in more detail in Chapter 3. Additionally, Chapter 3 explains the important differences between NBEs, Bridge Management Elements (BMEs), and NBI items.

1.7. Overview of Report

LCCA includes five general steps, which have been established through testing and development of past implementations of the method (Lund and Langlois 2019). An extensive review of the existing literature shows that LCCA consistently follows these five steps:

1. Establish design, preservation, and maintenance alternatives
2. Determine activity timing
3. Estimate agency costs
4. Estimate user costs
5. Determine LCC

The next-generation tool developed in this work for LCCA includes maintenance and repair components in its current form. However, it is expected that the tool will be modified to include other components at a later stage. The remainder of this report is as follows:

Chapter 2 of this report addresses and reviews current Iowa DOT maintenance and repair activities. The review highlights the potential gaps in information that future work must address.

Chapter 3 discusses the data used for the evaluation of the average age of a condition rating, which is ultimately used for life-cycle cost analysis.

Chapter 4 discusses survival analysis and the transition probabilities of condition ratings and illustrates how the average age of condition ratings are obtained through survival analysis.

Chapter 5 illustrates the installation guidelines and step-by-step execution of the developed MATLAB-based tool, called LCCAM.

Chapter 6 briefly describes how the developed tool can be integrated with existing bridge management applications for better management and cost analysis and provides the summary of the work described in this report.

CHAPTER 2. LIFE-CYCLE COST COMPONENTS AND MAINTENANCE TASKS REVIEW

2.1. Introduction

The most critical step in a LCCA is determining the factors that will affect the life-cycle costs. Depending on the application, LCCA can be broken down into any number of key components. LCCA has been used for decades for pavement design, and more recently it has been applied to bridge construction, maintenance, and replacement. LCCA can be a difficult process because it involves understanding any potential costs that may arise during a structure's lifetime. Different researchers have included various costs, which generally include the initial design and construction costs; maintenance costs, which are sometimes differentiated into preventive and corrective costs; extreme event costs; user costs; and environmental costs (Mahmoud et al. 2018, Safi et al. 2015, Hawk 2003, Bucher and Frangopol 2006). Often, these costs are broken down into the following recognizable categories: initial construction costs, maintenance costs, rehabilitation and replacement costs, cost of capital, and user costs (Mahmoud et al. 2018).

These cost components can be applied to both new and existing infrastructure. They allow for a direct comparison between different project solutions, which means that decisions are based on the "most economical long-term solution" rather than up-front costs alone (Mahmoud et al. 2018). LCCA can even be more important to existing structures that are in need of crucial maintenance and rehabilitation decisions; LCCA can save DOTs critical funding so that all of the agency's infrastructure, new and old, stays at higher performing levels for longer times due to proper maintenance.

This chapter first briefly discusses all major components of life-cycle cost analysis (Figures 2.1 and 2.2) and then various maintenance activities that are generally adopted all over the world.

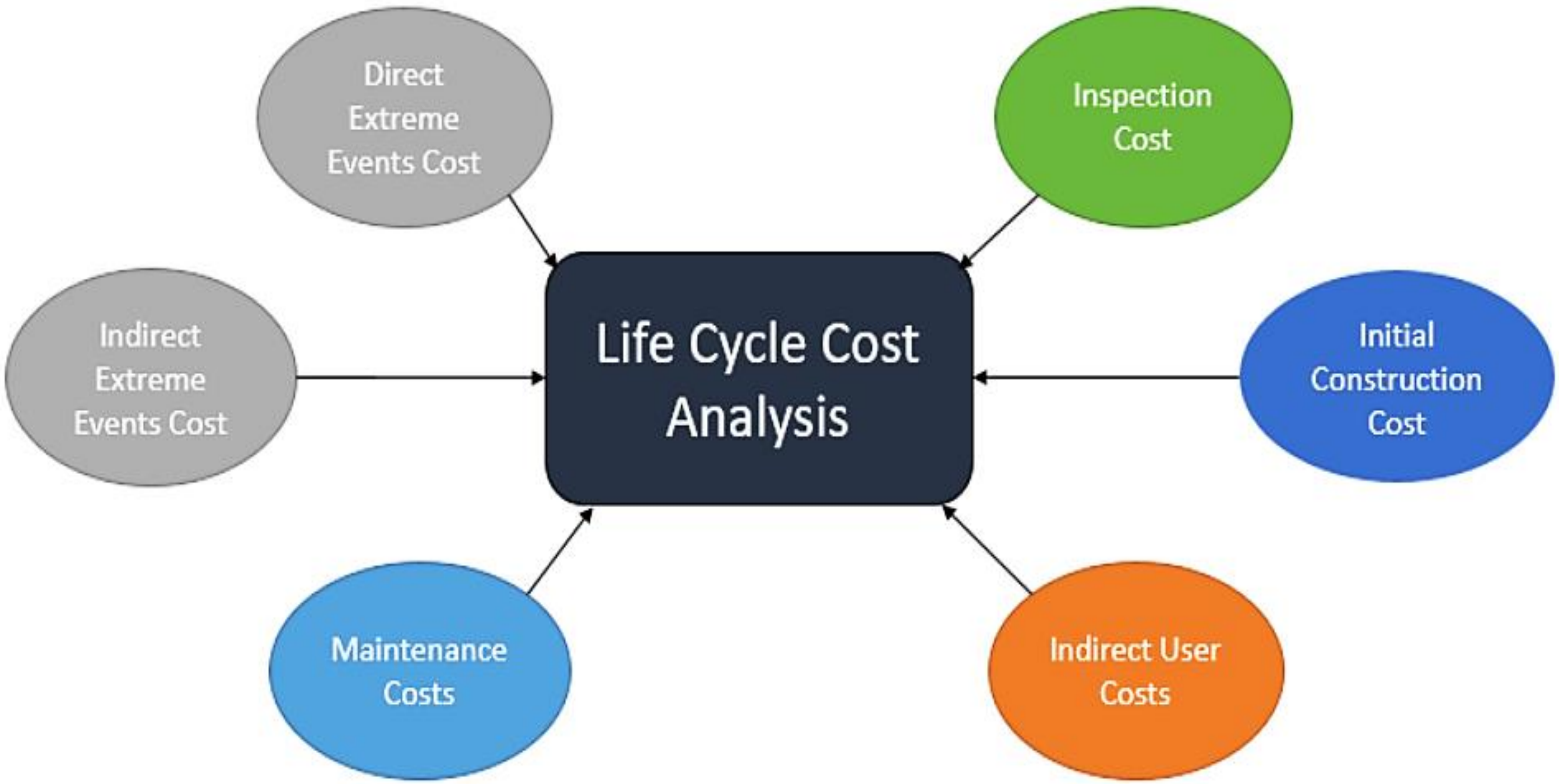


Figure 2.1. Life-cycle cost analysis cost inputs

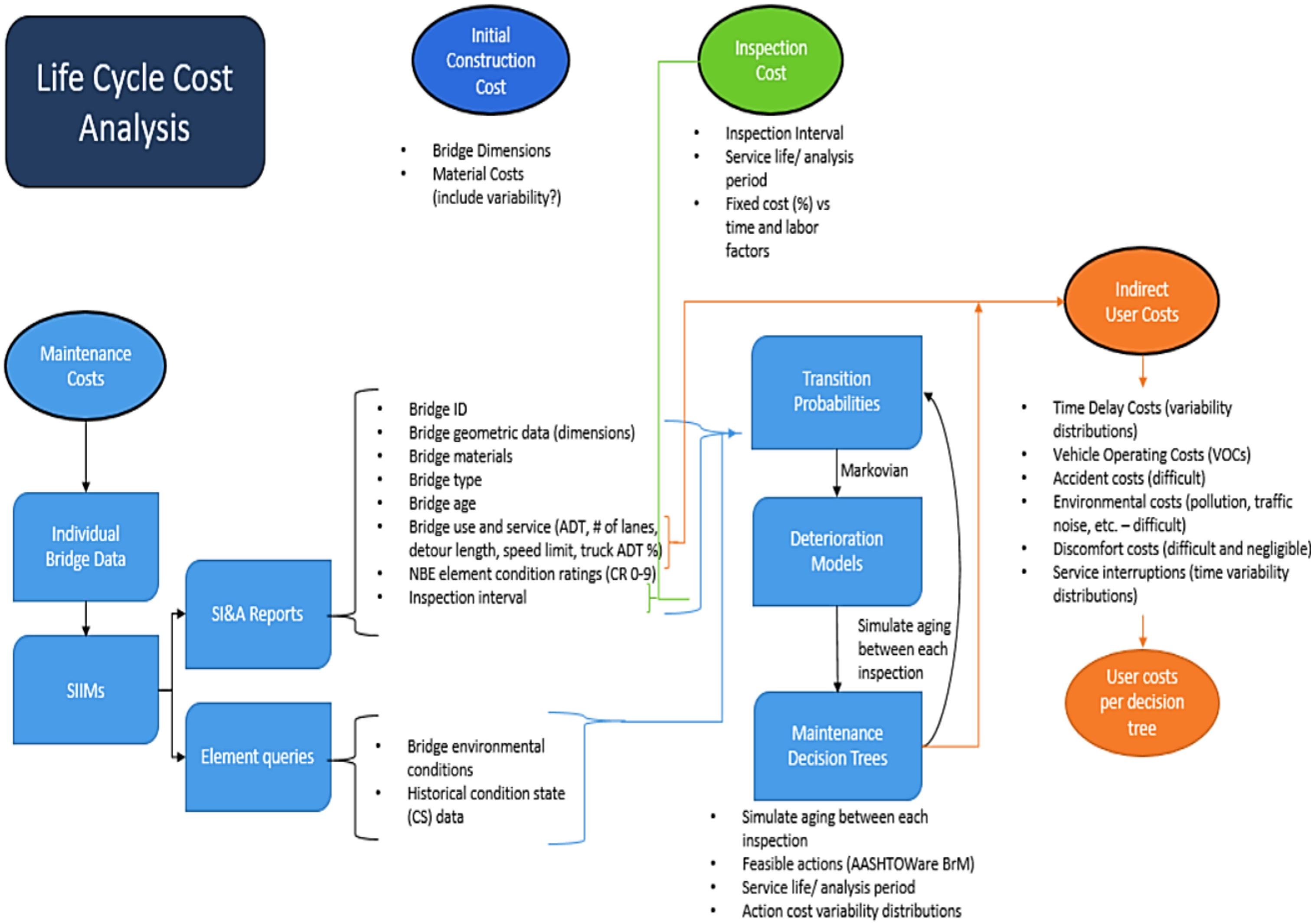


Figure 2.2. Flowchart of LCCA cost inputs

Because the LCCAM tool developed in this research is focused on bridge deck maintenance, deck maintenance activities are described in detail.

2.2 LCCA Components and Structure

The components included in a life-cycle cost analysis can be expressed using the following equation from Khatami et al. (2016) and are briefly discussed in the sections below:

$$LCC = C_C + [C_{IN} + C_M + C_M^u] + C_{sf} + C_{sf}^u \quad (2.1)$$

where, C_C is the initial construction cost, C_{IN} is the inspection cost, C_M is the maintenance cost, C_M^u is the indirect cost due to maintenance activities, C_{sf} is the direct cost due to extreme events, and C_{sf}^u is the indirect cost due to extreme events.

2.2.1. Initial Costs

Initial cost is generally deemed the simplest cost to configure because it is already expressed in the present value. It consists of the costs involved in designing the bridge or project, any project management, the construction work, and the inspection/quality assurance required before opening to the public (Mahmoud et al. 2018). Most of these costs are straightforward but are dependent on several factors. The bridge type, be it prestressed girder, concrete slab, steel girder, or another type, affects the time and resources required for design, which is also affected by bridge dimensions and location. The obvious next component of the initial costs would be the materials required for the bridge. Material choice can make costs vary considerably because certain materials require specially trained labor or must be made off site and shipped. The effects of material choice on how the bridge is constructed introduce a third factor, construction details. These cover any necessary details like the required labor type, site characteristics (e.g., over water versus over a roadway), and the duration of the project (Mahmoud et al. 2018). Once these details are established, the initial cost is calculated by summing the components and multiplying this total unit cost by the expected areas and volumes of the project. Previous bid data can also be used to estimate the initial construction costs.

These unit costs derive from multiple sources. Historical data can provide an estimation of the costs, as well as professional knowledge of the field. These both include numerous uncertainties and with probabilistic LCCA, these uncertainties must be captured to then produce a probability distribution.

Initial costs generally have less uncertainties than other cost components. Current material and labor costs are readily obtainable and therefore should not deviate greatly over the span of construction. Again, bids similar in scope or having like components can provide important and accurate insight for initial costs. Unfortunately, the traditional method of transportation agencies is to choose the lowest priced design bid, which fails to accurately represent all the cost components over the structure's entire life. This highlights the usefulness of LCCA. Instead of choosing the lowest initial bid, designers can choose the lowest LCC bid.

Iowa DOT has their known material and labor costs. The currently plan is to incorporate the available cost data they have for the first version of this LCCA tool. In the future, more will need to be recorded in order to create the probability distributions.

2.2.2. Inspection Costs

Inspection costs are often debatable regarding the level of detail to include. Some studies treat inspection costs as their own independent entity (Khatami et al. 2016), some choose to include inspection costs as a subcategory of maintenance costs (Mahmoud et al. 2018, Safi et al. 2015), while others vaguely include them with agency costs. Regardless, inspection costs are important because they are cyclical costs that occur throughout the lifespan of a bridge. Regular routine inspections are currently carried out every 24 months for each of Iowa's bridges under

FHWA guidelines. Bridges are subject to shorter inspection intervals when deemed necessary, generally for more detailed in-depth inspections that are a result of specific damage inquiries. The Iowa DOT's *Bridge Inspection Manual* delves into the criteria for both routine and in-depth inspections (Iowa DOT 2015). In-depth inspections include fracture critical member (FCM) inspections, which represent a detailed and "hands-on" approach to inspecting FCMs or the components associated with these FCMs and occur at a maximum of every 24 months.

For this study, only routine inspections, on a 24-month inspection interval are considered. Extreme events are also not considered at this level and therefore there is no need to consider in-depth inspections. This will keep the number of variables low for this iteration of the LCCA tool, and additional inspection costs can be added later in time as probabilities of events occurring that would necessitate the inspections are formed and added.

Another assumption IOWA DOT wishes to incorporate into their LCCA currently is the use of a fixed percentage of the initial construction cost as the inspection cost. By doing so, the initial project alternative choice will have a larger effect on the final LCC. Additionally, this deterministic approach will aid in the implantation of this tool until more inspection cost data has been recorded for the state. Work in the past has made similar assumptions in their LCCA. Khatami in their 2018 work assumed inspection and maintenance costs as fixed percentages of the initial construction. The inspection cost was a constant 0.3% of the construction cost while the maintenance cost varied some from 0.6-0.8% depending on the condition state of the structure (Khatami et. al. 2016). Some studies do not even include inspection costs in their analysis. Jaber (2018) worked to apply LCCA to high performance concrete for Arizona DOT. In their analysis, the cost components of the LCC were: initial construction costs, protection costs, and future repair costs ((Jaber 2016), (Rushing and Fuller 2002). The costs could be broken down into materials, repair estimates after the service life has been reached and the frequency of such, and finally any ‘financial parameters’ needed to reference all costs to a particular year with set inflation and discount rates (Jaber 2016). This method failed to include any maintenance costs prior to reaching service life that would preserve bridge condition and slow the progression of deterioration. Lastly Colorado DOT (CDOT), through careful and consistent data tracking and analysis, was able to determine the unit cost per inspection by year. This method of using statistical analysis of previous experiences will produce more accurate results than a fixed percentage.

2.2.3. Maintenance and Repair Costs

The maintenance and repair costs represent one of the prime components of a life-cycle cost analysis. Over the service life of the bridge, each maintenance decision influences the performance of the bridge and has a distinct effect on the overall LCC. The repertoire of maintenance and repair activities varies among agencies due to different budgets, work force sizes and skillsets, bridge types present, and more. It is important to acknowledge the difference between the terms “maintenance” and “repair,” which are often used interchangeably. Maintenance actions’ primary goal is to maintain or preserve the current condition state. Therefore maintenance, or preservation, activities are used to prevent deterioration or slow its progression. Performing these activities does not require the current bridge condition to be at or below acceptable levels. Repair or rehabilitation activities are intended to improve the current condition state of a bridge or bridge component by reversing the effects of deterioration by either restoring or replacing damaged members (Mahmoud et al. 2018, Hawk 2003). The “actions [are intended] to repair or replace elements that threaten bridge condition but do not by themselves represent an unacceptable condition” (Hawk 2003). An example could be a damaged deck joint.

The joint itself may not be at a point where it is failing to mitigate the effects of thermal expansion, but if the gland has a small tear that is allowing water to fall onto girders below, the joint may threaten the superstructure's condition and therefore necessitate R&R.

It is common for MR&R activities to be performed either on a cyclical basis or according to condition-based criteria. Washer et al. (2017) provide examples of maintenance tasks and their suggested cycles, as shown in Table 2.1.

Table 2.1. Estimated preventive maintenance frequencies

Bridge Component	Preventive Maintenance Type	Description	Action Frequency (years)
All	Cyclical	Sweeping, power washing, or flushing	1 to 2
Deck	Cyclical	Deck washing	1
		Deck sweeping	1
		Drainage cleaning/repair	1
		Joint cleaning	1
		Deck sealing	7 to 10
		Crack sealing	4 to 5
	Condition Based	Deck Patching	1 to 2
		Asphalt Overlay with membrane	12 to 15
		Joint seal replacement	10
		Drainage repair	1
Super Structure	Cyclical	Bridge Approach restoration	1
		Seat and beam end washing	2
	Condition Based	Spot or zone painting	As needed
		Debris removal	As needed
Substructure	Condition Based	Scour counter measures	As needed
		Cleaning debris	As needed

Source: Washer et al. 2017

The implementation of MR&R activities can also be categorized as either preventive or corrective. The decision to focus on either prevention or correction when making MR&R decisions is debated; is it more efficient to perform a maintenance activity before it is absolutely necessary in hopes of preventing additional costs, or should the activity be performed only when the condition state falls below acceptable or safe levels? LCCA enables agencies to test both options, creating parallel strings of maintenance and repair decisions, called decision trees, that result in individualized LCCs. Through the incorporation of risk assessment, the analysis also yields the respective probability distributions that allow agencies to make well-informed decisions based on a comparison of final LCCs.

Iowa DOT maintenance and repair activities currently have deterministic cost values, each consisting of a cost unit and a single dollar value. Each activity lists the relevant bridge elements it is applied to. Additionally, each preservation activity has a set of NBI criteria and NBE and BME element-level criteria that are used to determine when each activity is to be performed. NBI criteria impose a minimum condition rating for each NBI item to determine when a preservation activity is to be completed. If an item falls within these limits, the next criteria to be examined are the element-level criteria. The element-level criteria have both upper and lower bounds, categorized by the percentages of the components that fall into the four possible element condition states. To aide in the determination of user costs, the activities have average traffic control times.

The Iowa DOT's preservation activities also note which tasks are performed by Iowa DOT maintenance crews and which are contracted out. The entity performing the task affects costs, in that it is easy to track historical bid costs for contracted work, but Iowa DOT crew costs can have discrepancies that become uncertainties in LCC planning.

The Iowa DOT's preservation activities include a category stating whether the activity is expected to improve the NBI condition rating of the affected bridge component. Maintenance and preservation activities generally do not improve the overall condition rating; rather, they improve the individual elements the work is performed on. As an example, one preservation activity for decks is flood sealing. This activity is relevant to NBE elements 12, 13, 38, 15, and 16. (The element descriptions and the differences between NBI and NBE items can be found in

Chapter 3.) In order to use a flood seal, the NBI condition rating for the deck must be greater than 4. The threshold is greater than 4 because applying flood sealing to a deck with a lower condition rating may be ineffective and essentially a futile effort. Next, the element condition rating criteria must be met. There is a lower and upper bound; any condition better than the lower bound (i.e., the minimum amount of damage) is categorized as “do nothing,” and any condition worse than the upper bound (i.e., the maximum amount of damage) requires action. These condition states are at the element level and are on a scale of 1 to 4, with 1 being the best. The current lower bound at which a flood seal can be applied is a condition state of 2, meaning that flood sealing is not applied at a condition state of 1, and the upper bound is any of the following: more than 5% of the deck is in condition state 3, more than 15% of the deck is in condition state 2, more than 10% of the deck is in condition state 2 or 3, or crack widths are less than 1/32 in. If these criteria are met and the decision to go through with the activity is made, the Iowa DOT expects to pay $5 per square foot as of 2018, the NBI condition state will not improve, the traffic control time is currently not specified for this job, and the activity will be performed in-house by an Iowa DOT crew rather than a contractor.

Repair operations are similar in theory with a major exception. They too have condition-based criteria and a set unit cost. For the repair and rehabilitation activities, however, the condition state criteria are based solely on the NBI condition state of NBI items 58, 59, 60, 108A, 108C and other criteria based on NBI items 43A, 64, and 68. Additionally, condition states are expected to improve a determinate amount following the repair activities. The list of repair activities is rather limited. More on data gathering is presented in Chapter 3.

Performing a LCCA with such data would produce a singular deterministic value. There are no distributions in cost and no understanding of how activity timing affects the life-cycle of the bridge. If an activity is performed before the maximum deteriorated condition state boundary is reached, this can be considered preventive maintenance. If the maintenance is performed due to a perceived necessity based on the condition state, this is considered corrective maintenance. Repair and rehabilitation activities are corrective activities. Optimizing activity timing and correctly applying preventive and corrective activities can both prolong the lifespan of a bridge and increase its financial efficiency.

Bucher and Frangopol (2006) address the issue of optimizing maintenance strategies. The authors refer to the different strategies as time-based (preventive or cyclical) and performance-based (corrective, condition-based) maintenance. Both are included in an optimized maintenance scheme, but parameters must be established to make the timing decisions. These parameters are up to the discretion of the department, but Bucher and Frangopol (2006) include failure costs, safety level thresholds, and routine maintenance intervals. Other studies have considered factors such as expected service life, structural material, expected average daily traffic (ADT), and the surrounding environment in maintenance decisions (Mahmoud et al. 2018, Reigle and Zaniewski 2002). In fact, Bucher and Frangopol (2006) concluded that the resulting LCCs can be equivalent even with different design parameters, which opens the opportunity to analyze the trades-off between implementing time-based (maintenance after a constant time) versus performance-based maintenance (maintenance after the component reaches to a performance threshold). This conclusion resulted from an occurrence of minimization using each of the mentioned parameters and implementation of both time-based and performance-based maintenance activities.

In both time-based and performance-based maintenance a fixed rate of deterioration is assumed. However, the preservation activities can change the deterioration rate. This may result in lengthening or shortening the effective time (time period for which it is assumed that a component does not need maintenance) in time-based maintenance. Similarly, for performance-based maintenance, the activities reverse the deterioration that has led the component to reach the performance threshold. Upon returning to the original condition, there is a brief period of delayed deterioration. Again, this is assuming a constant deterioration rate and guaranteeing full restoration of the component's condition. This may not always be the case, as the effectiveness must be determined for each preservation or repair method used. Expert opinion can be a strong place to start, as well as the manufacturer's suggested lifespan of replacement components. These issues introduce uncertainty into the deterioration model that must be accounted for in a probabilistic LCCA. This project utilizes survival analysis to estimate the expected deterioration and therefore the required maintenance.

2.2.4. User Costs

The process of selecting infrastructure improvement projects, be it the construction of new roads, maintenance of bridges, etc., is becoming increasing difficult with the rising need to be diligent with spending while keeping the growing number of drivers safe and satisfied. The overall benefit to the community of each preservation and improvement option must be weighed, which may influence of the timing of the option's implementation or whether the option is even considered. The benefit is determined through calculating user costs incurred during the construction process and comparing that to the user costs after the proposed improvement strategy. Transportation planners rely on analytic tools (see Table 2.2) to "evaluate the relative merits of each candidate project and ultimately provide a means for allocating resources to that set of projects that will maximize the total benefits" (AASHTO 2003).

Table 2.2. Road user costs tools by state

State	RUC-specific	Non-RUC-specific (Traffic Analysis Only)
California	CA4PRS	HCM, SYNCHRO
Colorado	WorkZone RUC	
Delaware		HCS, Spreadsheet, QuickZone, SYNCHRO
DC	QuickZone, QUEWZ-98	SYNCHRO/ SimTraffic, CORSIM
Florida	FDOT RUC	
Hawaii		HCM, SYNCHRO
Illinois	DOT Spreadsheet, QuickZone	
Iowa	QuickZone, QUEWZ-98	
Kansas		HCM, Travel Demand Model, Simulations
Maryland	LOPB, LCAP	HCM, SYNCHRO, CORSIM
Massachusetts		HCS, SYNCHRO, SIDRA, Transyt-7F, TSIS-CORSIM, GDOT Roundabout Analysis Tool, VISSIM
Michigan	CO3	HCM, SYNCHRO
Missouri	QuickZone, QUEWZ-98	MoDOT WZ Impact Analysis Spreadsheet, VISSIM, CORSIM, SYNCHRO
New Hampshire	QuickZone, QUEWZ-98	HCM, SYNCHRO
New Mexico		HCM and Simulation
New Jersey	DOT Spreadsheet, QuickZone	
New York	QuickZone, AASHTO User-Benefit Analysis	CORSIM
North Carolina	QUEWZ-98	In-house detour and flagging program
Ohio	DOT Spreadsheet, QuickZone	QUEWZ-98
Oklahoma		HCM based Spreadsheet
Oregon		WZ Traffic Analysis tool
Pennsylvania	DOT Spreadsheet	
Rhode Island		HCM, QuickZone
Texas	RUC Tables	PASSER V
Utah		HCM, SYNCHRO, VISSIM
Virginia	HUB-CAP	
Washington	QUEWZ-98	SYNCHRO/ SimTraffic, CORSIM
Wisconsin		HCM w/spreadsheet, Quadro, SYNCHRO
Tennessee		HCM, Web based Queue/Delay Model
Wyoming		HCM, SYNCHRO

Source: Qin and Cutler 2013

Some bridge LCCA models avoid the use of some user costs. User operating costs can be considered negligible and instead only considered as “denial-of-use costs,” which consist of the costs due to bridge closures or restrictions that are borne by the user (Hawk 2003). Denial-of-use can lead to user delays, detours, and even crashes, all of which can significantly impact the LCC of a bridge.

In its present form, the application developed in this research for life-cycle cost analysis, LCCAM, includes only maintenance costs. However, the application can be modified later to include the other costs discussed above.

2.2.5. Future Present Value

In order to compare LCCs, each future cost must be referenced to the same year such that the effects of general inflation can be factored in. This equivalent present worth can then be compared side by side to other maintenance and repair schemes that may include projects at different points in time. Project timing, bridge service life, inflation rates, and discount rates can all affect how present worth is calculated. Additionally, these costs can be converted to uniform annual costs that can also be used for LCC comparison.

To express LCC in terms of equivalent present values, multiple factors must be determined and considered. The type of payments and the frequency of cost installments determine the present value equation to be used. Below are five equations representing five different ways to calculate present worth. The choice of an equation is dependent on the planned frequency of payments of the future costs. Within each equation, a key factor is the discount rate. The discount rate is explained and discussed following a brief review of each of the following present worth equations.

$$SPPWF_{i,n} = \frac{1}{(1+i)^n} \tag{2.2}$$

$$USPWF_{i,n} = \frac{(1+i)^n - 1}{i(1+i)^n} \tag{2.3}$$

$$GSPWF_{i,n} = \frac{1}{i(1+i)^n}\left[\frac{(1+i)^n - 1}{i} - n\right] \tag{2.4}$$

$$CRF_{i,n} = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{2.5}$$

$$PSPWF_{i,n} = \frac{(1+i)^n}{(1+i)^n - 1} \quad (2.6)$$

where, $SPPWF_{i,n}$ is a single-payment present worth factor at discount rate *i* (in decimals), for a single payment in year *n*; $USPWF_{i,n}$ is the uniform series present worth factor at discount rate *i*, over a period of *n* years; $GSPWF_{i,n}$ is the gradient series present worth factor at discount rate *i*, over a period of *n* years; $CRF_{i,n}$ is the capital recovery factor at discount rate *i*, over an analysis period of *n* years; and $PSPWF_{i,n}$ is the perpetual series present worth factor at discount rate *i*, with *n* equal payment intervals (Hawk 2003).

These terms are briefly described below:

Single-payment present worth factor

This factor can be implanted for projects that may only occur one time during a bridge's lifespan. Replacement of bridge decks is a strong example as generally this is only performed once if at all for most bridges (Hawk 2003). The SPPWF can convert this one the singular cost amount n years from the reference year, into a single present worth.

Uniform series present worth factor

If a fixed cost value is expected to occur each year for n years, the present worth can be calculated using the uniform series present worth factor (USPWF). These individual payments could represent annual payments to contractors for cyclical operations. It is important to note that this can only be used if the series begins at the start of the project or rather the initial year in reference. If not, additional use of SPPWF can bring the value from the USPWF to the referenced year (Hawk 2003).

Gradient series present worth factor

Cyclical maintenance activities often change in cost due to rising material and labor rates. If a uniform arithmetic rate (G) of increase is expected each year, the gradient series present worth factor (GSPWF) can be used to convert the cost to the present. SPPWF can also be implemented similar to its use with USPWF (Hawk 2003).

Capital recovery factor

If Iowa DOT wanted to take the cost of an activity and break that up into multiple payment installments, the equivalent uniform annual cost (EUAC) can be determined. This is done so by multiplying a capital recovery factor (CRF) by the total present worth of costs calculated with mentioned methods. Generally, this is used for converting the total cost to a uniform annual cost to be paid over the service life of the project or bridge (Hawk 2003).

This perpetual series present worth factor

In Hawk's 2003 report for NCHRP, Report 483 Bridge Life-Cycle Cost Analysis, he explains that due to the theory that bridges are constantly providing a service to the public, it is important to depict the spending in terms of present values, such as the EUAC such that the public can understand (Hawk 2003). This perpetual series present worth factor (PSPWF) requires a series of variable inputs. There will be a variable amount of payments of the constant value in yearly intervals from the initiation date. Hawk also adds that "this cash-flow series becomes a geometric-power series that is convergent for i greater than 0" where *i* is the discount rate.

2.1.8. Discount rate vs Inflation rate

In the previous section a parameter common to each of the present worth factors, *i* is used. This *i* is the discount rate but it needed to be explained where it comes from and how it can affect the LCC. After understanding the discount rate's influence, cost-optimization of maintenance activities will then rely upon "an optimum balance between the initial cost of investment and the future cost of maintenance (Van Noortwijk and Frangopol 2004).

Hawk describes the practice of cost discounting as "an attempt to place a worth on the funds being spent" meaning it can give a tangible quantity to the possible benefits or losses of timing of maintenance actions (Hawk 2003). By discounting costs to present values and summing all costs over a service life to formulate each alternatives LCC, the most cost-effective alternative can be determined (Demos 2006).

Due to changes in timing, costs can become incomparable on their own. Inflation can cause prices to change over time, generally with a gradual and steady rate. It is important to note that inflation focuses on the purchasing power of the capital at hand. Demos (2006) uses the example the "a 1980 dollar would, in general, have purchased more real goods and services in 1980 than a 2006 dollar would in 2006". Inflation is different from discounting. Discounting introduces the effect of time value opportunity. Inflation accounts for price effects but fails to deliver the benefits of a projects timing within a service life. Therefore, discounting should be used for bridge work as well as other public works (Demos 2006). These discount rates can range in value ad are generally dependent on expected lifespan of a project. Generally speaking, discount rates range from 2% to 8% but for public works like roadway and bridge work the range is typically 3% to 5%. Federal projects have been found within the range of 2% to 6%, Colorado DOT (CDOT) uses 4%, and other studies reviewed for bridge work use 3.5% ((Hawk 2003), (Khatami et. al. 2016), (Demos 2006)). For perspective, 0% discount rate would make timing "irrelevant" whereas a high discount rate favors investment with low up-front costs as future investments are discounted future. The present value equations above can be multiplied by the future values (FV) of maintenance and repair costs to determine the desired equivalent present values. The following equation, adopted from (Hawk 2003) demonstrates the mathematical relationship between the cost of a future expenditure and its equivalent present worth and how the discount rate plays a direct role:

$$PV = FV_N/(1 + DR)^N \quad (2.7)$$

where:

PV = present value of the expenditure

FV_N = future value of an expenditure made at time N

N = number of periods (years) between the present and future times

Discount rates based on expected time durations in literature often reference a common source. OMB Circular A-94 provides the guidelines and discount rates for benefit-cost analysis of federal programs. The source presents what it refers to as the two basic types of discount rates:

(1) a discount rate for cost-effectiveness, lease-purchase, and related analyses; and

(2) a discount rate for public investment and regulatory analyses. (Rushing and Fuller 2002)

The second type is applicable to LCCA of bridges as they are can be categorized as a public investment. Future discount rates can be obtained from such a source as it is federally regulated. At the time of this study we suggest a discount rate of 4% due to its widespread use in literature as well as its proximity to the recommended 3.9% by OMB for a 30-year real rate, which reflects the relatively longer lifespan of bridges (Rushing and Fuller 2002).

2.1.8.1. Iowa DOT current use of inflation rate

Under initial investigation, we were informed of Iowa's minimal investment in the use of discounting procedures. Use of inflation rates when considering future costs was the intended plan. We do present the information regarding discount rates as review of existing LCCA demonstrates its vital role in accurate financial planning and cost comparison. As mentioned, choice of discount rate is essential as under or overestimation of the rate can affect the projections of future costs. Careful use can lead to valid and reputable results.

2.1.9. Study Period: Service Life

Discount rates are to reflect the expected service lives of bridges. This section will discuss the service life of bridges and maintenance projects and how it effects LCCA. Service life is the length of time the bridge is expected to prove useful. The condition criteria that define when a bridge is no longer useful is determined by the agency in question. Many agencies expect an average of 30-50 years of useful life from bridges but as of recently, AASHTO specifies that bridges be created with the expectance of a 75 year service life ((Transportation Equity 1998), (Morcous and Hatami 2013), (Hawk 2003)). A study by Mattson and Sundquist (2007) have even noted lifespans ranging up to 120 years for average road bridges in their proposed three class system of bridge service lives [11,44].

Service life of alternatives effects the final LCCs. If alternatives different in life expectancy, this must be addressed. The service life will not always be the analysis period. For example, if maintenance alternatives are being considered for an existing bridges and the activities preservation will conserve a bridge for either 5 or 10 years, the analysis period can be 10 years and for one maintenance scheme, it would be expected the activity with a 5 year lifespan would be repeated to make the 10 year service life. Determining a common analysis period simplifies the LCCA and allows proper comparison of final LCCs of the alternatives ((Transportation Equity 1998), (Hawk 2003)). Any remainder to the service life post the analysis period can be an added value to the LCCs. Professionals must judge the condition of bridges using the most current criteria to determine when their condition state becomes unacceptable and therefore unsafe, ending its service life. As an example, a study for CDOT stated that "service life is taken as the time required, in years, for a new bridge deck to reach NBI condition rating 5" (Hearn 2007). It continues by specifying that if the bridge plans include rehabilitation work, then the service life estimate can be extended to represent the time from initial construction to the second occurrence of NBI rating 5. Different agencies and researchers have proposed different definitions. A study by the Virginia Transportation Research Council proposes the service life does not include the time for major repairs, but only "routine maintenance operations," alluding the federal push for extending bridge deck service life to 100 years (Bales et. al. 2018).

Some studies reviewed propose the use of population models to estimate service life of bridges based on information from similar bridges. Four different probability distributions can be used to create these deck population models, Rayleigh distribution, Rayleigh distribution using a time-shifted origin (xo-Rayleigh distribution), Exponential distribution; and Exponential distribution using a time-shifted origin (xo-Exponential distribution) (Hearn 2007). The models proposed were to produce the probability a bridge deck in Colorado would reach NBI rating 5, indicating the answer in years (Liang et. al. 2010). Parameters such as element, bridge and material type as well as the possibility of rehabilitation efforts were used to incorporate the uncertainty of service life predictions (Liang et. al. 2010). Sufficient data is necessary for accurate results. Chapters Three and Five will discuss the importance of data and the need for a large store of useful data that has been recorded methodically.

2.1.10. Sensitivity Analysis

LCCA can be affected by any one of the mentioned variables in this chapter. While probabilistic LCCA can display the confidence and the likelihood of certain outcomes, it may be difficult for the using agency to understand the main contributors to the end results. A sensitivity analysis can identify the effects of the input variables and pinpoint those that have the greatest effect on the LCCA output. Such information is what leads to innovation as cost increasing problems can be reduced or eliminated and replaced with more cost-effective methods (Reigle and Zaniewski 2002).

Sensitivity analysis has been performed in other works for factors such as discount rates and the number of years of data to reference. Liang et al. (2010) used a sensitivity analysis to show the effects of discount rates on bridge deck costs in Colorado and was able to determine the least expensive decks by understanding the influence of discount rates on the outputted LCCs (Liang et. al. 2010).

2.3 Overview of Bridge Maintenance Tasks

This section provides an overview of generally adopted maintenance tasks or activities for various bridge components. Because the tool developed in this work for life-cycle cost analysis is focused on deck maintenance, activities related to deck maintenance are discussed in detail and other activities are discussed briefly. Based on the bridge component, the maintenance activities can be classified as follows:

- Concrete deck/slab
- Steel girder/beam
- Prestressed precast concrete beam
- Reinforced concrete beams
- Concrete column/pier wall
- Concrete pier cap
- Reinforced concrete abutment
- Fixed joint
- Expansion joint
- Bank protection for bridges over roadway

- Bank protection for bridges over water
- Bearings
- Approach pavement

2.3.1. Concrete Deck/Slab

Concrete decks/slabs have a multitude of associated maintenance tasks due to the high level of wear and tear that occurs through constant use and exposure to harsh elements. Cracks, spalls, and delamination are very common, and many methods have been tried by the Iowa DOT to mitigate and correct the effects of each.

2.3.1.1. Crack Chasing/Sealing

Cracks in concrete are often expected. They are caused by slabs deforming from loads, prestressing, and temperature variations. These cracks can lead to water and salt infiltration, a serious problem that can result in reinforcement corrosion, and additional cracking/spalling due to freeze-thaw cycles. Additional causes of cracks can be found in references such as ACI 224.1R (ACI Committee 224 2007).

Crack chasing, also known as the bottle method, is “the process of cutting into cracks in concrete so that they can be waterproofed with a sealant and repaired with an epoxy or some other filling compound” (United Professional Caulking & Restoration n.d.). First, the cracks must be cleaned of contaminants using high-pressure water, air, or a vacuum (Iowa DOT 2014) before applying the sealers as per the manufacturers’ instructions. These sealers consist of a variety of materials, including epoxies and resins that are topically applied. A common example of these resins is high molecular weight methacrylate (HMWM) (Washer et al. 2017). Some additional materials include asphalt, urethane, and silicone. It should be noted that most crack chasing does not intend to restore tensile strength, but to seal the slab from harsh environmental stressors. However, some studies have suggested that epoxies may partially enhance structural performance. There is some debate on the longevity of crack sealing and the cost associated with it. Professional companies often believe that cyclical, preventive application of crack sealing can extend the lifespan of bridges up to 10 years more than similar treatments such as chip seals and micro paving (Cimline 2003). However, research has pointed to much shorter lifespans, especially compared to penetrating sealers, of only three to five years, with the effectiveness diminishing even after three years (Washer et al. 2017).

Other sources, such as the Minnesota DOT (MnDOT), have sponsored studies that have called for cyclic crack sealing at least once every five years with currently used products, and hence Oman (2014) notes that MnDOT’s current recognized interval is five years. However, the cost of such actions would be impossible to cover if this policy were to be used for all applicable bridges (Oman 2014). Budget restrictions are a common predicament among DOT agencies nationwide, emphasizing the need for optimization of maintenance procedures.

ACI 224.1R-07 states that for any concrete bridge maintenance, the extent of the damage must be evaluated, as well as the cause; then, the repair activity can be selected from a list of seven actions that act as objectives for the maintenance tasks (ACI Committee 224 2007). The choice of action affects the material used to repair the crack.

Generally, bridge decks qualify as crack chasing candidates when cracks are spaced two or more feet apart and easily identifiable. Differing material types for crack fillers are recommended depending on the deck width (Washer et al. 2017).

For crack chasing and many other maintenance activities, traffic control operations need to be established on the bridge. The extent of traffic control is dependent on the damage present, and for this reason many suggest that such maintenance should be paired with other maintenance to make efficient use of any lane closure, with the exception of tasks that would prevent any other work at the time, such as flood sealing, which is covered in this chapter (DeRuyver and Schiefer 2016). Minimizing traffic disruptions minimizes the costs borne by the bridge users. More is explained in the User Costs section of this chapter.

Crack chasing can be performed by an in-house maintenance crew or contracted out. Typically for the Iowa DOT, crack sealing is performed by an in-house crew and requires two hours of traffic control per lane. The method can be applied to NBE elements 12, 13, 38, 15, and 16, and current maintenance procedure requires the deck to have an NBI condition rating greater than 4. Crack chasing does not improve the NBI condition rating and is therefore considered a preservation maintenance activity. It can be performed on a cyclical or as-needed basis. Future optimization using LCCA may affect these protocols. Many agencies believe that this activity should be used as part of a preventive maintenance strategy because it protects the critical deck component from accelerated deterioration (Washer et al. 2017). The mentioned lifespan of such treatments can bring into question the cost and performance differences between cyclical and corrective application. Such uncertainty in timing is addressed in Chapter 4 of this report.

2.3.1.2. Deck Patching

Over time, as bridge decks crack and wear, spalling of the deck surface can occur. Repetitive abuse from drivers' wheels, freeze-thaw cycles, snow removal, and underlying flaws in the concrete itself can all add to the formation of spalled concrete decks. A method of preservation is deck patching. Patching can be performed to various depths of the deck, partial and full, dependent on the extent of the damage and engineering judgement. Partial-depth deck patching generally follows the criteria put forward by the Illinois DOT:

Partial-depth repairs shall consist of removing the loose and unsound deck concrete, disposing of the concrete removed, and replacing with new concrete. The removal may be performed by chipping with power-driven hand tools or by hydro-scarification equipment. The depth shall be measured from the top of the concrete deck surface, at least 3/4 in. (20 mm) but not more than half the concrete deck thickness. (Illinois DOT 2018)

Full-depth patching is required for more extensive damage that proceeds throughout the depth of the deck. The amount of concrete removed is up to engineering judgement. A general rule of thumb is that full-depth patching is to be used for all areas "in which unsound concrete is found to extend below half the concrete deck thickness" (Illinois DOT 2018). The Illinois DOT breaks full-depth patching into two payment classifications depending on the area of the patch, where a Type 1 patch is greater than 1 square foot but less than 5 square feet and a Type II patch is greater than 5 square feet (Illinois DOT 2018).

Generally, for the Iowa DOT, deck patching is performed in-house and is performed on a condition-based scheme because it is classified as a corrective activity. It can be applied to NBE 12, 13, 38, 15, 16 and BME 510 and currently has custom condition state criteria if it is to be applied. Traffic control is inevitable, but it is difficult to estimate the time required for repairs without extensive analysis of previous applications. Costs for deck patching are dependent on the material used and the depth and extent of patching.

For a step-by-step repair method, see Wipf et al. (2003).

2.3.1.3. Epoxy Injection

Epoxy injection is an effective way to bond cracked concrete. Epoxy is beneficial because it can aid in restoring partial strength to the concrete section. Although the strength added is minimal, it can reduce the chances of secondary damage (Barlow 1993). An additional advantage is that some epoxies are known to be moisture-tolerant and can be applied in moist environments. However, this moisture hinders their structural capability due to less-than-ideal bonding between the epoxy and the cracked surfaces. Unfortunately, unless the reason the cracks formed in the first place has been corrected, cracks are bound to happen again. ACI 224.1R notes that if the initial problem goes uncorrected, there are three ways that maintenance can address the crack: "(1) rout and seal the crack, thus treating it as a joint; (2) establish a joint that will accommodate the movement and then inject the crack with epoxy or other suitable material; and (3) install additional support or reinforcement at the crack location to minimize movement" (ACI Committee 224 2007).

Additionally, epoxy applications require a great deal of preparatory work as well as skilled labor. Cracks must be completely cleaned if the bonds are to be secure. Cracks must be then sealed to prevent epoxy from leaking out past the limits of the crack, or else the potentially expensive epoxy may be wasted. Venting ports must be added to apply a vacuum to the crack, forcing the epoxy into all the paths of the crack. Epoxy must be mixed in the proper amounts necessary for the job at hand. Allowing epoxy to sit for too long prior to application can cause difficulties injecting it and failure to completely fill the voids. The epoxy is applied under pressure using numerous apparatuses. ACI 224.1R-07 lists the following: "hydraulic pumps, paint pressure pots, or air-actuated caulking guns" (ACI Committee 224 2007).

Epoxy is used as part of multiple Iowa DOT preservation activities. Epoxy can be injected into cracks as a chaser and sealer, applied as a thin overlay to protect the wearing surface, and injected as an overlay to create a longer lasting bond with the surface. The method can be applied to NBE 12, 13, 38, 15, 16 and BME 510 with established NBI and element-level condition criteria. As current Iowa DOT data show, epoxy injection can be performed on a cyclical basis on average every 10 years. The Iowa DOT states that epoxy injection may have the ability to improve the condition rating of the deck by 1 point on the NBI rating scale but cannot exceed a rating of 7. Therefore, epoxy injection can be seen as either a preservation or condition-based activity. Future LCCA can determine the most efficient use and timing of the preservation activity.

2.3.1.4. Flood Sealing with Sealer

Each year bridge decks are exposed to corrosive salts and chloride solutions, which are applied to create safer driving conditions for road users. Consistent exposure can cause these chemicals to seep past the concrete cover or infiltrate through existing cracks and damage the existing reinforcing steel. Crack sealing can be performed if the crack density is relatively low. However, this treatment becomes ineffective when crack densities increase. Additional factors affecting the decision to apply crack sealers can be the deck size; the necessary traffic control, because there are different cure times for crack chasing and flood sealing; material cost; the cause of the cracks; and the surface roughness of the deck (DeRuyver and Schiefer 2016). A well-known method of preventive maintenance to address these problems and limit the deck's exposure to corrosive chemicals is known as flood sealing.

Flood sealers, also known as penetrating sealers or healer sealers, are an efficient method that combines the properties of crack chasing and deck sealing. Their efficiency is heightened on decks with high crack densities because applying a flood sealer in such cases is more cost-effective than chasing individual cracks (Osman 2005). The application method is known as flood-coating, in which the deck surface is submerged (flooded) in the sealer to allow it to cure on the surface and fill in cracks. Cracks in concrete decks can occur for a multitude of reasons and therefore range in size, making some micro-cracks invisible to the eye and therefore causing them to be missed during crack chasing. Flood sealing can fill these cracks and stop their progression before they open to the point at which they are visible. Crack chasing can be more beneficial when cracks are caused by local stresses and bridge engineers wish to monitor future crack propagation in a particular area (DeRuyver and Schiefer 2016). Additionally, an aggregate can be added so that cars have a textured riding surface, increasing user safety by increasing slip resistance (Oman 2014, DeRuyver and Schiefer 2016, Michigan DOT 2019).

Flood sealers can consist of different base materials. As discussed above, epoxy can be used as a sealer for cracks in concrete and is an effective way to prevent water and salt infiltration. Epoxy can be applied using one of two methods: by hand to seal cracks individually or as a thin overlay applied by flooding the surface with two coats of epoxy. Epoxy overlays are known for their flexibility, longevity, and provision of a highly improved wearing surface. Silane treatments have been being incorporated into Iowa DOT maintenance schemes more regularly in recent years. Silane is known for its ability to prevent moisture penetration and chloride intrusion by its ability to coat the entire deck surface while flowing into and filling any cracks present (Washer et al. 2017). The Iowa DOT uses flood sealing as a cyclical maintenance activity on bridge decks meeting specific condition criteria, uses in-house maintenance crews, and has not documented average traffic control times. Therefore, the future data recording discussed in Chapter 5 includes the recording of such information.

The use of bridge sealing as a preventive maintenance activity is debated because the longevity and effectiveness of sealers can vary. Both parameters are highly susceptible to the environmental stressors they are constantly afflicted by. As a result, each state follows different protocols when sealing their bridges, if they use sealing at all, as noted in Washer et al. (2017). The authors of that study surveyed multiple agencies and recorded their comments on their use of bridge sealing, including whether they used it, the material used, the time of initial application, and the application interval (Washer et al. 2017).

Pritzl et al. (2015) investigated the effectiveness of sealers and the effects of different application frequencies. The report's literature review highlights the conflicting opinions on the most appropriate timing for applying sealers. The authors claim that to maintain the effectiveness of sealers and prevent long-term chloride penetration, sealers must be reapplied periodically. Even if a bridge is sealed immediately after construction, if it is non sealed on a cyclical basis, it will have higher chloride concentrations throughout its lifespan compared to a bridge that was not sealed at construction but sealed periodically thereafter (Pritzl et al. 2015).

Therefore, sealers can be an effective preventive maintenance strategy. LCCA would allow for deterioration models to simulate various application scenarios and determine the most cost-effective approach. In the meantime, research has been done to estimate flood sealer lifespans. It must be reiterated that these are dependent on the multitude of factors that vary for each bridge.

Washer et al. (2017) summarized the conflicting estimates of penetrating sealer service lives from the existing literature. The values range from 3 to 11 years with a large variability between estimates. The variability in the results shows the need to incorporate risk and variability in estimations of LCCs.

2.3.1.5. Epoxy Overlay

Epoxy is currently used for multiple preservation activities. The substance acts as both an adhesive and a coating to protect the deck and act as a wearing surface. Similar to flood sealers, epoxy overlays can improve skid resistance when aggregates are mixed in. However, the two products differ in how they protect and maintain the bridge deck. Both require extensive preparation of the deck prior to flood application, but epoxy overlays require more detailed preparation, increasing the closure time and affecting user costs. According to DeRuyver and Schiefer (2016), deck preparation rates for epoxy overlays can be anywhere from 600 to 850 square feet per hour compared to 1,600 to 1,700 square feet per hour for flood sealing if a single BW SCB16 Shotblaster is used. After preparatory work, the two methods are applied similarly and therefore can both be laid down at rates ranging from 1,000 to 3,500 square feet per hour per layer. Additional time discrepancies arise from an epoxy overlay's need for multiple layers. Each layer of sealer and overlay requires a two-hour cure time, and an epoxy overlay is applied in two layers, adding to the closure time of the project.

Epoxy overlays and penetrating healer sealers also protect the deck differently. Healer sealers penetrate into cracks, filling them to prevent moisture intrusion even as the coating on the deck wears down. Epoxy overlays bridge cracks and create a strong bond with the deck surface, creating an impermeable layer that prevents water and chloride infiltration (DeRuyver and Schiefer 2016). This highlights the importance of the preparatory work for epoxy overlays, because failing to properly apply the material can cause delamination and therefore moisture infiltration (DeRuyver and Schiefer 2016).

Research on epoxy overlays over the past two decades has significantly improved the application techniques for, increased the longevity of, and lowered the costs associated with epoxy overlays. Installation requires technical preparation that necessitates trained labor if the overlay is to last for its expected lifetime. In a study sponsored by the Michigan DOT, DeRuyver and Schiefer (2016) summarized the results of the Michigan DOT's use of epoxy overlays. The authors stated that epoxy overlays can be applied to "any deck greater than 1 year old with a fair or better deck top and bottom condition" (DeRuyver and Schiefer 2016), which fits with current

Iowa DOT protocol. The Iowa DOT requires a minimum deck condition rating of 6, and the element-level criteria must show that the bridge is in a better bridge condition than that required for flood sealers. Epoxy overlays can be categorized as preventive maintenance and corrective maintenance because they prevent deterioration and have the potential to increase the condition rating, though the condition rating is limited to a maximum of 7. Epoxy overlays are generally applied by contractors for the Iowa DOT and sometimes require multiple nights for each stage of work. They have an expected service life of approximately 20 years, which can make their relatively expensive upfront costs more palatable given that flood sealers last maybe half as long. LCCA would allow for definitive comparisons between the two methods and how they affect the final LCC of a bridge.

Epoxy overlays have limitations. As mentioned above, they are highly susceptible to problems resulting from poor application, deck moisture during installation, snowplow damage, and more, which can affect their effectiveness and longevity and add uncertainty to an analysis. Additionally, they cannot be applied to bridges with a deck condition rating of less than 4 because they cannot be used to simply hold together a broken top surface. Epoxy overlays do disrupt traffic for longer durations than the potential alternatives, so user costs in the LCCA can affect the final decision to use epoxy overlays. A material-based cost comparison is shown in Table 2.3 for epoxy overlays and healer sealers.

Table 2.3. Unit cost comparison of thin epoxy overlay and healer sealer components

Cost Component	**Thin Epoxy Overlay**	**Healer Sealer**
Cost of Epoxy per Gallon	$18.00	$28.00
Cost of Epoxy per Square Foot	$1.35	$0.28
Cost of Aggregate per Pound	$0.10	$0.06
Cost of Aggregate per Square Foot	$0.40	$0.12
Cost of Shot Blasting per Square Foot	$0.71	$0.34
Combined Cost per Square Foot	**$2.46**	**$0.74**

Source: DeRuyver and Schiefer 2016

The costs in Table 2.3 come from a Michigan DOT study on thin epoxy overlays (DeRuyver and Schiefer 2016). In addition to providing these costs, the study estimated the total cost per square foot for contracting out the jobs. In reference to 2016 (the year of this study), a flood sealer would cost about $2.45 per square foot, and a thin epoxy overlay would cost about $3.75 per square foot.

2.3.2. Steel Girder/Beam

2.3.2.1. Spot Painting

Coatings on new bridges are typically expected to last 20 to 30 years (Hopwood et al. 2018) before any major rehabilitations of the coating are necessary, with exceptions based on environment and use. Spot painting is used on bridges in an effort to preserve the current topcoat of the steel superstructure and protect against corrosion and deterioration. Bare steel can corrode quickly, causing damage to bridges, especially in areas prone to water exposure such as the areas below bridge joints. Road salts accelerate this process, requiring more frequent repainting of the bridge. Painting an entire structure is laborious and can be expensive. Therefore, this is often delayed until absolutely necessary, which can cause those sections of the steel with the highest exposures to become severely deteriorated, requiring section replacement. Spot painting is a quick method to protect exposed steel and prolong the life of the sections until more extensive maintenance is required. Spot painting therefore has the potential to be the “lowest cost option (in terms of total cost) for restoring overall coating integrity and protection on many bridges” (Hopwood et al. 2018). An important factor in the success of spot painting is the workmanship applied to the task. Specifically, surface preparation is a key factor in the longevity of the repair. Additionally, the NCHRP spot painting manual notes that the following factors should be considered when selecting coatings:

- Matching the compatibility and durability of existing coatings
- Surface preparation
- Soluble salt contamination
- Work environments and conditions
- Surface tolerance
- Application requirements
- Painter skill/coating friendliness
- Project costs

The additional service life added by spot painting is highly variable because exposure to the elements can easily vary among bridges. Variations between one-, two-, and three-coat systems can cause this fluctuation in longevity. One- and two-coat systems generally lack the zinc layer that acts as a rust preventive barrier in a three-coat system (Hopwood et al. 2018). The Missouri DOT uses a penetrating primer made of calcium sulphonate on bearing beam sections adjacent to the bearings to mitigate corrosion (Washer et al. 2017). The difference in lifespans can be upwards of a factor of three, where one- and two-coat systems typically extend a component's lifespan by 5 to 7 years while a three-coat system can provide an additional 15 years of service life for a component. Spot painting generally occurs 15 to 20 years after the initial coating; the additional 5 to 15 years can help the coat as a whole reach its intended service life. These spot paintings may be supplemented with zone painting, a similar technique discussed in the following section. At the end of the coat's service life, the options are either over-coating or complete removal of the remainder of the existing coat using abrasive blasting and application of a new coat. A new coat would be necessary after the "overall breakdown" of any existing or repaired coat after 35 to 40 years (Hopwood et al. 2018). As Iowa's bridges age, and a large portion of them are reaching the time when a new coat is necessary, cost-efficient decisions will be an absolute obligation for the Iowa DOT to manage its existing infrastructure.

Spot painting addresses areas of stressed paint on steel structures and components in an effort to prevent deterioration. This makes the activity both a corrective form of maintenance, in that it is employed on a conditional basis, and a preventive maintenance activity. Its effectiveness given its cost is often debated. While some, such as Hopwood et al. (2018), believe that spot painting is the most cost-effective method, other data, such the average costs of various painting methods used by the Iowa DOT, paint a different picture. At $40 per square foot, spot painting is the most expensive painting method, followed by zone painting, full over-coating with removal of the existing coat, and full over-coating, at $20, $10, and $5 per square foot, respectively. The higher costs for spot painting can be caused by the need to employ skilled labor and use job-specific equipment and materials for small areas as opposed to dispersing these costs over a large area of work. This may be the Iowa DOT's reasoning for limiting the use of spot painting as well as over-coating. Most painting activities for the Iowa DOT are contracted out. Similarly, the Iowa DOT has been phasing out full painting of bridges by incorporating weathering steel, which does not require paint, in its bridges, lessening future maintenance costs and obligations.

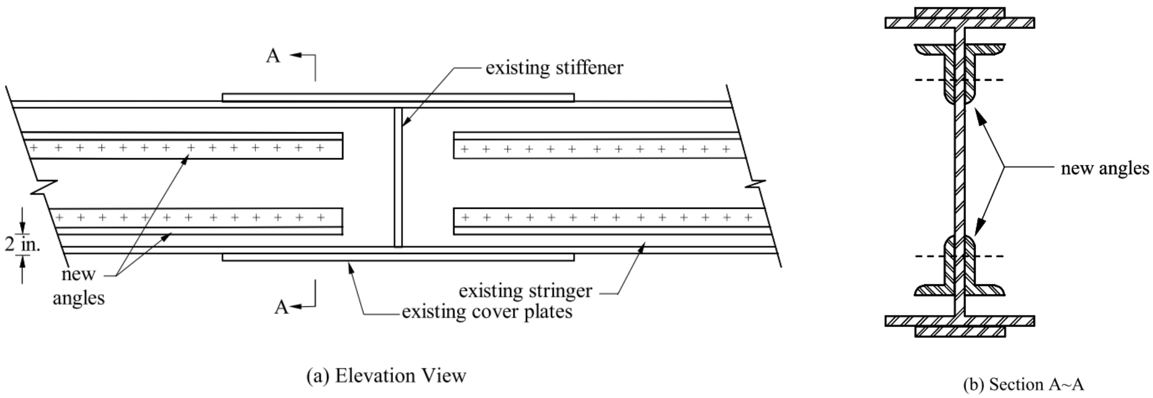
2.3.2.2. Zone Painting

Zone painting is similar to spot painting but generally applies to a larger section of the bridge and its components. This method may be used in the presence of more widespread deterioration or vehicle impacts with girders that require repair. Zone painting is actually used in Iowa, whereas spot painting is not. The condition criteria for the use of this maintenance task require greater deterioration of components, amounting to as much as twice that of spot painting's requirements. The task is not intended to improve the NBI condition rating of the components and can disrupt traffic up to one week per every 5,000 square feet of material painted. (See the previous section on spot painting for a comparison of the traffic control requirements for both techniques.) This timeframe also applies to all other structural painting activities except for over-coating, which only requires three days per every 5,000 square feet. The lower amount of time required for over-coating can be attributed to the lower amount of surface preparation necessary. As mentioned in the previous section, over-coating is currently not used by the Iowa DOT. A proper LCCA can allow the agency to compare the effects of various painting-related preservation activities on the final LCC of a bridge. For additional information, see the previous section on spot painting.

2.3.2.3. Girder Repair

Deterioration of steel superstructure components can be caused by a multitude of factors; superstructures are consistently exposed to harsh environments caused by weather, the surrounding ecosystem, deterioration of the deck above leading to water and chloride exposure, vehicle collisions, fires, overloading, stream debris, fatigue cracking, and thermal stress (Iowa DOT 2014). Due to the possibility of reduced load carrying capacities or failure of the structure caused by weakened superstructure components, necessary actions such as girder repair and section and girder replacement must be implemented when deemed necessary. Therefore, these are condition-based corrective maintenance activities.

Additionally, as building codes develop and the population grows, bridges are expected to supply passage to increased loads, sometimes greater than those for which they were originally intended. Therefore, girders sometimes need to be retrofitted to be strengthened to meet the new load requirements. As shown in Figure 2.5, the Iowa DOT performs retrofitting by bolting angles near both the top and bottom flanges on each side of the beam in order to increase the moment capacity (Wipf et al. 2003).



Wipf et al. 2003, Iowa State University

Figure 2.5. Strengthening of steel girders

No cost or condition information regarding the strengthening of steel beams was obtained for this study from the Iowa DOT. Future investigation may yield more results and aid in cost analysis.

2.3.2.4. Section Replacement

For a steel beam that has been partially damaged due to collision, corrosion, or other means to the point at which its load carrying behavior is compromised, the damaged section is cut out and replaced with a new welded-in section (NYSDOT 2008). This requires lifting the bridge to clear the damaged portion of the beam and allow for the new section to be welded in. Lifting the bridge necessitates traffic control, which involves either closing the bridge or, if possible, redirecting traffic to keep loads only on the undamaged portion of the bridge. The sections that are replaced can range in size.

Similar to the previously discussed maintenance activities, preparatory activities and the workmanship put into a section replacement job are imperative to the success of the repair and the safety of the bridge. Failures in welds, jacking points, or other design assumptions can ultimately lead to failure of the bridge and endangerment of bridge users and maintenance crews.

No cost or condition information was obtained for this study from the Iowa DOT regarding section replacement and girder replacement of steel beams. Future investigation may yield more results and aid in cost analysis.

2.3.2.5. Girder Replacement

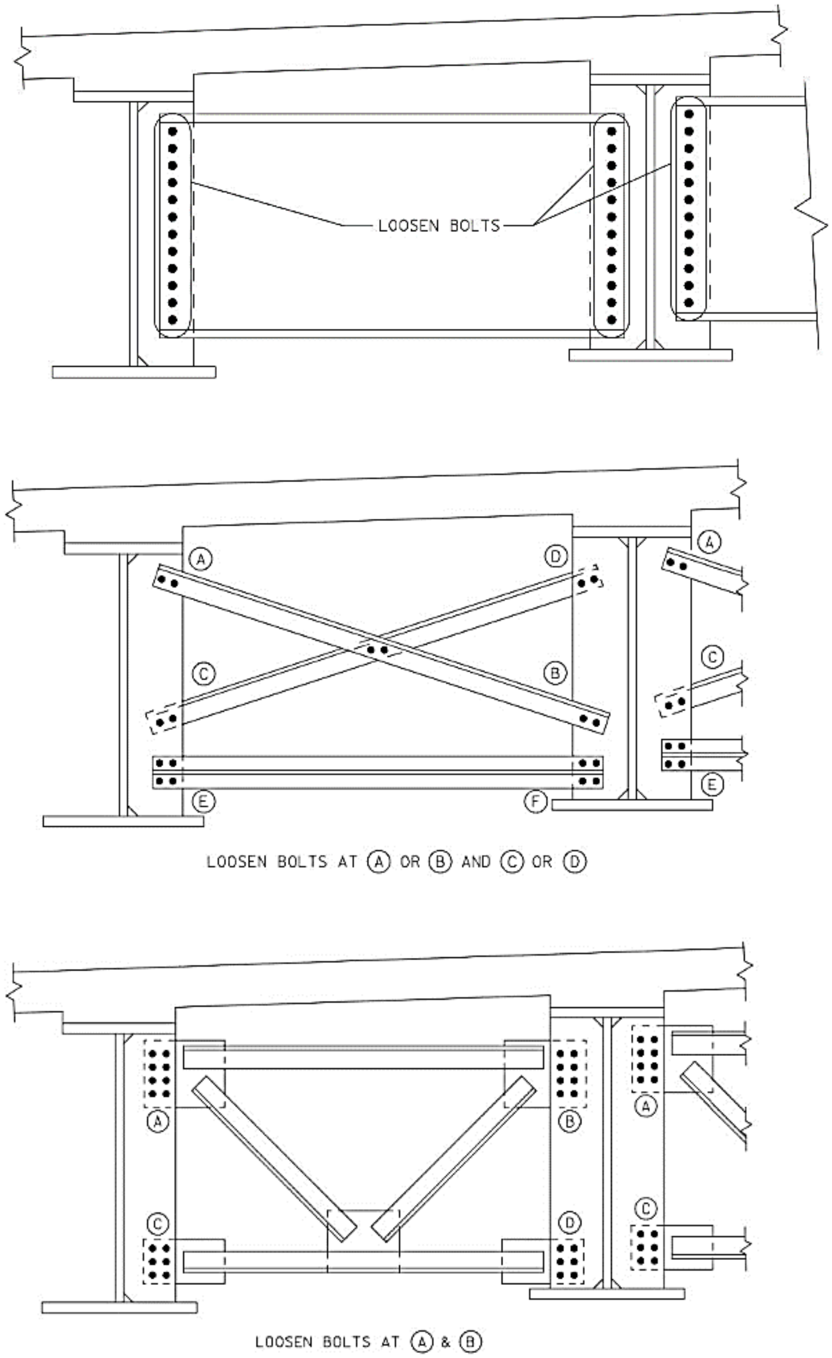
Years of gradual deterioration, collisions with vehicles, changes in required load ratings, or any combination of these factors can lead to the need for girder replacement. As opposed to girder repair and section replacement, the damage to or change intended for the structure in this situation is to such an extent that it can only be solved by complete replacement of the girder. This type of maintenance is considered a bridge rehabilitation project, and it is important to determine the cause of the deterioration before making maintenance decisions. If the causes are not mitigated, then the problem will only persist with the new beam. An example of this is broken or leaking expansion joints that allow water and road salts to drain directly onto the bridge's superstructure. Many professionals recommend prioritizing fixing or removing the expansion joints prior to any superstructure maintenance. In a report for the Iowa DOT, Wipf et al. (2003) detail the steps necessary for replacing a bridge girder. Hours of planning and development add to agency costs. Jobs of this size are commonly contracted out, and traffic must be restricted, adding to the maintenance and user costs, respectively.

As mentioned above, no cost or condition information was obtained for this study from the Iowa DOT regarding girder replacement of steel beams. Cost data used in conjunction with deterioration data in a LCCA would aid in repair prioritization and potentially limit the need for such large rehabilitation projects.

2.3.2.6. Fatigue Prevention (Loosening Diaphragm Bolts, Cutting Back Connection Plates)

As steel bridges are subjected to out-of-plane bending as well as repetitive flexure from cyclical vehicular loading, fatigue can cause damage in the form of cracks in the webs of the girders. Generally, this occurs in what is referred to as the “web-gap,” which consists of the portion of the girder’s web between the welds of the top flange and web, and the welds connecting the diaphragm connection plate to the web (Wipf et al. 1998). Additionally, this can occur where the transverse diaphragm stiffeners meet the girder’s web. These zones are prone to “variable tensile stresses or reversal of stresses from compression to tension” (Iowa DOT 2014). Cracks in these areas can lead to additional deformation of the members and ultimately brittle failure of the bridge. Therefore, it is important to both recognize the causes and signs of this distress and be familiar with prevention and repair methods. For a steel girder, the most common sign of fatigue failure is the initiation of a fatigue crack in a tensile zone of the girder. Left unattended, a fatigue crack can continue to propagate and can ultimately lead to total member failure (Iowa DOT 2014).

There is some debate on how to treat this type of fatigue. One accepted way recommended by the Iowa DOT is the loosening of diaphragm bolts. Loosening these bolts will reduce the rigidity of the connection and prevent the formation and propagation of fatigue cracks in tensile zones. Figure 2.6 shows the selection of bolts to loosen.



Iowa DOT 2014

Figure 2.6. Fatigue prevention by loosening of bolts for (top) bent plate or channel diaphragm, (middle) X-braced cross frame, (bottom) K-braced cross frame

A study on the Iowa DOT's recommended method by Wipf et al. (1998) showed that the bolts on both the interior and exterior girders must be loosened to yield the best improvement. If only the exterior bolts are loosened, there may be adverse effects on the interior web gaps. The authors found that by loosening the bolts on both the interior and exterior girders, the recorded stresses in each were reduced. Additionally, the study compared the performance of X- and K-type bracing and determined that the K-type diaphragms "yield longer fatigue life" (Wipf et al. 1998).

Another method of fatigue crack prevention, specified by AASHTO, is to include a connection between the connection plate and the top flange to transfer positive moment. However, Wipf et al. (1998) note that this is more realistic for new bridge design because retrofitting existing structures using similar methods can be costly.

Lastly, the complete removal of the diaphragms between girders has been suggested to prevent fatigue cracking. A study by Stallings et al. (1996) showed that removal of the diaphragms has insignificant effects on normal loadings, and the increase in longitudinal girder stresses would not exceed AASHTO specifications. Calculations must be performed to ensure that the bridge would be safe after the diaphragms are removed, bridge length being the primary deciding factor. Extreme events such as seismic events, collisions, or floods can apply large loads, increasing girder deflections (Stallings et al. 1996). This method does not provide the additional load resistance needed for these events that diaphragms with loosened bolts would provide.

2.3.2.7. Fatigue Crack Repair: Drilling Arrest Holes

The prior section reviewed ways to prevent fatigue cracking in bridges. However, it is often difficult to eradicate all possibility of crack formation, and many existing bridges subject to out-of-plane bending and cyclical loading already have this damage. Iowa had 955 steel girder bridges as of 2018 (Iowa DOT SIIMS n.d.). Meanwhile, Iowa DOT inspections have reported web cracking at diaphragm connection plates where there are expected zones of negative moment (Wipf et al. 1998). The ends of these fatigue cracks are often difficult or impossible to detect with the naked eye and therefore require a form of non-destructive testing to aid in inspections. Magnetic particle testing can locate the approximate locations of the crack ends (Iowa DOT 2014). It is important to determine the locations of the crack ends to stop the progression of the cracks.

A common retrofit for fatigue cracks is to drill a 2- to 4-inch diameter hole at the end of the crack, such as those shown in Figure 2.7.

Iowa DOT 2014

Figure 2.7. Arrest holes drilled in diaphragm stiffener

These holes relieve the stress in that area to prevent additional cracking and the future progress of existing cracks. An engineer should be consulted and make the final decision to apply this mitigation strategy after careful analysis of the situation, and the hole must encompass the end of the cracks (Iowa DOT 2014).

Some research suggests that hole-drilling is not the most effective method for treating fatigue cracks. Wipf et al. (1998) claim that the holes cause an increase in “the flexibility of the web gap and, consequently, increase the out-of-plane distortion” and that the stress in the web gaps is insignificantly affected when the holes are close to the connection plates.

The Iowa DOT has implemented hole-drilling to mitigate fatigue crack propagation for years. Iowa DOT bridge preservation cost and criteria data include bridge and component condition criteria for drilling arrest holes, loosing connection bolts, and cutting back connection plates. Cost and time data for these methods are not available at this time and will need to be investigated. Further inquiry with the Iowa DOT would provide information such as whether these tasks are performed in-house, which can suggest where possible cost and time information might be found.

2.3.3. Prestressed Precast Concrete Beam

Prestressed concrete construction has been used in 1,847 of Iowa’s bridges (Iowa DOT SIIMS n.d.). Prestressed concrete has many advantages over general reinforced concrete. However, it is important to perform diligent maintenance to ensure the expected behavior of structures made with prestressed concrete. Prestressed concrete relies on the initial compression produced by tensioning steel cables that run through or along concrete beams. This initial compression can be used to negate dead loads, service loads, or a combination of loads, depending on the structure’s desired performance. Additionally, prestressing can prevent the cracking of concrete beams by maintaining a state of compression in the beams, where concrete is strongest. Minimizing the number of cracks results in a lower probability of water and salt infiltration and therefore less deterioration of beam components.

Regular maintenance for prestressed beams is important because regular use and abuse causes deterioration of these members, and the additional technical complexity of these beams can cause them to be compromised at exponential rates if left to deteriorate. General maintenance includes patching spalls and crack chasing and sealing, and more extensive repair includes beam end and entire beam replacement and post-tensioning of the span.

A common type of damage to prestressed concrete beams or reinforced concrete superstructures is impact damage from vehicle collisions. Prestressed concrete beam bridges are frequently found as highway and railroad overpass structures, and impact damage from over-height vehicles is a common occurrence (Iowa DOT 2014). Repair procedures are outlined in Section 6.2 of Iowa DOT *Bridge Maintenance Manual* and are summarized in this report in the following sections on concrete cracks and spalls resulting from vehicle strikes.

Additionally, a commonly damaged section of reinforced concrete beams and prestressed concrete beam bridges is the ends of beams, which are subject to damage from leaking bridge joints. The runoff deposits chlorides from de-icing salts, which are heavily used in the cold Iowa winters. The moisture is able to penetrate the concrete cover and carry the corrosive chemicals to the rebar and prestressing strands. Cracks open as the beams undergo freeze-thaw cycles, allowing increased infiltration and resulting in spalling and increased cracking. Additionally, the corrosion of reinforcing bars and strands can result in changes in the pre-tensioning of the beam and therefore the beam’s performance. A loss in strength or unsafe deflections can lead to bridge closure or failure.

2.3.3.1. Crack Chasing/Sealing

Prestressed beams are sometimes damaged by vehicular impacts. This can cause cracking in the beams, starting at the top flange of the beam and progressing downward towards the point of impact (Iowa DOT 2014). Engineer inspection is required to determine whether the strength of the beam has been compromised and the beam needs replacement. If the collision is not severe, the beam may only be cracked and can be fixed using epoxy injection. Similar engineer inspections are used to determine the use of crack sealing on concrete decks. Information on Iowa DOT preservation activities indicates that such jobs are usually performed by in-house maintenance crews, require two hours of traffic control per beam, and cost $10 per linear foot (LN) as of 2018. The cost and condition criteria are equivalent to those for the crack chasing on bridge decks.

2.3.3.2. Patching Spalls

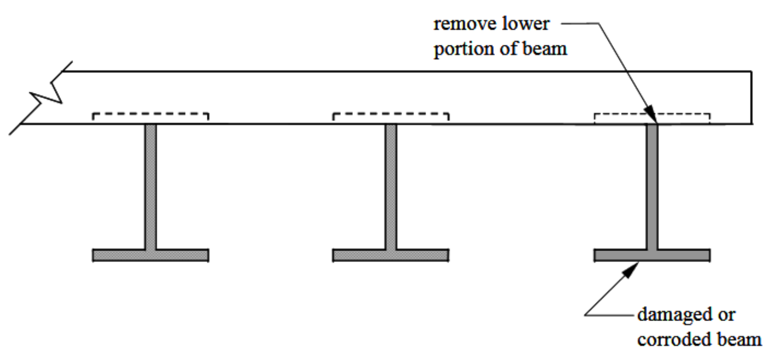
As with reinforced concrete, the depth of spalling is a main factor in deciding the degree of maintenance to be performed on prestressed concrete beams. All underlying steel, including prestressed or flexural reinforcement, must be inspected, cleaned, and, if necessary, reset or replaced; any damaged or loose concrete must be properly removed, and the remaining surfaces prepped for a new pour. Depending on the presiding agency, the extent of the damage and an engineer's professional assessment may determine the exact method of repair.

As mentioned above, prestressed beams are sometimes damaged by vehicular impacts. The collisions can cause cracking, addressed in the previous section, and can damage areas of concrete that would need to be properly removed, cleaned, and patched. The size of the patch required can dictate the material used in the patch. Common material choices are concrete, epoxy, and epoxy mortar (Iowa DOT 2014). Prior to patching, the area must be cleaned of any broken concrete, and the underlying reinforcement must be checked and repaired if necessary.

Spalling repair for prestressed concrete beams is similar to that used for concrete decks, in that the depth of the repair required determines the materials, time, and costs necessary. Information on Iowa DOT superstructure patching costs is available for the following NBE items: 104, 105, 109, 110, 115, 116, 143, 144, 154, and 155. Note that the items listed here are made of reinforced and prestressed concrete. The patching is generally performed in-house, impacts traffic and therefore affects user costs, and may improve the NBI condition rating of the superstructure by a maximum of 1 point. The current cost estimate for patching is $60 per square foot as of 2018, and the repair is expected to extend the service life of the beam by five years.

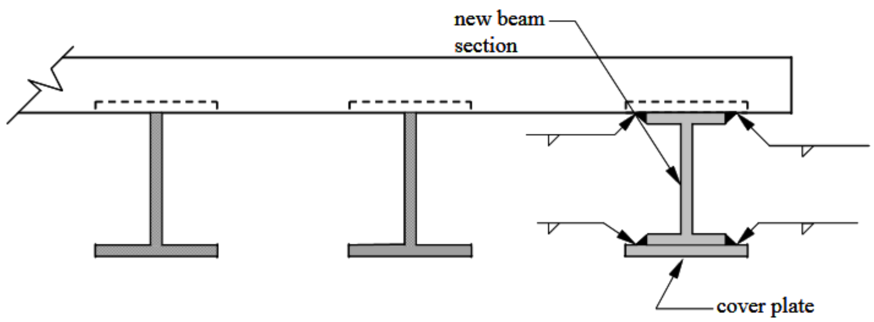
2.3.3.3. Beam End Repair

Prestressed beam ends are often sealed to prevent moisture and chloride penetration due to runoff that seeps through leaking deck joints. It is important to seal prestressed concrete beam ends because corrosion of the strands can cause weakening of the entire beam and may cause the bridge to deteriorate at an accelerated pace due to increased deflections. Repair of damaged beam ends (Figure 2.8) can be costly.

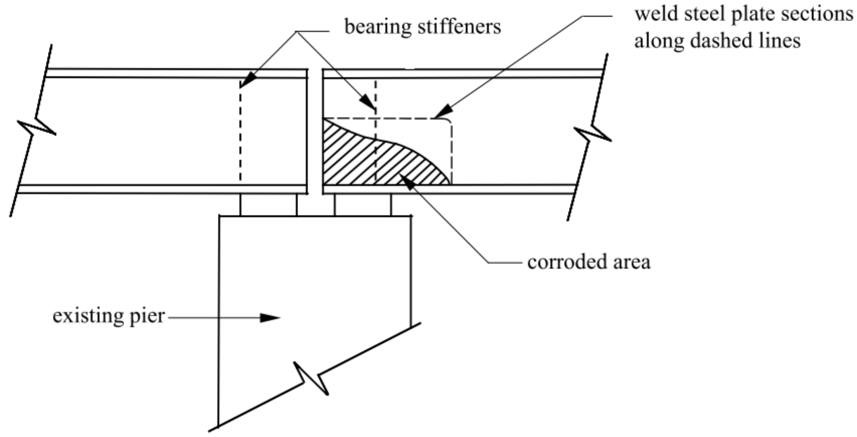


(a) Composite Slab with Damaged Beam

Figure 2.8. Repair of damaged steel beam ends



(b) New Beam Section Welded in Place



Wipf et al. 2003, Iowa State University

Figure 2.8. (continued)

The Iowa DOT estimates that each beam end repair costs $1,500 as of 2016. This corrective maintenance is performed based on specific condition-based criteria and can increase the NBI condition rating of both the superstructure and the substructure by as much as 2 points to a maximum condition rating of 7.

2.3.3.4. Girder Replacement

Prestressed girders, in comparison to reinforced concrete girders, are replaced more often due to their more complex technical design. As a girder ages, strands can snap due to fatigue or corrosion. As strands snap, the beam's performance will degrade from its original specifications and eventually become unsafe. A study performed by the Pennsylvania DOT in 2009 concluded that it is more practical to replace a girder once "25% of the strands no longer contribute to its capacity" (Harries et al. 2009). At this point, the process of girder replacement is similar to that of a non-prestressed beam, which was explained in a previous section.

2.3.3.5. Post-Tensioning

Post-tensioning can be performed on prestressed beams that have not reached the point of replacement. Post-tensioning extends the lifespan of the girder by restoring the original induced stresses and the flexural capacity. There are multiple methods for post-tensioning, but the two most common are discussed here. First, as the less intrusive method, external anchors and tendons can be attached to the girder and tensioned to apply the confining stresses needed to simulate those lost. A second method is to cut into the beam where the strands have snapped, either due to corrosion or a collision, and replace the damaged tendon sections with short splices. The splices allow the remaining sections of the original strands to be used to restore the beam's strength. These splices are then grouted over to prevent further deterioration (Harries et al. 2009).

2.3.4. Substructure

2.2.4.1. Concrete Columns/Pier Walls

Substructure deterioration stems from overloading, weathering from exposure to water and road salts, impacts from vehicles and stream debris, and scour from erosion. Additionally, shifts in adjacent bridge components, such as abutment rotation, can cause shifts in loads, creating excess lateral loads and further damaging the structure (Iowa DOT 2014).

Concrete columns and pier walls are therefore subject to damage similar to that discussed above for other concrete components. Cracking and spalling are common and must be addressed in order to maintain the bridge's load carrying capacity. For these repair methods, refer to sections in this report on concrete bridge decks. These methods also apply to substructure NBE items 204, 205, 210, 213, 215, 217, 220, 226, 227, 233, and 234.

2.3.4.2. Reinforced Concrete Abutments

Abutments are often subject to a multitude of loads as well as harsh environmental conditions. Being surrounded on multiple sides by earth can lead to moisture infiltration that can cause corrosion as well as spalling. Additionally, chloride-laden runoff can accelerate these effects. This acceleration can be caused by the gradual deterioration of expansion joints, typically placed between the deck and the approach slab and the abutment and the approach slab. The approach slabs can induce mechanical loads due to rotation against the backwall that deteriorates the tops of the abutments (Iowa DOT 2014). The repair activities mostly include patching spalls, crack chasing/sealing, and shotcrete repair (Figure 2.9).

NYSDOT 2008

Figure 2.9. Shooting material for shotcrete repair

2.3.5. Joints

2.3.5.1. Expansion Joints

The Iowa DOT incorporates a range of expansion joint types in its bridge designs, ranging from simple gaps for small bridges to a variety of sealed joints, with a preference for the latter. The specific types of expansion joints and descriptions and diagrams of each can be found in the Iowa DOT's *Bridge Maintenance Manual*. Their use is critical to both the performance and the longevity of a bridge. Joints allow for thermal movement of bridge components to mitigate induced lateral loads that can lead to cracking and crushing of bridge deck ends. Additionally, sealed joints attempt to prevent deck runoff from penetrating the bridge's superstructure and substructure components that can be affected by water and chloride. These deck joints are therefore subjected to a multitude of stressors that quickly lead to their deterioration and, all too often, failure. These stressors include, among others, entrapment of sand and gravel, which can punch holes in glands; pounding loads from trucks continuously driving over the joints; excessive sun exposure; and snowplow blades (Iowa DOT 2014). Many researchers are pushing to eliminate the use of expansion joints altogether (Husain and Bagnariol 1999). Many of the maintenance activities mentioned in this report are necessitated by failed expansion joints that allow deck runoff to infiltrate the bridge's superstructure and substructure and cause accelerated deterioration (Washer et al. 2017).

2.3.5.2. Cleaning Strip Seals and Glands

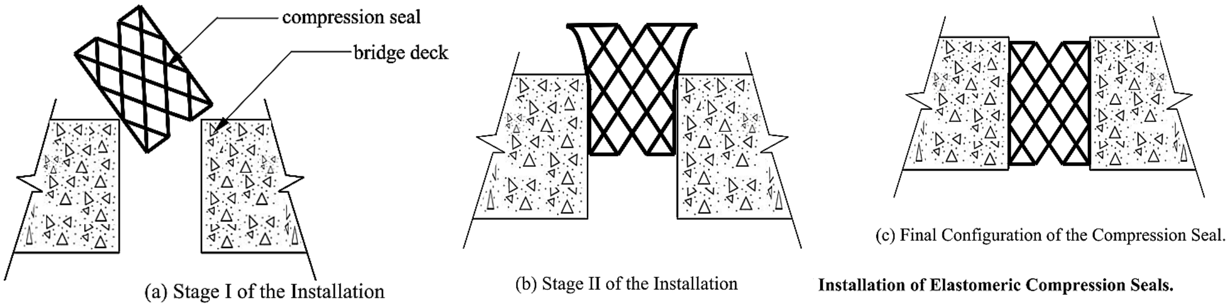
A preventive form of maintenance is to clean out any debris within the joint glands and seals to lessen the potential for tearing and puncture. This is done by either sweeping the joints or washing the joints with water. The Iowa DOT's procedures suggest that this be completed at the same time as deck cleaning. The procedures emphasize that the work should be completed when bridge elements are in a thermally contracted condition and joints are in an open configuration, therefore, a cooling but not freezing weather is the most suitable (Iowa DOT 2014). Owing to this, these activities are generally performed on a cyclical basis. The Iowa DOT estimates that sweeping costs an average of $50 per joint, with an hour of traffic control for each joint, which adds one year to the service life of the joint. For washing, the cost increases to $200 per joint and two hours of traffic control for each joint, which adds two years to the service life of the joint.

2.3.5.3. Replacing Joint Seals or Glands

The expected lifespan of joint seals and glands is variable and can depend on factors such as the width of the gap, the manufacturer, and the material type. Iowa typically uses neoprene compression seals and strip seal glands in its expansion joints. The state expects a service life of 10 to 15 years and 15 to 20 years for each, respectively. These seals/glands are then replaced when current condition criteria are met. Replacement is encouraged in weather similar to that mentioned in the previous section, which allows the bridge components to contract. It is important, however, that the joint be accurately measured so that the correct size of seal or gland is installed (Iowa DOT 2014). Replacement can cause the need for traffic control that can range in time from a few hours to several days. The replacement will generally cost $300 per linear foot of joint and can add upwards of 10 years to the service life of the joint. However, proper installation is crucial for the success of the joint (Wipf et al. 2003). It should be noted that the entire gland or seal is not always replaced; only the damaged portion may need replacement. Figures 2.10 and 2.11 demonstrate how seals are replaced.

NYSDOT 2008

Figure 2.10. Installing joint seal



Wipf et al. 2003, Iowa State University

Figure 2.11. Stages of elastomeric compression seal installation

2.3.5.4. Repairing Joints: Section Replacement

As mentioned above, only the damaged portions of joints need to be replaced. It is not uncommon for the concrete around a section of a joint to be damaged or elevated as a result of a failing joint. Joints may need to be cut, trimmed, replaced, or eliminated to ensure the safety of the surrounding components. Steel sliding plate expansion joints often have portions that are elevated, which can be hooked by snowplows or cause damage to vehicles driving over the bridge. Appropriate portions of such joints can be removed based on the extent of the damage. However, the slide plate portion is generally retained to prevent road debris from falling into an otherwise open joint (Iowa DOT 2014). Additionally, new joints can be placed after the surrounding area has been repaired. A new joint can cost the Iowa DOT $1,500 per linear foot if the condition criteria are met. A new joint can add 25 years to the service life of the bridge and protect the underlying superstructure and substructure.

2.3.5.5. Eliminating Joints: Convert Stub Abutment to Semi-integral Abutment

Researchers and the Iowa DOT have been advocating for the removal of expansion joints within bridges. Instead, they recommend using integral or semi-integral abutments, with the expansion joints being located "between the end of the approach slab and the beginning of the roadway paving" (Iowa DOT 2014). Eliminating the joints in the main structure can minimize the exposure of many bridge components to moisture and de-icing salts, which cause a large portion of bridge deterioration issues, and can allow for simpler maintenance schemes.

This option is largely intended for new bridge designs. Existing bridges can be converted, but this is not always feasible. Factors that can affect the inclusion of expansion joints include the structure's length, type, and geometry; the superstructure type; the number of spans; and the surrounding environmental conditions (Iowa DOT 2014, Husain and Bagnariol 1999). A report by Husain and Bagnariol (1999) suggested that conversions are applicable to bridges supported by rigid or flexible foundations and that have a maximum length of 150 meters (about 492 feet). In that study, flexible foundations included unrestrained abutments, such as stub abutments on a single row of piles to act as a hinge. The study also noted that the effects of creep and shrinkage are almost negligible on structures less than 25 meters long, making them possible conversion candidates too (Husain and Bagnariol 1999).

Information on Iowa DOT preservation activities provides condition criteria for when a stub abutment might be replaced with a semi-integral abutment. Per linear foot of bridge width, the conversion would cost an of average $2,000, improve the existing NBI condition rating by 1 point, and extend the service life by 35 years. This method can act as preventive maintenance for the entire bridge because if the conversion is successful, the elimination of joints in the bridge deck would keep most of the harsh chemicals and moisture at the top of the bridge and away from the structure below.

2.3.6. Bank Protection for Bridges over Water

Bank protection is critical to ensure the safety of bridges over water. Erosion and scour can occur quickly, even overnight during harsh storms. Proper riprap design and maintenance can prevent large damages and the consequent expenses. This is explained in a report by the U.S. Department of the Interior's Bureau of Reclamation, which states, "Monitoring and maintenance of longitudinal or direct bank stabilization methods helps ensure successful performance over the lifespan of the protection" (Baird et al. 2015).

The report claims that riprap failure is often due to "excessive scour, upstream channel migration and inadequate tie-backs, or insufficient rock sizes and gradation" (Baird et al. 2015). Investigative inspections may need to be employed in order to understand the extent of scour occurring at a bridge because water can block the view during normal inspections. Fortunately, there are some warning signs that inspectors can look for, including dislodged riprap at the water's edge that can signal the need for revetment. Revetments can range in price depending on the material type, the area to be covered, and the protection type. Iowa DOT cost information currently prices scour protection at $50 per square foot to increase the substructure element-level condition state to 1, potentially extending the substructure element's lifespan by 10 years.

2.3.6.1 Rehabilitating Bank Protection: Replenishing Riprap

Riprap can be lost due to excessive scour. Replenishing this riprap quickly, as well as inspecting it during peak flows to add material where deemed necessary, can prevent any further erosion that may cause harm to the bridge (Iowa DOT 2014, Baird et al. 2015). The riprap's slope affects its performance; a 1V to 2H slope is more effective and will last longer than a 1V to 1.5H bank in a high-energy stream (Baird et al. 2015). Again, inspection is key to success, because simply adding revetment to an existing stream may cause flow restriction, which can increase the speed and therefore scour potential of the stream or create a damming effect and flood areas and bridges upstream (Iowa DOT 2014).

2.3.6.2. Rehabilitating Bank Protection: Other Revetment Types

A common form of slope protection is the use of concrete, often seen under bridges spanning highways. It is vital to take action at the first signs of damage, because replacing a single panel costs less than replacing a larger area. The damaged portion can either be removed and replaced altogether, broken into rubble to act as riprap, or, if the damage is minimal, backfilled with flowable mortar to prevent collapsing and cracking (Iowa DOT 2014).

Another form of slope protection may be to replant vegetation. Vegetation helps to hold the soil surrounding bridges and prevents erosion resulting from runoff. Biodegradable fabrics and hay are commonly used to aid in the regrowth of this vegetation as they retain moisture and provide an ideal environment for the sprouting of new vegetation (Baird et al. 2015).

2.3.7. Bearings

Iowa's bridges often incorporate bearings into their designs to accommodate differential movement, rotation, and thermal movement. These bearings can become full of grit due to leaking joints. They can also be exposed to road salts, sand, and water, all of which can corrode and lessen the effectiveness of the bearings, eventually rendering them useless. While this may not cause immediate failure, over time the structural members will be subjected to rotation and movement that they were not originally designed for, which will ultimately lead to failure.

2.3.7.1. Lubricating/Greasing

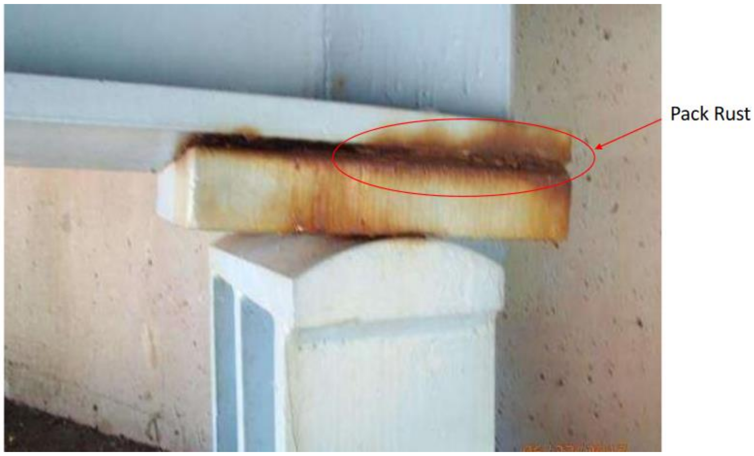
Bridge bearings are under immense loads. Friction between any components can quickly cause deterioration and failure of the bearings and ultimately the bridge. Additionally, a seized bearing can fail to transfer lateral loads and can cause changes in the loading of the structure, leading to the deterioration of other bridge components. Proper lubrication should be applied to bridge bearings to ensure proper movement of the bearings and to prevent moisture infiltration that can lead to corrosion and pack rust. Lubrication should be performed on a cyclical basis as a preventive measure. The Iowa DOT uses in-house maintenance crews to perform bearing lubrication, which requires two hours of traffic control per stage and costs an average of $100 per bearing. The traffic control is necessary because the bridge must be jacked in order to clean and lubricate the bearings. This maintenance applies to Iowa's sliding and rocker bearing types (Wipf et al. 2003). An example of a bearing being greased is shown in Figure 2.12.

NYSDOT 2008

Figure 2.12. Typical bridge jacking to grease bearings

2.3.7.2. Removing Pack Rust from Moveable Bearings

Pack rust is the buildup of corrosion within the crevice of two adjoining surfaces, as shown in Figure 2.13.



Patel and Bowman 2018

Figure 2.13. Pack rust on a rocker bearing

Due to the tight tolerances of bearings, they have a high risk of the formation of pack rust. Pack rust can cause accelerated corrosion within a crevice if left un-neutralized and can cause bearings to seize. Different agencies have different methods to address pack rust. Oregon DOT uses a system of mechanical cleaning; the water saturated pack rust is first heated to a temperature range of 250°F to 400°F and then removed mechanically (by hammering the connection plate). In Missouri, a rust penetrating sealer made up of calcium sulfonate is used to mitigate the effects and occurrence of pack rust (Patel and Bowman 2018).

2.3.7.3. Sealing and Painting

Another important preventive maintenance activity for bridge bearings is sealing and painting. Moisture is bound to reach the bearings, and if left unattended the buildup of debris will trap the water and the corrosive chlorides. Painting bridge bearings provides a protective coating against these stressors. The bearings must be washed and rust free before painting. Washing bearings costs the Iowa DOT $100 per bearing, which alone can require two hours of traffic control but will prolong the lifespan of the bearing by approximately five years. After washing, any pack rust is then removed and neutralized. Bearings should also be lubricated at this point. The process of painting may require an entire day of traffic control by a maintenance crew and cost an average price of $200 per bearing. Painting bearings can extend the lifespan of the bearing by as much as 10 years and prevent unnecessary stresses due to thermal loading in structural members (Iowa DOT 2014).

2.3.7.4. Replacement

Preventive maintenance of bearings is key to avoiding the cost of replacing bearings. However, if the deterioration of a bearing becomes excessive, engineering judgement may call for its replacement. This is a costly activity for the agency, but it affects user costs as well due to the necessary traffic control, which may involve either diverting traffic or closing the bridge altogether for potentially several days for each bearing because the beams must be jacked for safe removal of the failed bearings (Figure 2.14).

NYSDOT 2008

Figure 2.14. Removal of existing bearing pad

This can be a rather intricate process because failure to uniformly jack all bearings may cause additional stresses in various bridge members, furthering the extent of the damage and the costs of repair (Iowa DOT 2014, NYSDOT 2008).

2.3.7.5. Resetting

Finally, bearings may require what is known as a reset. Thermal expansion may cause greater movement than the bearing's sliding or rotational capabilities allow for. The bearing needs to be reset back into its original functioning position in order to continue functioning properly (Iowa DOT 2014). The Iowa DOT expects an average cost of $3,000 per elastomeric or rocker bearing reset as well as an entire day of traffic divergence. Typically, these jobs are performed by in-house maintenance crews.

2.3.8. Approach Pavement

Approach slabs are subject to multiple deterioration problems that can greatly affect user experience. Commonly, approach slabs are under pounding loads, which may cause the underlying fill to settle and form voids. Water can then infiltrate these voids and lead to cracking and settlement of the approach slab, which may harm any existing expansion joints and damage vehicles that are subject to sudden changes in pavement elevation and potholes caused by spalling (Iowa DOT 2014). Therefore, it is important to prevent water infiltration below approach slabs. Joint seals aid in preventing bridge runoff from affecting the underlying ground. Patching potholes can lessen their propagation and prevent the need for larger scale repairs.

2.3.8.1. Leveling with Hot Mix Asphalt (HMA)

Settled and potholed approach slabs may be repaired using hot mix asphalt. These repairs are considered "semi-permanent" because they are not structural and only temporarily extend the life of the slab. This type of repair also does not address the original cause of the damage, which therefore must be addressed in a different way. Additionally, this method is not to be used where the damage extends into the full depth of the slab; in such cases, more extensive work is required. The benefit of this approach is the speed with which it can be applied (Iowa DOT 2014). Patching can take as little a few hours and therefore has a minimal impact on traffic. The Iowa DOT estimates the average cost of HMA patching to be $25 per square foot, with different traffic control times depending on the extent of the damage. This patchwork can be completed by both in-house maintenance crews and certified contractors.

2.3.8.2. Raising with Flowable Mortar

As mentioned in a previous section, settling of the fill can cause stress in and settlement of the approach slabs. Voids in the underlying soil must be filled to correct the problem. There are several methods for doing this. However, the most common method and the one used in Iowa is to use a flowable mortar to fill the voids (Iowa DOT 2014). Commonly known as mudjacking, the process involves coring the approach slab to determine the extent of the damage and the voids and pumping grout below the concrete to raise the slab to the initial design level, matching that of the bridge (Iowa DOT 2014, Abu al-Eis and LaBarca 2007). This method can prevent the need for a new approach slab, which may be rather costly. For the Wisconsin DOT, the cost of mudjacking averages $40 to $60 per square yard of the approach slab. It can be a cost-effective approach if done correctly and if all voids are filled. This method requires complete closure of the bridge until the process is finished (Abu al-Eis and LaBarca 2007).

CHAPTER 3. DATA GATHERING AND ANALYSIS

Life cycle cost analysis cannot be performed without adequate data. Probabilistic LCCA requires a much larger quantity and wider variety of data than deterministic LCCA. State DOT agencies often have databases, stockpiling inspection and bridge data they have collected over years of inspections and maintenance projects. Unfortunately, there has been minimal effort to link this data to decision making processes. If the future LCCA tool is to integrate multiple data sources, these sources will have to be identified and their data analyzed. Some sources may prove sufficient while others will lack the necessary level of detailed required for a full analysis. If a LCCA tool is to be created specific for Iowa DOT, then the Iowa DOT data sources must be tapped and then the data collected, stored, managed, organized and analyzed so that it is in a useful form. This useful form will consist of many probabilistic distribution's functions.

Iowa stores its inspection information in the Structure Inventory and Inspection Management System (SIIMS) database. All NBI data required by FHWA federal regulations, as well as condition data for both NBI and NBE and BME elements is stored in SIIMS and can be queried based on requested criteria. Detailed explanations and background information of NBI, NBE and BME components are presented in this chapter. This chapter also elaborates on the evolution of visual bridge inspections. Changes inspection methods, as well as person bias between inspectors introduces possible errors and uncertainties into inspection data. Existing SIIMS data are used in this report to see its potential to be used for deterioration modeling, to predict bridge deterioration and make appropriate expected maintenance and repair schemes, and to evaluate LCC. Additionally, historical data can aid in the estimation of service lives, as seen in Chapter Two. As time continues, the inspection data is expected to become more in-depth and accurate, building on the existing databases now and providing a wealth of information to more accurately predict condition trends (Mao and Huang 2015).

In order to sum the LCCs, cost data is required. Cost data can fluctuate due to a number of factors. It is to be mentioned here that different activities are performed either by in-house maintenance crews or by contractors and can dictate the availability of cost information and where to obtain it. As discussed in Chapter Two the relative cost data does exist however more detailed data will be necessary to implement probabilistic LCCA. Additional data sources in literature and neighboring states for cost information will therefore be discussed. Hopwood II et al. (2015) noted that even after a detailed review of existing literature as well as meetings with DOT officials from several states and the FHWA, "that current available life-cycle cost information for the full range of PM activities is limited. Other information was obtained from journals and reports" (Hopwood et. al. 2015). This is referencing preventative maintenance (PM) activities however it shows the difficulty gathering information in general when there is constantly an array of variables that can affect the costs.

3.1. Bids and Maintenance Crew Costs

State maintenance crews cannot be expected to possess all the skills and tools to complete every possible type of preservation and repair activity. The cost to keep and store the equipment and to train staff for more advanced work and for large scale projects can be less cost effective than contracting trained professionals to complete a job. Additionally, with more than 4000 state owned bridges in Iowa, crews would be spread thin if there were no contractors to complete some of these jobs. Determining which activities are completed in-house or by contractors is up to the discretion of the agency in charge. As discussed in Chapter Two that Iowa DOT has differentiated who is expected to complete many of Iowa's activities. Therefore, cost data can be obtained as inputs for LCCA. Ideally, each possible activity needs its respective cost distribution curve. This will require future data gathering and analysis from multiple sources. Preservation and repair costs used in the review were averages proposed by Iowa DOT officials. Bid costs can be a crucial source of future data mining. Iowa DOT has thousands of pages of previous and existing bids from contractors around the state. Each job that has been bid on has a summary page with important planning information. The contract period is listed in terms of days required to finish the project. This can be used to calculate expected traffic disruptions and the effects on user costs. The primary county listed provides a location for the bridge in question, which can be important as LCCA evolves to include the effects of environmental exposure. More on Iowa specific environmental exposure research will be discussed in Chapter Five. Work type is listed which can be used to aid in filtering and attaching the information to the appropriate task. The project award amount can then be used as an overall cost for an activity. Note this cost encompasses multiple items involved whose prices fluctuate based on quantity. These items of the bids can then be found under the bid information pages, breaking the job into the bid items i.e. deck repair, deck patching, traffic control, equipment mobilization, etc. Each item has a quantity required for that job with specified units, a unit price, and the total price for that item. The unit price and respective units will be most important. A collection of unit prices for any particular item can help to formulate data trends in the items expected costs. The distribution can then be inputted into the LCCA to provide realistic LCCs. Bid data can be found on Iowa DOT's website and has bid tabulations for each month from January 2014 to the present, potentially holding thousands of data points.

Cost data accumulation is more difficult for those tasks performed by in-house maintenance crews. Crews can range in size by the day and may attempt to perform similar maintenance tasks on multiple bridges in a day. This can lead to poor documentation of material use and costs, as well as time requirements. Pinpointing unit costs can then become close to impossible without due diligence in recording procedures. Brief interviews with Iowa DOT personnel have confirmed this situation. Authors recommend detailed documentation of all maintenance activities to provide cost distributions for each task to serve as inputs for LCCA for Iowan Bridges. In addition, to compensate for any cost data currently unavailable for in-house maintenance, individual interviews with the six districts of Iowa DOT can be useful. Meeting with the experts of each may provide preliminary data to be used for immediate implementation, allowing for data stores to grow.

3.2. Private Collections and Experts in the Field

Using expert elicitation is common amongst research and work towards developing bridge LCCA. Adams and Juni (2003) used costs collected from bridge maintenance crews in an effort to supplement Pontis ((Hearn 2012), (Adams and Juni 2003)). Similarly, Sobanjo and Thompson (2001) worked to establish cost data for Pontis actions and used expert elicitation to do so as they claimed the cost units of actual work data were not compatible with those of Pontis and needed to consult experts to supplement Pontis BMS" (Hearn 2012). Hopwood II et al. (2015) surveyed several mid-western to identify maintenance activities and specify whether they are preventative maintenance (PM), condition-based activities, categorized as repairs, or rehabilitation activities (Hopwood et. al. 2015). Hearn (2012) was able to extract data for maintenance activities from a variety of states around the U.S. Their work is full of various datasets compiled from the recorded data of a multitude of states. The datasets include major bridge component specific maintenance costs, with the number of occurrences and the unit cost information for each. Similar datasets for element specific actions, available actions per condition state, bid tabulations that also make note of the terrain of the bridge location, recommending actions based on distress levels as well as the associated transition probabilities and expected unit costs (Hearn 2012). Not only did Hearn collect the data from Colorado DOT but similar data from multiple states including California, Idaho, Louisiana, Delaware, and Oregon. These data points can be used to add to existing data and fill gaps in data so that Iowa DOT may have a basis to evolve their data recording processes and start the use of LCCA. For this study, Iowa DOT officials are interviewed for their input on maintenance activities. Information obtained from these interactions is discussed in the following section.

3.3. Currently Accessible Data for Iowa

As stated in Chapter Two of this report, Iowa DOT already has up-to-date cost data for the Initial construction costs component of LCCA. Iowa DOT's LRFD Bridge Design Manual contains tables depicting basic cost information for preliminary bridge design. They are intended to provide a rough idea of what new bridge items may cost by specifying relative unit costs in terms of the present year (Iowa DOT 2010). For more detailed cost data Iowa DOT has two programs at the time of this report. Iowa DOT's Project Scheduling System (PSS) is used to manage their current highway program. The program can use current cost values and apply a standard 4.5% inflation rate for any future cost calculations if a project is to be completed in the nearby future. The cost data to be inputted for this comes from the second program, iPDWeb. IPDWeb can estimate construction costs using historical data that is constantly updated. As mentioned in earlier, a major problem reported of LCCA implementations elsewhere is the lack of updating in cost data. iPDWeb updates daily and uses the most relevant data to the project at hand. Users can input filters so that data is custom tailored to the intended job. iPDWeb does not include any contingency or risk in its estimates but does provide a distribution of costs with the standard deviation from the average. Generally, for new bridge design cost estimation, the standard procedure for Iowa DOT is to consult iPDWeb for cost information which will then be input into PSS. If the year intended for the project start is not the current year the programmed fiscal year can then be inputted into PSS so that it applies the inflation rate for every year in between. This software is also available to contractors for Iowa and therefore may help to regulate pricing between state maintenance crews and contractors. The iPD software packages are available at https://iowadot.gov/bridge/programs/iPDWeb%20Project%20Cost%20 Estimating%20for%20OBS.pdf. (Iowa DOT 2010).

3.3.1. Expert Elicitation

3.3.1.1. Conferences

Early into this project the authors had the opportunity to sit in on the first annual Midwest Bridge Preservation Peer Exchange conference. The goal of this conference was to begin communications between different Iowa DOT districts to promote sharing of knowledge and experience on preservation activities. The conference gave way to understanding the general need amongst Iowa DOT personnel for a tool that could provide a tangible perception of the expected lifespan of any maintenance actions. Lifespans of various bridge components and repair methods were being exchange based solely off experience with large deviations between different representatives. This brings about the questions as to why their experiences are so different and which factor affects the life cycle of these bridges. In Chapter Five of this report the use of de-icing salts in Iowa and the differences in quantities among the state's six districts is discussed. Comparing salt use with average transition probabilities in Chapter Four may provide insight into the effects of road salts on Iowa bridges and aid in providing proper preservation activities.

3.3.1.2 Survey of Experts in Field

One of the initial goals of this project was to gain expert knowledge and contacts through the use of a survey. LCCA research in the past has relied on the participation of their peers to gather useful information and gain new sources of data. Multiple surveys have been mentioned in this work, some of which served as inspiration while conceptualizing questions for this study. A survey is sent out to state DOT employees whose positions place them in close ties with bridge maintenance. The associate job titles can be seen in Table 3.1. A total of 11 respondents from Iowa and the surrounding Midwest DOTs were recorded and summarized in the following document.

Table: 3.1 Job Title Entries

Bridge Construction and Maintenance Engineer
Bridge Scoping Engineer
Bridge Scoping Engineer
Transportation Engineer III - Structure Management Section NDDOT
Bridge Construction and Maintenance Engineer
Assistant State Bridge Engineer
Engineer of Bridges and Structures
Bridge Maintenance and Inspection Engineer
District 6 Bridge Crew Leader
Bridge Inspector 2
District Repair Specialist

Respondents were asked a series of questions regarding bridge element maintenance tasks. The main objective of the survey was to determine what maintenance and repair tasks were being performed in-house by the state DOT maintenance crews and which were being contracted out to other companies. These tasks were grouped based on their associated bridge element and as expected, the inferences made following attending the Peer Exchange conference, few tasks are completely exclusively in-house. This can be seen in the plots in Figures 1a and 1b. As it can be observed, for the majority of bridge components surveyed, both options to complete tasks be- it in-house or by contract are always possibilities and neither has any particular exclusivity. The options “Contracted Out” and “Both” for many of the elements have similarly distributions which arises the question, what is the determining factor between contracting out a task and performing it in house? This question will be readdressed in the final chapter, Chapter Five, of this report that focuses on the future of LCCA in Iowa.

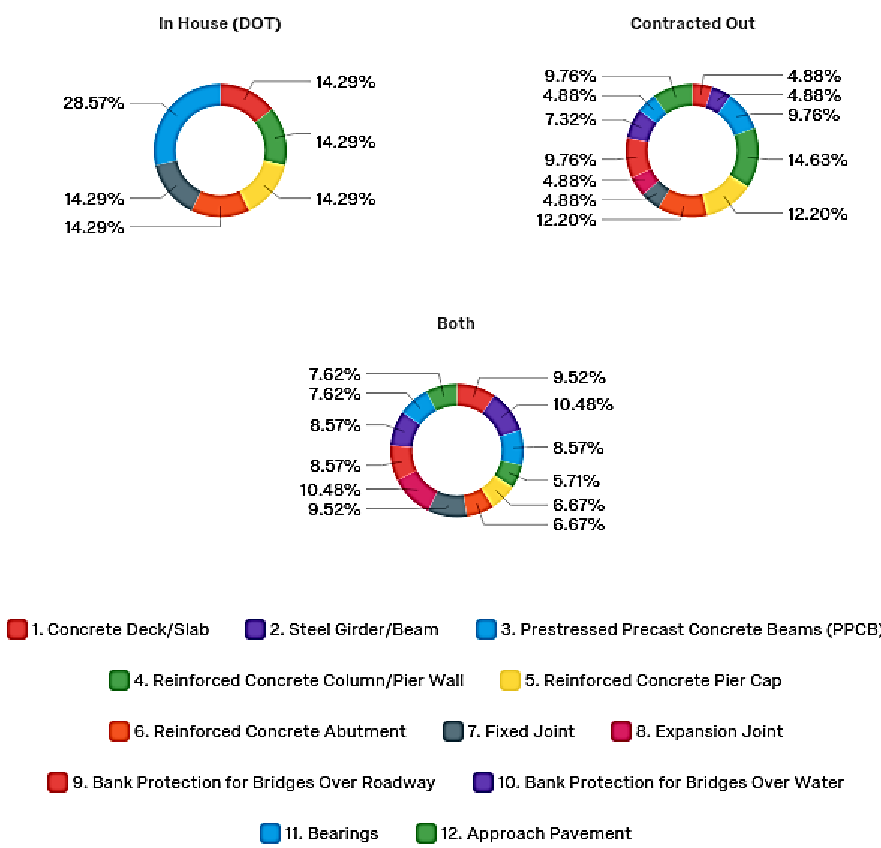


Figure 3.1 (a) Survey Results of Who Completes the Maintenance Activities

#	AWA.FIELD	In House (DOT)		Contracted Out		Both		SIMPLETABLEWIDGET.TOTAL
1	1. Concrete Deck/Slab	7.69%	1	15.38%	2	76.92%	10	13
2	2. Steel Girder/Beam	0.00%	0	15.38%	2	84.62%	11	13
3	3. Prestressed Precast Concrete Beams (PPCB)	0.00%	0	30.77%	4	69.23%	9	13
4	4. Reinforced Concrete Column/Pier Wall	7.69%	1	46.15%	6	46.15%	6	13
5	5. Reinforced Concrete Pier Cap	7.69%	1	38.46%	5	53.85%	7	13
6	6. Reinforced Concrete Abutment	7.69%	1	38.46%	5	53.85%	7	13
7	7. Fixed Joint	7.69%	1	15.38%	2	76.92%	10	13
8	8. Expansion Joint	0.00%	0	15.38%	2	84.62%	11	13
9	9. Bank Protection for Bridges Over Roadway	0.00%	0	30.77%	4	69.23%	9	13
10	10. Bank Protection for Bridges Over Water	0.00%	0	25.00%	3	75.00%	9	12
11	11. Bearings	16.67%	2	16.67%	2	66.67%	8	12
12	12. Approach Pavement	0.00%	0	33.33%	4	66.67%	8	12

Figure 3.1 (b) Survey Results of Who Completes the Maintenance Activities

For each bridge component, queries have been made regarding which maintenance activities are performed and what could be the deciding factor for determining who will perform the maintenance. Responses ranged in terms of reasoning and level of detail. One response was able to encompass the general consensus while in itself brings about some important questions. The response for determining who completes tasks was: "scope of repair, access, urgency, bridge maintenance availability, traffic," which although brief is very straightforward and shows the complexity caused by a multitude of variables in each maintenance decision. Additionally, it shows the difficulty in compiling cost data as generalizations are usually made so that data can be applicable to more than the specific bridge it represents. A predictive life cycle cost analysis tool would require extensive cost compiling for each activity. Any uncertainties or variables must be considered while examining the costs. Extent of damage, weather conditions, traffic, and ease of access all can vary by project, highlighting the importance of large datasets to minimize the effects of outliers while potentially exposing variables that can cause sways in project costs.

These costs for each activity will have to be recorded and tracked from both district engineers, and as stated in a previous section, Iowa DOT's existing bid records. Plans for this future work can be found in Chapter Five.

3.3.1.3. Personal Meeting with Iowa DOT Staff: Preservation and Rehabilitation Activities of Iowa DOT

At the time of this survey we did not have some of the key preservation activity data from Iowa DOT. After multiple individual interviews and meetings, data on Iowa DOT's main preservation and repair activities was obtained. This data was analyzed and discussed in Chapter Two of this report in the review of maintenance activities. Valuable cost information as well as condition criteria, traffic control times, expected condition improvements, activity timing and information on who is generally expected to perform those activities. With little to no background on these figures, it can only be assumed that they represent actual values. If to be used in a risk-based LCCA, uncertainties would be assigned to each figure to represent potential cost and time distributions. Future analysis of bid information and detailed recording of in-house work may supplement this information and provide backing as well as realistic probabilities. Also, this data provided insight on how current Iowa DOT treats some maintenance tasks as preventative maintenance and others as corrective. As in Chapter Two, preventative maintenance is often cyclical and is an effort to slow progression of deterioration of bridge components. Proposed LCCA when paired with risk-based transition probabilities (to be discussed in Chapter Four) can then determine the most fiscally responsible timing of these activities.

An excellent example in literature of the extent of data manipulation required to begin the implementation of LCCA resides in the work *Life Cycle Cost Analysis Rehabilitation Costs* by Melody A. Perkins of CDOT Pavement Design. The study addresses the need to compare costs of differing repair methods to maximize efficiency and cost effectiveness. While this study focused on rehabilitation of pavement, the principals still apply. The goal was to have LCCA to create "the most realistic and factual comparison" (Perkins 2015) of costs over the lifespan of a project. The study used data from 692 pavement rehabilitation projects in the state of Colorado, each of which had an initial pavement cost of $2,000,000 or more. The costs of these potential projects used existing bid price data, and these prices were adjusted to reflect the size of the project in terms of the product's standard unit of measurement. Additionally, all cost information and projects studies were within a set time frame, between 2001 and 2014. This created the need to normalize prices to the present year of 2014. Each rehab activity was itemized by the number of projects that it occurred in in the time range, the total units, the total normalized dollar amount, and the normalized average cost per unit. They took into account different variables like thickness of pours, and product types when considering the costs of each technique but recognized this was not enough. Differences in service lives of the treatments could cause large variations in final life cycle costs and therefore the study recommends future development of associating these costs with the correct service lives.

3.3.2. SIIMS

Iowa's inspection database has been referenced in previous chapters. The Structure Inventory and Inspection Management System (SIIMS) is a crucial component to Iowa's future with LCCA. SIIMS contains all NBI level data Iowa DOT records of each bridge. The following section will elaborate more on NBI and element level data. For probabilistic LCCA, historical data is necessary to create the transition probabilities to be discussed in Chapter Four. NBI and element level data was obtained from SIIMS to find trends in many parameters including bridge types, ages, materials and condition states. Reinforced concrete decks were found to be the most common deck type across the state, Chapter One specifies that the focus on this initial integration of LCCA will be decks, expanding to additional bridge components as data stores become more detailed. Discrepancies among SIIMS data, most likely due to user error were noticed. Occasional changes in quantity totals for bridges between inspections and fluctuation in condition states with no maintenance or repairs noted were the two main concerns. Similar variations were seen in Hearn's (2012) analysis of CDOT's element level data, noting that the larger discrepancies were in the costs probably stemmed from unit changes during reporting (Hearn 2012). In the following section, we will see how expected inspection information has changed and developed. These changes may have caused bias in inspectors' assessments, or it may be due to the individual character of the inspectors.

3.4. NBI vs Element Level Data: Evolution of Inspections and Condition Rating Techniques

The first two chapters of this report referenced condition state data and their importance in LCCA. Also mentioned was the difference between NBI and element-level condition data. The role of condition states, determined through bridge inspections, in maintenance decisions has increased significantly since the initial steps towards standardization in the 1970s. Numerous systems have been created, modified, and retired in that time, and therefore a brief history of these systems is crucial for understanding how they are intermingled. Historical data cannot be used if inspection methods are inconsistent, and therefore states have developed inspection guidelines specific to their needs. Iowa's current *Bridge Inspection Manual* (2015) provides an in-depth look at the condition rating systems that have been used in Iowa. A summary of Iowa's background as well as synopsis of the systems alluded to within the manual is provided here.

Bridge failures in the latter half of the 1900s prompted the demand for standardized inspections of bridge condition. Prior to standardization, bridge inspections could best be described as random and biased. The depth of inspection as well as the overall results of assessments were dependent on the individual inspector, making it difficult to fully understand the existing condition of the bridge and compare it to that of others. This bias led to misunderstandings of bridge health, and therefore proper maintenance actions were not taken.

Multiple bridge collapses across the US in the 1950s and 1960s that killed several travelers inspired the 1968 Federal Highway Act. The act required the FHWA to establish the National Bridge Inspection Standards (NBIS), which mandated states to systematically maintain a detailed account of all bridges on federal-aid highways. This catalog of bridges would become known as the National Bridge Inventory (FHWA 2004). Shortly after, the Federal-Aid Highway Act of 1970 was enacted to further federal efforts to maintain bridges and protect the safety of users. In this, AASHTO's *Manual for Maintenance Inspection of Bridges* was developed, along with the FHWA's *Bridge Inspector's Training Manual*. Inspection training was emphasized to avoid additional preventable collapses. Following shortly after, in 1971, the initial NBIS was published after the Federal Register requested the opinion of the states, which supported the development of the proposed NBIS (Iowa DOT 2015).

The advances in inspection and maintenance techniques originally only applied to bridges in the federal-aid highway system. However, under the Surface Transportation Assistance Act of 1978 these inspection and maintenance requirements were extended to all bridges on public roads that measured greater than 20 feet in length. The sole exception for bridges within a state's boundaries were those owned by federal agencies (Iowa DOT 2015). The mandated inventory acted as a list of information for each bridge, to be reported upon inspections that were to be performed at most every 24 months, with some exceptions. These exceptions can be found in Iowa's *Bridge Inspection Manual*. The list of NBI information can be seen in Table 3.2.

Table: 3.2 National Bridge Inventory Elements

Item	Description	Item	Description
1	State Code	55	Minimum Lateral Underclearance on Right
2	Highway Agency District	56	Minimum Lateral Underclearance on Left
3	Count (Parish) Code	58	Deck Condition Rating
4	Place Code	59	Superstructure Condition Ratings
5	Inventory Route	60	Substructure Condition Ratings
6	Features Intersected	61	Channel and Channel Protection
7	Facility Carried by Structure	62	Culverts Condition Ratings
8	Structure Number	63	Method used to Determine Operating Rating
9	Location	64	Operating Rating
10	Inventory Route, Minimum Vertical Clearance	65	Method used to Determine Inventory Rating
11	Kilometer Point	66	Inventory Rating
12	Base Highway Network	67	Structural Evaluation Appraisal Ratings
13	LRS Inventory Route, Subroute Number	68	Deck Geometry Appraisal Ratings
19	Bypass, Detour Length	69	Underclearances, Vertical and Horizontal Appraisal Ratings
20	Toll	70	Bridge Posting
21	Maintenance Responsibility	71	Waterway Adequacy Appraisal Ratings
22	Owner	72	Approach Roadway Alignment Appraisal Ratings
26	Functional Classification of Inventory Route	75	Type of Work
27	Year Built	76	Length of Structure Improvement
28	Lanes On and Under the Structure	90	Inspection Date
29	Average Daily Traffic	91	Designated Inspection Frequency
30	Year of Average Daily Traffic	92	Critical Feature Inspection
31	Design Load	93	Critical Feature Inspection Date
32	Approach Roadway Width	94	Bridge Improvement Cost
33	Bridge Median	95	Roadway Improvement Cost
34	Skew	96	Total Project Cost
35	Structure Flared	97	Year of Improvement Cost Estimate
36	Traffic Safety Features	98	Border Bridge
37	Historical Significance	99	Border Bridge Structure Number
38	Navigation Control	100	STRAHNET Highway Designation
39	Navigation Vertical Clearance	101	Parallel Structure Designation
40	Navigation Horizontal Clearance	102	Direction of Traffic
41	Structure Open, Posted or Closed to Traffic	103	Temporary Structure Designation
42	Type of Service	104	Highway System of the Inventory Route
43	Structure Type, Main	105	Federal Lands Highways
44	Structure Type, Approach Spans	106	Year Reconstructed
45	Number of Spans in Main Unit	107	Deck Structure Type
46	Number of Approach Spans	108	Wearing Surface/ Protective System
47	Inventory Route, Total Horizontal Clearance	109	Average Daily Truck Traffic
48	Length of Maximum Span	110	Designated National Network
49	Structure Length	111	Pier of Abutment Protection [for navigation]
50	Curb or Sidewalk Widths	112	NBIS Bridge Length
51	Bridge Roadway Width, Curb-to-Curb	113	Scour Critical Bridges
52	Deck Width, Out-to-Out	114	Future Average Daily Traffic
53	Minimum Vertical Clearance Over Bridge Roadway	115	Year of Future Average Daily Traffic
54	Minimum Vertical Underclearance	116	Minimum Navigation Vertical Clearance

Unfortunately, collapses following these efforts still occurred and put additional emphasis on the need for specialized inspector training, with specific attention given to “fracture critical” bridges and underwater bridge components (Iowa DOT 2015). Therefore, the Surface Transportation and Uniform Relocation Assistance Act of 1987 was passed, which officially expanded the scope of existing programs to cover such components (Federal register 2004). AASHTO continued to evolve its inspection techniques, tools, and reference materials in subsequent years. As inspection methods improved, the capability of information did too. Data could be used to understand deterioration and performance rates and give insight into material choices and maintenance strategies. However, standardized inspection data requirements would be needed to provide greater detail in inspection information. Therefore, in the 1990s the practice of inspecting bridge condition at the individual element level was introduced.

By the year 2000, most states had adopted AASHTO’s “Commonly Recognized (CoRe) Elements for Bridge Inspection” over the existing NBIS (Thompson and Shepard 2000). The CoRe Elements, developed at the end of the 1980s and revised throughout the 1990s, were preferred because they provided a set of commonly used bridge elements that could easily be tailored to the needs of each agency. Additionally, the standards provided strict definitions of condition states for each element, as well as feasible action options to address those condition states. The CoRe Elements were created to address the “deficiencies of the NBIS,” four of which are listed in Thompson and Shepard’s (2000) *AASHTO Commonly-Recognized Bridge Elements*. First, the authors claimed that the NBIS’s breakdown of the bridge’s condition state into only five major parts—deck condition state (NBI Item 58), superstructure condition state (NBI Item 59), substructure condition state (NBI Item 60), channel protection condition state (NBI Item 61), and culvert condition state (NBI Item 62)—failed to provide sufficient information to appropriately determine repair strategies and cost estimates. The second drawback listed was that the 0 through 9 rating scale used by the NBIS for the condition ratings only describes the severity of the deterioration present and not the cause nor the proportion of the member's total quantity affected. The third and fourth drawbacks are that the failure to attach a quantity to the condition state observed may lead to misinterpretations by those other than the individual inspector and prevent the proper maintenance strategy from being executed, ultimately leading to continued damage or unnecessary use of funding (Thompson and Shepard 2000).

These shortcomings within the NBIS were to be addressed by the development of the Pontis Bridge Management System. Pontis, developed in 1990 by the FHWA, had its own condition rating system based largely around the CoRe Elements. Therefore, the development of the CoRe Elements should be discussed first. To begin, rating and recording the condition of individual bridge elements, as opposed to solely the main structural components (NBI items 58 through 62), became standard practice in the early 1990s as more detailed inspections became important for bridge performance and maintenance. Standardizing these bridge elements and condition states allowed for greater potential use of the inspection information, in that bridges in different environments and states could be compared for more innovation in the field, leading to more efficient and more appropriate designs for expected demands and environmental conditions.

AASHTO claimed that its goal for CoRe was "to completely capture the condition of bridges in a simple way that can be standardized across the nation while providing the flexibility to be adapted to both large and small agency settings" (AASHTO 2010). To achieve this goal, a set of bridge elements was formulated that consisted of two element types, National Bridge Elements and Bridge Management Elements. All elements have two requirements: the quantity standardization of condition states and the categorization of the four condition states into four descriptors, “good” (1), “fair” (2), “poor” (3), and “severe” (4) (AASHTO 2010). The difference between NBE and BME is that the former represents the primary structural bridge components necessary to determine the condition and safety of the bridge, whereas the latter includes the components “typically managed by agencies utilizing Bridge Management Systems,” such as wearing surfaces, protective coatings, joints, etc. NBE items can be further broken down into variations of the deck, superstructure, substructure, and culverts and include the option to add bridge rails and bearings (AASHTO 2010). In summary, the AASHTO CoRe Elements were intended to set standard element definitions and condition states to be used during inspections that would allow the association of bridge element quantities matching those definitions.

Pontis was developed under the primary influence of AASHTO’s CoRe standards. In Pontis, each bridge element has 3 to 5 condition states with standard descriptions and associated feasible maintenance actions, similar to CoRe. The Iowa DOT adapted and published a Pontis *Bridge Inspection Manual* in 2009, adjusting the element definitions to represent the general elements found in Iowa’s bridges. In addition to the descriptions and condition states, the Pontis manual provided each element with a respective unit of measurement, method of measurement, condition reporting method, relevant “smart flags” similar to those used by AASHTO’s CoRe, and the expected accuracy of measurement. Environmental conditions served as an additional input in Pontis to account for element exposure. The environmental condition ratings were largely based on ADT or direct exposure to the surrounding environment. In 2011, the CoRe system was replaced by the AASHTO *Guide Manual for Bridge Element Inspection*. This was done in an effort to change element-level descriptions to include terminology that describes the “multiple distress paths” to which the elements may be subjected (Iowa DOT 2015).

In 2012, MAP-21 was signed into law. The bill required all bridges on the NHS and those receiving federal funds to have element-level data reports by 2014. In the state of Iowa, more than 4,000 bridges fall into this category. Currently, Iowa inspections use NBIS methods to report the mandated inspection data for these structures. The information is documented and recorded in Iowa's SIIMS database and is easily found in each bridge's Structure Inventory and Appraisal (SI&A) Report. Section 2.2.2 of the Iowa DOT's *Bridge Inspection Manual*, last updated in 2015, contains the "General Condition Rating Codes" for the state of Iowa. As seen in the manual, NBI items 58 through 60 share a set of descriptions that classify each rating numeral, with 0 being a failed condition state and 9 being an excellent condition state. Separate lists are also given for items 61 and 62. A generalized table of these condition states for bridge decks, superstructures, and substructures is shown in Table 3.3.

Table 3.3. General Condition Ratings for Deck, Superstructure, and Substructure
(synthesized from**:(**Iowa DOT 2015)

N	*Not Applicable*
9	*Excellent Condition*
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 of primary structural elements. 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 it back in light service.
0	*Failed Condition* - Out of service; beyond corrective action.

More than 40 years since its original development, the NBIS has been reformed and adapted in order to create a system that can accurately depict the condition of bridges and lead to a safer driving environment. However, after MAP-21 was passed, the mandated level of routine inspections was to cover, as previously stated, element-level data. This means that every applicable NBE and BME item on a structure must be assigned an individual condition rating that notes the total quantity by unit measurement of the element and the respective quantities of each condition state. The rating system Iowa uses was influenced by the AASHTO CoRe Elements, where each element has standardized condition ratings. All elements have four possible condition state ratings that are given common descriptions: “good” (1), “fair” (2), “poor” (3), and “severe” (4). Maintaining a standard number of condition states per element allows for greater potential use of the information as well as more consistent ratings by trained inspectors.

Element-level inspections are now part of routine inspections. There are three main recognized inspection types in Iowa: Initial, Routine, and In-depth. As explained in Section 1.4 of the Iowa DOT’s *Bridge Inspection Manual,* Initial Inspection is the very first inspection of the bridge, be it the first inspection after initial construction or following a major reconfiguration of the bridge such as widening or rehabilitation. The data provided by an Initial Inspection include the required federal NBI data, any typical Iowa DOT inspection data, and the “baseline structural condition” that notes any preexisting problems. Routine Inspections occur on a two-year basis for each bridge according to federal regulations. The inspection consists of all required NBI data, updates on the physical and functional condition of the bridge, element-level condition ratings, and any other observations and measurements necessary to accurately portray the bridge’s condition. Finally, In-depth Inspections involve more specialized inspection of “one or more members above or below the water level to identify any deficiencies not readily detectable using Routine Inspection procedures" (Iowa DOT 2015). Scheduling an In-depth Inspection does not affect the scheduling of Routine Inspections but may affect traffic for required access.

3.5. NBI Data Sources for This Study

A drawback of SIIMS is that cycling through previous inspection years is extremely tedious. SIIMS does allow the user to apply a seemingly endless combination of query filters to return specific desired information. Unfortunately, the data displayed are only from the most recent inspections. Recalling previous years' data requires stepping through each bridge individually and accessing each inspection year's SI&A report. This report was briefly explained in the previous section, but the point to be highlighted here is the lack of efficiency in the method of retrieving past data. This issue barred the researchers of this study from easily obtaining previous element-level data and required Iowa DOT personnel to be contacted to obtain previous years' element data. The data provided were rather unorganized and, without a large amount of manipulation, were almost unusable. Only four years of existing element-level data were available, and in each year the number of bridges varied greatly, further limiting the amount of usable data. Additionally, the data included many of the same discrepancies described in the discussion of SIIMS above, including variations in total quantities, especially cases where the sum of quantities in each of the four condition states did not always equal the claimed total quantity of the respective bridge.

These issues raised concerns and caused a lack of trust in the current element-level data and ultimately led to the decision to focus on NBI deck data. These data seemed more consistent and provided a larger range of data, dating back to 1983. As stated, however, the data proved difficult to obtain from SIIMS, so an external NBI data website developed by the FHWA, https://infobridge.fhwa.dot.gov/Data/SelectedBridges, was used in this study. The nation as a whole has 616,096 bridges. Filtering only Iowa bridges, this number was reduced to 24,123 bridges. Reducing this further to only include bridges with Nation Bridge Element Data we are left with 4,172 bridges to consider (FHWA 2019). While the site also failed to have a method to filter data by year, it allowed easier access to each bridge's previous years' inspection data and researchers were more able to filter through and record the necessary data for the transition probabilities to be seen in Chapter Four. These are the bridges affected the six state DOT districts on a daily occurrence. The site also provides some current performance data, depicting information by percentages of the bridge count. This includes the percentages of bridges in Good, Fair, and Poor condition, breaking them town to compare as subsets: all bridges, interstate bridges, NHS bridges, and non-NHS bridges (FHWA 2019).

Chapter Four will discuss our plans with Iowa's available data and the potential computing power it beholds. The importance of data recording, compiling, and analysis will become evident as we elaborate on the significant influence it has on the successful implementation of LCCA in Iowa.

CHAPTER 4. RISK BASED LIFE CYCLE COST ANALYSIS

4.1. Introduction

The goal of this chapter is to present and examine a LCCA that can be used to determine LCC for maintenance and repair alternatives, as well as new construction, while introducing risk assessment. Initial inspiration to do so came from the Moving Ahead for Progress in the 21st Century (MAP 21) Act as explained in Chapter One. Its intent is to incorporate risk into asset management programs to “improve or preserve the condition of the assets and the performance of the system” (112th Congress 2012).

Bridge management systems (BMS) are excellent tools to store bridge data and suggest possible maintenance strategies based off historical data of similar bridges. The United States’ use of BMS is limited and generally fails to be much more than a database of inspection data. Incorporation of risk is necessary for accurate condition predictions if decision-making algorithms are to be developed as singular deterministic values are not enough to provide realistic estimates. As the nation’s bridges continue to age and many are approaching or are past their initial intended service life of 50 years, it is important to create deterioration models to simulate real-world conditions if these bridges are to receive the proper maintenance and repair that they require in a timely and cost effective manner ((Wlaschin 2012), (ACI Committee 562 2016)). Including uncertainty in bridge project parameters will aid to the final results of LCC by displaying the likelihood of each alternative outcome, leading to more informed decisions. To do so, transition probabilities are generated, based on existing data and supplemented with future data to continuously adapt.

Before continuing, it must be addressed that the terms “uncertainty” and “variability” have been used throughout this report but have yet to be fully defined. Xu et al. in their 2012 work defined LCC uncertainty as a potential deficiency that can be a result of lack of knowledge and can cause the differences we see between model-based predictions and the real world (Xu et al. 2012). As it is seen in this report, gaps in data due to variances such as new environments or bridge types can lead to these uncertainties as well as just a lack of previous data being recorded or accessible. Transition probabilities are created for each condition state of bridges because this uncertainty changes as every point in the service life, and therefore we reiterate that we cannot use linear deterioration models with deterministic values. Any possible outcomes without existing data to predict the probability are considered uncertain. The second definition we need is variability. This is an attempt to measure an input’s randomness within generally well understood ranges of data or options (Ilg 2017). Additional definitions of commonly used phrases in stochastic LCCA modeling can be found in Table 1 of Ilg et al (2017).

4.2. Background and Overall Process

Existing deterministic LCCA models based expected maintenance schemes to reflect those of similar bridges in the past, assuming identical deterioration, or close to it, and no change in deteriorate rate caused by preventative maintenance. As it can be observed from Figure 2.2 in Chapter Two, preservation activities slow the rate, changing the slope, and potentially extending the service life —valuable information to consider that is missed with deterministic modeling. Probabilistic LCCA again uses similar data, but it also incorporates the transition probabilities and uncertainties in the data ((Mao and Huang 2015), (Transportation Equity 1998), (Reigle and Zaniewski 2002)).

Ilg et al. defines uncertainty similar to that mentioned above but notes that it is a broad term used to “encompass all uncertainty and variability in LCC” and that “limiting the scope of uncertainty quantification in LCC fosters misguided decisions” (Ilg 2017). Past research has taken steps to systematize uncertainty (Ilg 2017). Unfortunately, creating all-encompassing classifications and standardizations has proven difficult and futile. Ilg et al. present uncertainty as a complex subject with a multitude of subcategorization possibilities. In this report primarily parametric uncertainties are considered. Parametric uncertainties are primarily data based, focused on the lack of data necessary to model the desired components for the Markovian chain modeling within the Monte Carlo simulations. Parametric uncertainties stem from risk based LCCA’s necessity for “high-quality data” and a large magnitude of it. This effectiveness, or the “reliability” of the data is affected by the “accessibility, quality, and accuracy,” (Ilg 2017) all of which can be affected by DOT practices. Obviously, there are large gaps in data, lessening its accessibility due to the simple fact that past data was not being gathered to meet the needs of a system that was not even in existence in the state yet (Kishk 2008). Data quality has greatly improved as discussed in Chapter Two of this report as inspection methods have evolved immensely over the past four decades. Still human error and individual inspector bias can interject data collection errors, therefore affecting data quality and accuracy. This must be closely monitored or the uncertainties of human bias must be considered and added as inputs to the analysis ((Osman 2005), (Ilg 2017)).

Two more instances of uncertainty that will greatly affect how we intend to model LCCA are the uncertainty due to “different assumptions and starting points” (Ilg 2017) and the “general variability and inherent randomness in data and processes increase uncertainty” ((Saassouh and Lounis 2012), (Ilg 2017)). Inherent randomness at each step along the decision trees produced as

Markov chains will affect each and every step after, therefore affecting the probability of that chain of events and the final LCC. Some of this randomness can be captured in the proposed transition probability matrices. Variability in assumptions and starting points will then be modeled using Monte Carlo simulations which allow us to iterate a desired number of Markovian chains. More information on this modeling can be found in the following sections of this report.

Future goals are to make the LCCA tool adjustable to each bridge with inputs for various factors affecting bridge health. Environment type can be a parameter, for instance we may start by segregating probabilities by districts; analyzing salt use in each district will be a future goal of this project which we can then present the potential effects fluctuations in de-icers have on bridge health and deterioration rates. ADT or expected ADT will need to be a factor that affects transition probabilities. Others will include use of preventative maintenance, material choices, deck types, superstructure types, inclusion on joints within the deck, and so forth. Each will be an input that can be adjusted for the specific conditions of the prospective bridge. Determining appropriate uncertainties will be dependent on the extent of the historical data available. Agencies will be able to step through the expected timeline of the bridge and compare the effects of alternate maintenance schemes, not only on the LCC but the performance of the bridge ((Mao and Huang 2015), (Transportation Equity 1998), (Hawk 2003)).

A large factor to consider in probabilistic LCCA, is the uncertainty in costs. Costs fluctuate due to time, demand, size of purchase, material type, current condition state of the component/bridge in question, ADT, discount rate, maintenance frequency, and inspection interval ((Transportation Equity 1998), (Morcous and Hatami 2013), (Hawk 2003)). Accurate deterioration modeling can predict appropriate timing to implement maintenance strategies and Monte Carlo simulations can be used to iterate through the probability distributions of costs and result in LCCs for each alternative (Girmscheid 2008). Mao and Huang (2015) used Monte Carlo simulations with probability distributions they deduced for the costs of MR&R on deck expansion joints ((Mao and Huang 2015), (Transportation Equity 1998)). Often these costs are unknown due to their variability and lack of recording. Efforts have been made to use expert judgment to estimate costs which can then produce probability distributions based off an experts' "best estimates." as shown by Hawk (2003) (Figure 4.1)

Example distribution on a "best estimate"

Variation from best estimate value (%)	-50	-30	-20	-10	0	10	20	50	100	Sum
Probability	0.02	0.05	0.10	0.10	0.30	0.20	0.15	0.05	0.03	1.00

Suppose "best estimate" = 100

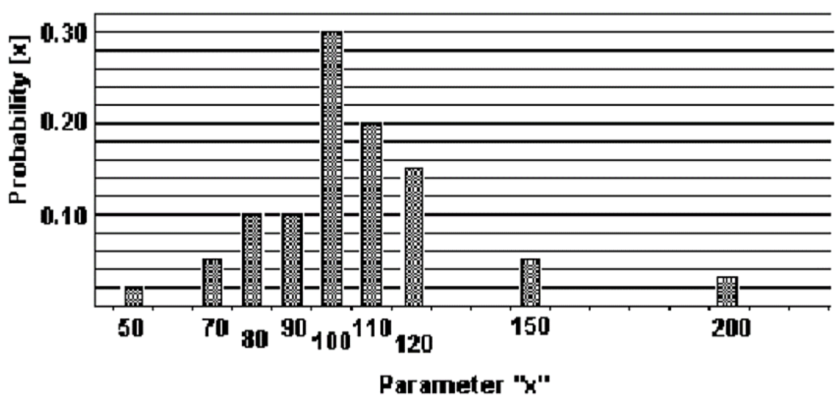


Figure 4.1: Probability density distributed on "best estimate" (adopted from: (Hawk 2003))

There are multiple types of probability distributions to model LCCA. Morcous and Hatami (2013) cite seven different types of distributions in their analysis of an early LCCA program called RealCost. A table found in their work provides a summary of these distribution types as well as the values that must be provided by the system user to input them into the LCCA. More about probabilities distributions will be discussed in the modeling portion of this chapter.

4.3. Transition probabilities

To reiterate, bridges are in a constant battle with deteriorating forces. Assuming a linear deterioration along a bridge's lifespan is inaccurate and fails to consider the influences of existing damage and the present and future condition states. As time progresses, both the condition state and safety of the bridge are bound to worsen if not slowed or reversed (Bucher and Frangpool 2006). To model deterioration, we need to quantify the probability of it occurring. Although deterioration is definite, the rate at which it will occur is not, and can change drastically based on the overall condition of the bridge or components in question. Again, having differing starting assumptions can affect this transition between states also and therefore iterating simulations are necessary to understand how differing starting points affect the end results.

Bucher and Frangopol (2006) assumed that under no maintenance or repairs, performance vs. time would produce a linear slope. A linear slope as deterioration rate is expected to increase as the condition state worsens. An example could be the effect of paint on steel girders on the condition state. At good or near-new condition, a CS 1 for element level condition states, the rate of deterioration of the girder due to exposure of de-icing chemicals and weather could be slow. As time continues, the paint can crack and age, allowing intrusive chemicals to reach the exposed steel, causing corrosion which can then expand and cause more paint to chip off and further exposure to the elements. As the beam deteriorates, its exposed surface area increases, and logically we would expect an increased deterioration rate. We could then anticipate section loss from corrosion. Changes in section equates to changes in allowable loading. If loading does not change, the increased stress on the decreasing area can further exacerbate the damage, and even shift it to adjacent elements that are now taking up the slack as the girder is not performing to its original design specifications. This non-linear effect can be seen in Figure 4.2 adopted from

(Van Noortwijk and Frangopol 2004). They emphasize the extension of service life through the use of maintenance and repair activities.

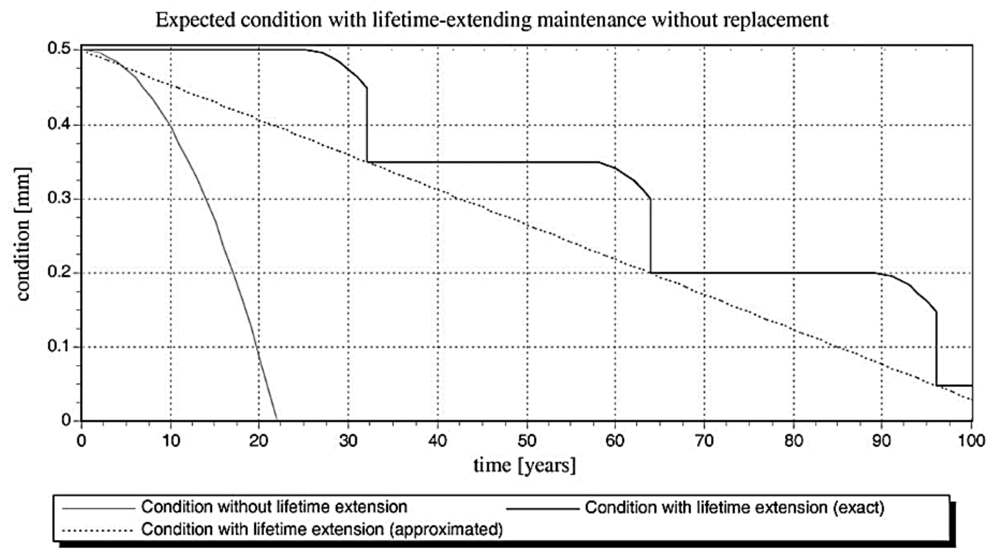


Fig. 2. Expected condition of the steel with 'repeating' lifetime extension in terms of grit blasting.

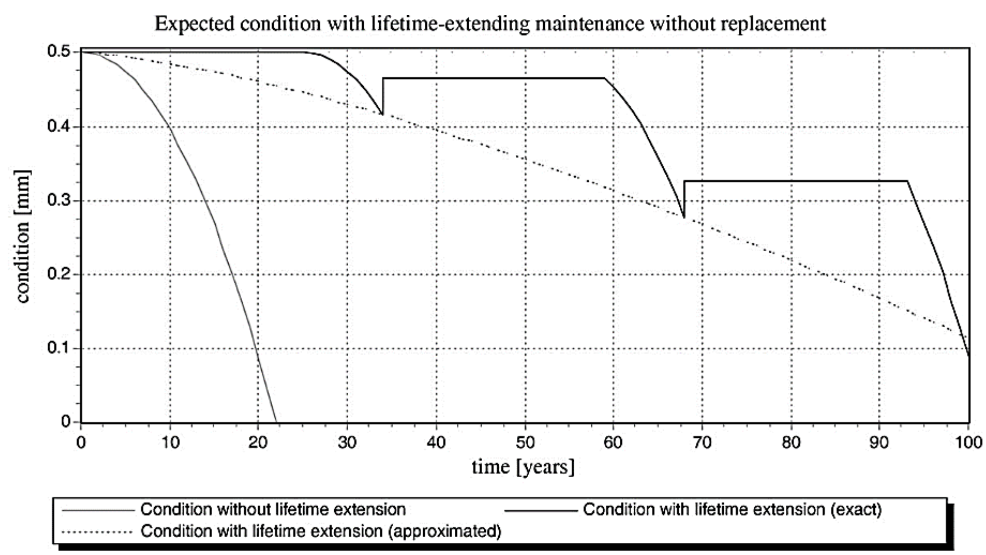


Fig. 3. Expected (hypothetical) condition of the steel with 'non-repeating' lifetime extension in terms of condition improvement.

Figure 4.2 (a,b) Depicting expected condition with lifetime-extending maintenance (adopted from: (Van Noortwijk and Frangopol 2004))

Bucher and Frangopol's (2006) inclusion of preservation and repair activities is however important to recognize as each of these drastically affect the slope of deterioration. Preservation activities, which can represent cyclical or preventative tasks, decrease the slope for the time they are deemed effective. Repair methods are shown to return the performance of a bridge to a previous state and assume this "like-new" condition therefore a brief time of no deformation following the repair before then continuing with a deteriorate rate equates to that of the past (Bucher and Frangpool 2006). Monte Carlo simulations and Markov chain models will be explained in the next section as we discuss how we intend to model the deterioration and the associated LCCs.

4.3.1 Markov-Chains and Transition Matrices

The importance of stochastic modeling of bridge deterioration has now been established. Markov chain models were chosen due to their widespread use in existing literature, providing ample support into their implementation into condition state prediction. Khatami (2018) cited multiple works ranging from the late 1980s to present day in their review of existing literature that used Markov chains to estimate the performance of bridges. These Markov chains are highly dependent on historical data to estimate transition probabilities between possible condition states ((Transportation Equity 1998), (Bucher and Frangpool 2006), (Khatami et. al. 2016)). Markov chains use these probabilities to predict the possible bridge condition at each step. Predictions are therefore based solely off the current condition state of the bridge and are unaffected by the bridge's history. With no preservation or repair activities, there is a chance this chain would be a singular string of events depicting the increasing deterioration of a bridge as a "do-nothing" approach to its maintenance is upheld. Incorporating activities to slow or regress the deterioration introduce new options at each step, essentially creating parallel chains that each have differing outcomes with respective probabilities.

The transition probabilities make up a transition matrix. This matrix is generally an upper triangle (Khatami et. al. 2016) containing the probabilities of a bridge condition transitioning from one state to the next. Some assumptions must be made in order to calculate these probabilities. First, we assume that deterioration is continuous and therefore must step through each condition state as the condition decreases. This is appropriate to assume as Iowa DOT does not wish to include extreme events currently. Earthquakes, vehicle impacts, and similar events can cause immediate damage and drops in condition state but excluded at this point in time; future investigation and data analysis can aid to incorporate the probability of these events if desired. This assumption helps to cause the upper-triangle layout of the transition matrix because a bridge can only transition to the surrounding condition states, creating a 0 probability for transition to other condition states. For example, a deck in CS 8 can transition to a 9 or a 7. It cannot make a leap to 6 or a 3 as we are not considering natural hazard at this time. Now obviously through deterioration, the deck could not transition to a 9 without assistance. This brings us to the second assumption, that a condition state cannot improve without maintenance or repair activities. This assumption is rather logical; however, it is necessary to assert that natural deterioration can only progress in one direction. Depending on the maintenance or repair activity, the condition state can in theory make leaps over several condition states towards improvement.

Determining the transition probabilities requires a large amount of previous inspection data. Some recognize this as a drawback of probabilistic LCCA and the use of Markov chain models ((Xu et al. 2012), (Kishk 2008)). The matrices can be made for both NBI level components condition states and the individual element level condition states. Due to the lack of a sufficient amount of element level data, this report will use NBI level inspection history to propose possible transition probabilities, again with a focus on the decks. Therefore, each transition matrix will be a 9x9 due to the nine possible NBI condition states. Each transition probability is calculated by an associated hazard function between the two condition states —or the probability the bridge component will transition to the next condition state by the next interval ((Hearn 2012), (Khatami et. al. 2016)). Our interval of deterioration will be two years; this will be explained in a following section. Historical data will provide multiple iterations of both before and after condition states to calculate the transition probability, p_{ij}, between two states. This process can be used for a predetermined number of discrete increments, n, with the initial condition, X_t, at the start of the analysis interval. Similarly, the condition state following the interval will be written as X_{t+n}. If $X_t = i$ at the start and $X_{t+n} = j$ at the end, the probability p_{ij} of the transition is expressed using the equation below. The equation can be read as 'the probability that the condition state at a time $t + n$ is j if the condition state at time t is equal to i and is equal to the probability that the condition state after n intervals is equal to j if the initial condition state is equal to i. Therefore this transition probability will be known as p_{ij} and is a function of the interval n. This equation highlights the memoryless-ness characteristics of Markovian transition probabilities. The age of the bridge does not necessarily affect the future condition states, only the current condition state can. This is known as n-Step Transition Probability and will allow us to treat preservation and repair activities as direct additions to the existing CS. Each possible transition state has its respective probability and together make a transition matrix as seen in P below. Notice that once a structure deteriorates to CS 0, it is impossible to leave this state. This is what is known as the absorbing condition state where p_{11} = 1 and the probability of leaving CS 0 is zero (Khatami et. al. 2016).

$$\Pr(X_{t+n} = j \mid X_t = i) = \Pr(X_n = j \mid X_0 = i) = p_{ij}(n) \qquad (1)$$

$$P = \begin{array}{c|cccccccccc|} & 9 & 8 & 7 & 6 & 5 & 4 & 3 & 2 & 1 & 0 \\ \hline 9 & p_{99} & p_{98} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 8 & 0 & p_{88} & p_{87} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 7 & 0 & 0 & p_{77} & p_{76} & 0 & 0 & 0 & 0 & 0 & 0 \\ 6 & 0 & 0 & 0 & p_{66} & p_{65} & 0 & 0 & 0 & 0 & 0 \\ 5 & 0 & 0 & 0 & 0 & p_{55} & p_{54} & 0 & 0 & 0 & 0 \\ 4 & 0 & 0 & 0 & 0 & 0 & p_{44} & p_{43} & 0 & 0 & 0 \\ 3 & 0 & 0 & 0 & 0 & 0 & 0 & p_{33} & p_{32} & 0 & 0 \\ 2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & p_{22} & p_{21} & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & p_{11} & p_{10} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & p_{00} \end{array}$$

Figure 4.3 Demonstrative layout of transition probability matrix

Markov chains have been described to use probability matrices to predict the future condition states of bridges. In doing so, they create a sequence of events, resembling a decision tree, of which each event in sequence is probabilistically related to another. These trees can act as a plot of the possible deterioration sequences given a specific starting condition and can factor in additional variables if data allows to create such specific transition probabilities. Figure 4.4 depicts a sample Markov chain, representing the first few inspection intervals of a bridge and the possible deterioration we may see. Each arrow represents the chosen two years interval between inspections. It is observed that each possible transition in the tree is accompanied with its respective transition probability from our earlier matrix. Note that the deterioration Markov chain depicts only the preservation or the decrease in condition state. Upon introducing repair procedures more possibilities at each interval can be instated, with more condition states and therefore more sequences within the Markov chain, as seen in Figure 4.5. The available condition states following a proposed repair in a Markov chain sequence will reflect the maximum improvement expected from the repairs. Figure 4.5 is only demonstrative and does not necessarily reflect the possible improvements for deck condition states.

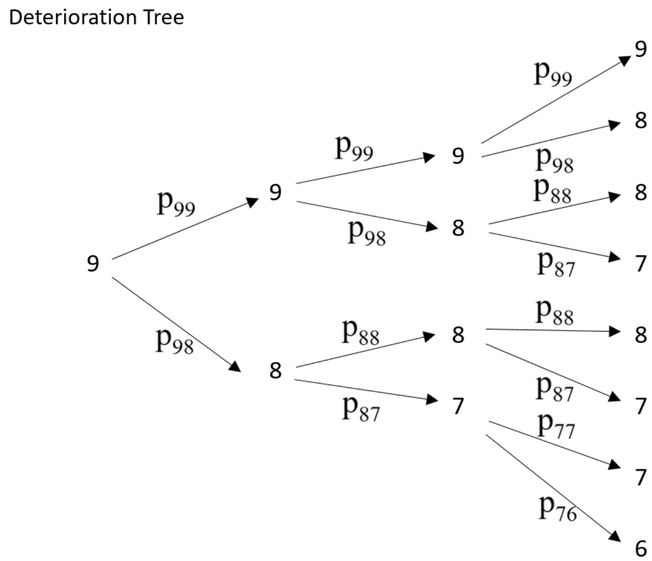


Figure 4.4 Deterioration Tree

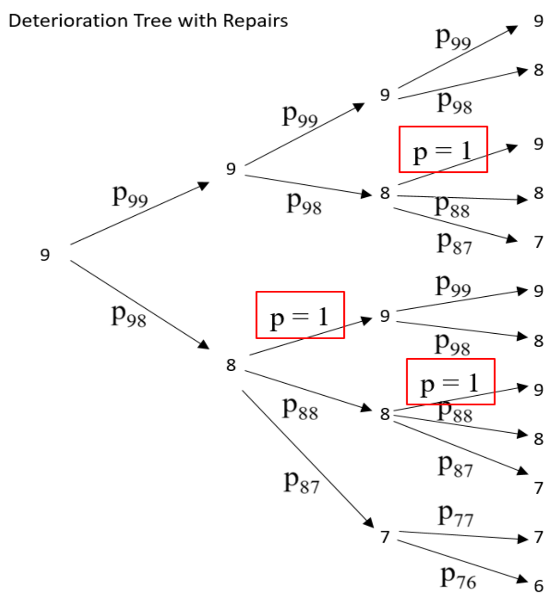


Figure 4.5 Deterioration Tree with Repairs

In this example, we see an expected improvement probability of 1 for any implied repairs. Once repairs are introduced, with an infinite budget a Markov chain decision tree could be infinite as there would be sequences within the chain, also referred to as branches, that will never lead to the bridge failing. This is rather unrealistic because although it would be ideal, the funding necessary to constantly maintain a bridge at like-new condition would result in zero funding for the remainder of the structures in the bridge network, if that. Therefore, a cusp is required to act as a cutoff. In this study a pre-determined service life as discussed in previous chapters is used. For example, if the bridge was intended to provide a 50-year service life, with two-year intervals we would have 25 steps within the Markov-chain. Some branches would have reached failure prior to that, with a minimum of nine intervals if the claimed deterioration assumptions are applied and the model must step through each condition state until reaching CS 0. CS 0 in Chapter Two was shown to be considered NBI's "Failed" condition state and signifies a structural failure. Iowa DOT however can apply restrictions that leave a large safety margin by not waiting for "imminent" failure and instead declaring a limit for acceptable condition state, otherwise known as a condition failure where a "structure fails to meet its main function requirements" (Van Noortwijk and Frangopol 2004).

4.5. Decision Trees

A decision is the opportunity for an analyst to choose between multiple alternatives and their respective course of actions (Hawk 2003). Figure 4.5 depicts that from each existing condition state, there will be predetermined options. Suppose that at CS 9, available options are to implore a preservation activity (PA) or follow the "Do Nothing" approach, noting repair methods cannot bring the CS to a higher rating and are therefore not an option. Each decision is followed by the possible resulting condition states, so each option "splits" into multiple subalternatives (Hawk 2003). Any repairs or preservation activities will have definite probabilities of the resulting condition states as energy and resources are being inputted to guarantee a desired condition state. The decision to "Do Nothing," allows the bridge or component to continue to deteriorate and follow the estimated transition probabilities. Figure 4.6 can be referenced as a demonstrative example.

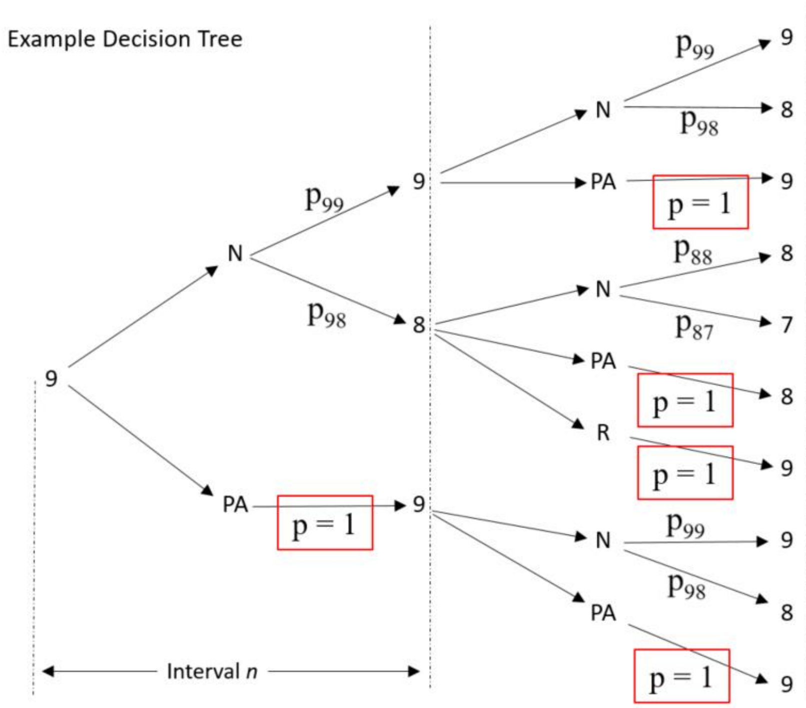


Figure 4.6 Decision Tree

Here also, there are two steps in one interval, the decision and the resulting condition states. The decision to make a repair or perform a preservation activity ensures a probability of 1 to a pre-determined condition state. Each decision to actively participate in the maintenance of the bridge is associated with a cost. The mentioned Monte Carlo simulation will input a random value from the established probability distributions of these costs. Additionally, as bridges deteriorate into lower condition states with age, we can assume the extent of damage is greater and the cost of the repair or activity is expected to increase ((Mao and Huang 2015), (Transportation Equity 1998)). Mahmound et al.'s (2018) perspective is to determine the probability of the necessity for repairs and replacements based on the age of the bridge which differs from our prediction of deterioration method. They do recognize that the "do nothing" approach early in a bridges lifetime is acceptable as "most of its deterioration is minimal and non-serious with respect to the serviceability of the bridge" whereas later in the service life, repair methods will be more frequently necessary to maintain a serviceable condition state of the bridge, increasing the annual costs(Transportation Equity 1998)]. This can be applied to the expected user costs imposed by the implementation of maintenance activities. The greater the deterioration, the larger the project to repair, and the greater the effects are on the public user, increasing user costs. Decision trees allow us to see and compare the timing of maintenance activities. Not only do they effect the deterioration, but each future cost must be appropriately discounted as discussed in Chapter Two. Dependent of the discount rate, timing these activities can have large effects on the final LCC. Timing effects user costs as well. As populations grow, increase in ADT can be expected and so more users are affected by each disruption in traffic, further increasing user costs. The multitude of sequences within a Markov chain will therefore be beneficial towards creating efficient planning of bridge activities. It must be stated that a year with the decision to "do nothing" do not imply a year with no costs. For example, inspection costs are still expected as current FHWA regulations require the inspection of federally funded bridges every two years.

All costs are subject to the variability due to material type, environment, location, as well as other aforementioned factors. The Monte Carlo simulations will essentially reproduce the Markovian chains for a desired number of iterations and change the costs inputs. Each chain's cost inputs will be random and the respective cost probabilities will be a result of the combined variability and the deviation from each costs' most probable value within their own probability distributions.

4.6. Optimal Solution for maintenance activities

The goal of implementing probabilistic LCCA is ultimately to be as efficient as possible with maintaining Iowa's bridges as budgets get tighter but demand continues to rise. Choosing the most cost-effective sequence in the MCMC simulations requires some basic criteria to be established. Each Markov Chain will have hundreds of branches that represent possible sequences, all with unique LCCs. Some will be outrageously expensive as bridges will be kept in like-new condition and others will be inexpensive as they followed a do-nothing approach and allowed the bridge to deteriorate until it reached a failed condition. We want to choose the sequences that provide the desired service life, and end at the desired condition (Van Noortwijk and Frangopol 2004). Iowa DOT would need to specify the desired outcome, for example CS 4. Ending at a desired CS would mean all funding put into the bridge was used to its fullest extent. Therefore, we want to pick the sequence in each Markov Chain that ends at a desired CS, at the specified service life, and is has the lowest LCC.

4.7. Deterioration and Decision Interval

It is stated that the interval for deterioration estimation and the interval to be used in the decision trees is two years. The 24-month inspection interval that currently is maintained by Iowa DOT is the main inspiration for this. With more than 4,000 bridges in the state, inspecting every year instead of being able to divide that total in half, would be a large commitment and a cost-benefit analysis would be required to justify the large change. Khatami (2018) investigated the effects of differences in inspection intervals, creating transition probabilities between four condition states, with an individual transition matrix for 1, 2- and 3-year inspection intervals.

The transition matrices can be found at the end of this chapter. Their conclusion was the "probability of remaining in State 1," that being the best condition state for the study, "decreases as the inspection interval increases" crediting the "continuous deterioration processes" (Khatami et. al. 2016). It can be assumed that with larger durations of time between inspections, damage can go unnoticed longer and accelerate the deterioration of the bridge. So again, at this time we suggest use of a two-year interval that will reflect the existing data while not imposing additional annual inspection costs on the agency nor accelerating deterioration. Lastly, some preventative maintenance strategies that occur on one-year cyclical intervals will need to be accounted for in deterioration models.

CHAPTER 5. MATLAB BASED APPLICATION (LCCAM) DEVELOPED FOR CHOICE OF OPTIMAL MAINTENANCE ACTIVITY

5.1. Introduction

For this project, a MATLAB based application was developed to use as an introductory tool for LCCAM. Utilizing this chapter as a guide, a user will receive both a detailed explanation of the application as well as walk-through examples to demonstrate the application's ability to choose the optimal maintenance activity for the bridge in question. At each step of the application, users can compare the LCCAMs of various maintenance interventions to determine the most cost-effective construction plan for their bridge. The LCCAMs of each maintenance activity are determined using maintenance cost, service life extension, and the improvement of the condition state. Utilizing this data, the application suggests to the user the optimal maintenance activity for their project. This chapter will cover each component of the MATLAB application from the application's installation process, to guidelines for user input, to evaluation of optimal maintenance activity for bridge decks.

5.2 Installation guidelines

5.2.1 File Package to Launch

Files for Standalone Package
LCCAM.exe
MyAppInstaller_web.exe

5.2.2 Installation

Once the zip file has been downloaded and its contents extracted to the computer, the user must run the MATLAB Runtime installer, MyAppInstaller_web.exe. It is necessary to have administrator rights for this step. The LCCAM application can then be launched. For more information or troubleshooting, refer to the “Package and Distribute” section of MATLAB’s Compiler documentation.

5.3 Input Guidelines and step by step Execution

Proceed using the following steps in order to properly use the application.

Step 1: Upon executing the LCCAM application, the deterioration curve for the Iowa bridges over a 100-year period is displayed. This deterioration curve is formulated using data from Iowa’s 24,000 bridges evaluated using stochastic models. The average age of a bridge deck’s condition rating is used to determine the transition probabilities, as explained in Chapter 5’s section of survival functions. The purpose of this curve is to visually inform the user of expected deterioration rates and may therefore influence maintenance activity planning.

Step 2: Step 2 is the first point of user input requested by the application. Users must input the bridge deck’s current condition rating that must be within a preset range of 9 to 4. Previous sections have explained that a condition rating less than 4 requires more direct attention to repair the bridge to be user worthy.

Step 3: In Step 3 the application requests the user to input the condition state that will act as the triggering mechanism to deploy desired maintenance activities. To elaborate, say the bridge deck’s condition rating is currently an 8 and the user wants the maintenance to be performed once the deck rating reaches 6.

Step 4: In Step 4, the application displays a menu of all available maintenance options for the condition rating entered in Step 3. The user has the option to choose an individual maintenance activity or to compare multiple options. Again, these options are dependent upon the inputted condition rating of the deck in Step 3 and therefore help display how options can be limited by user choices. Example menus of maintenance activities can be seen in Figures 5.1-5.4.

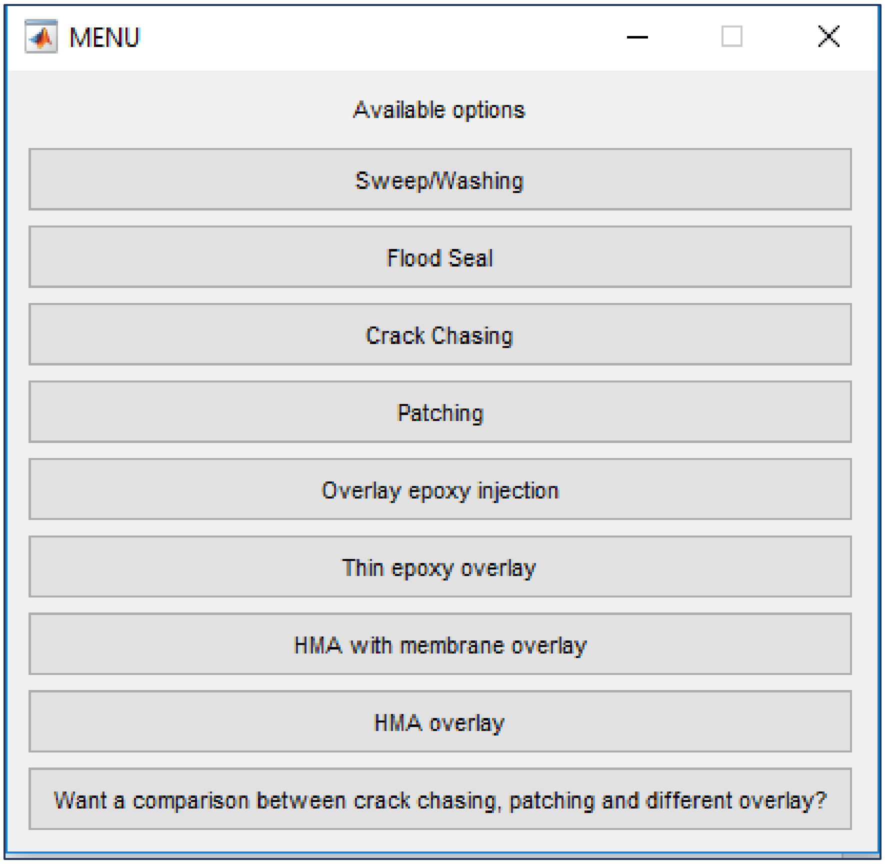


Figure 5.1: Menu for condition rating 7-9

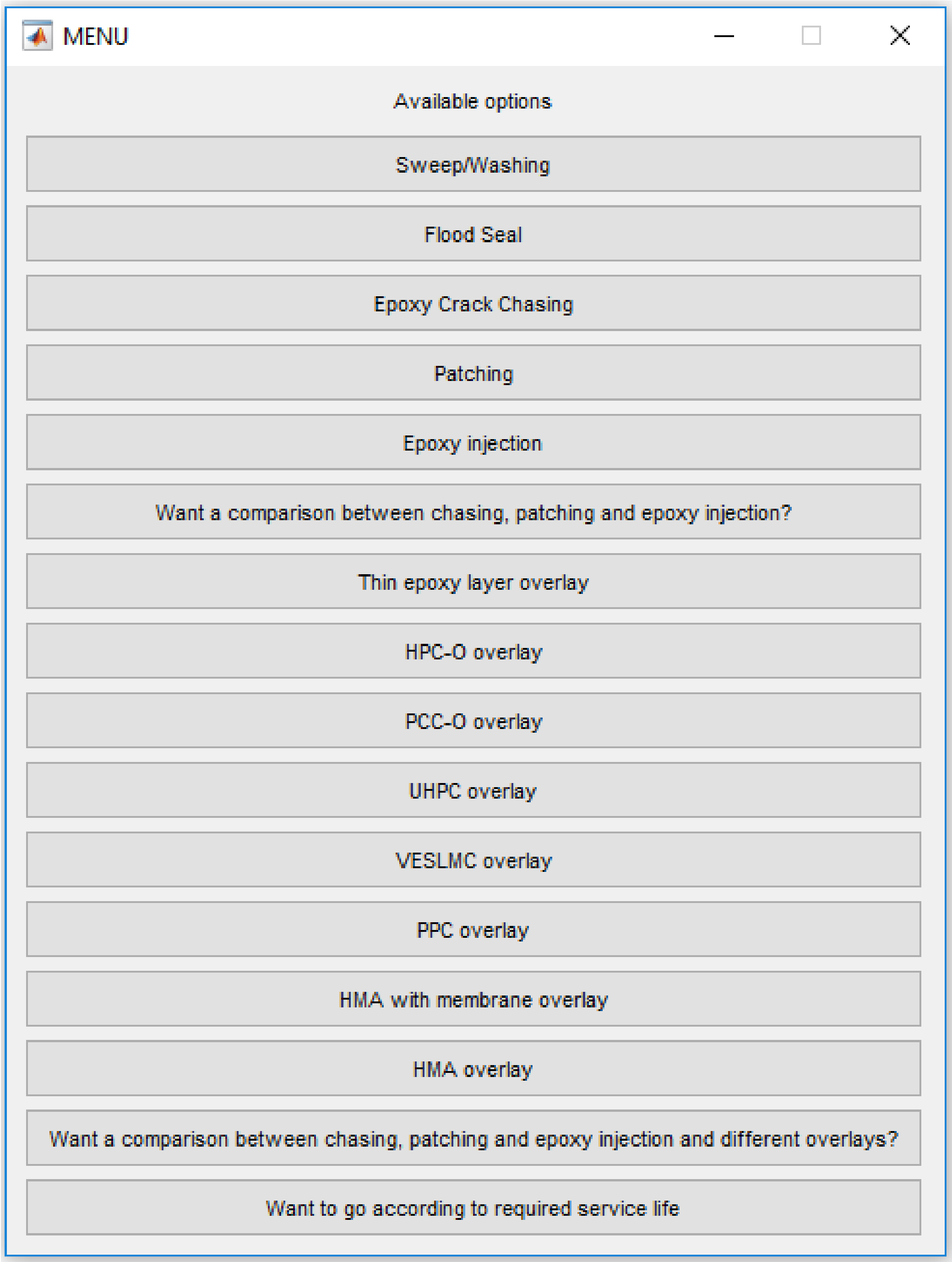


Figure 5.2: Menu for condition rating 6

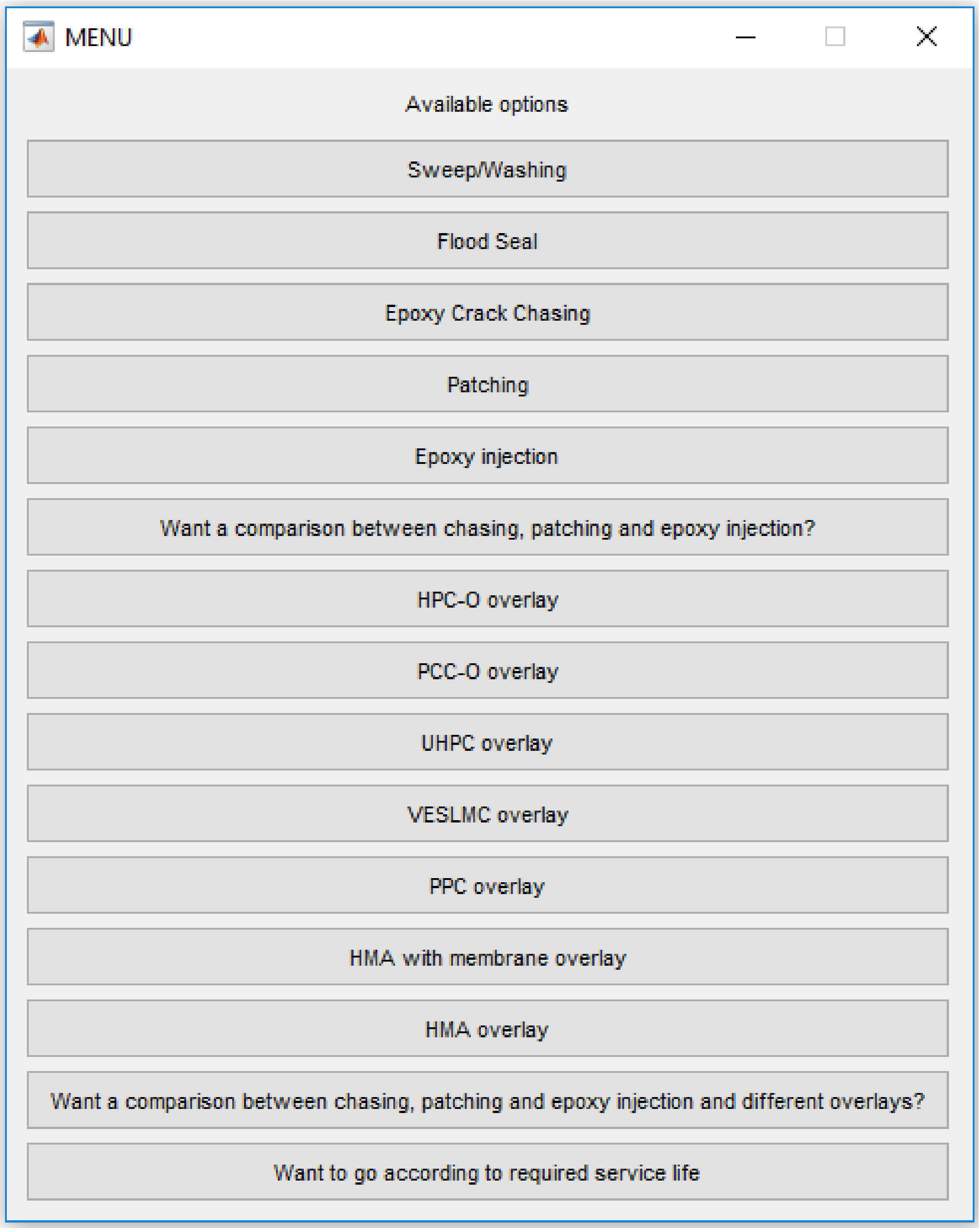


Figure 5.3: Menu for condition rating 5

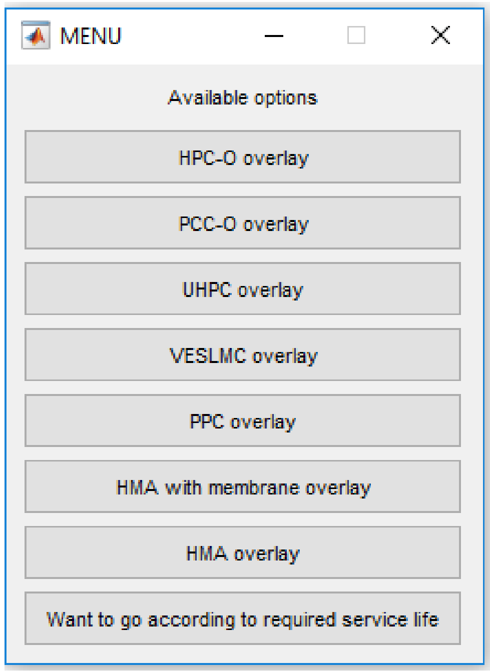


Figure 5.4: Menu for condition rating 4

Step 4.1: Any option chosen will prompt the application to produce another menu showing the salient options associated with each maintenance activity. This step provides the user with data on the costs and service life extensions of these each option. An example would be the menu displayed for the "Sweep/Washing" option shown in figure 5.5. The user can then understand the associated implications of any choice to which they can either continue with the current selected option or return to the main menu and choose another activity.

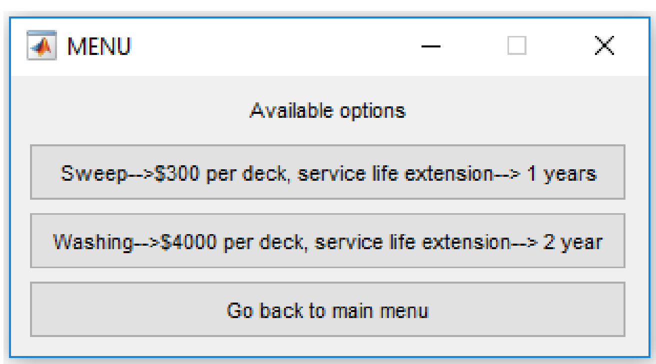


Figure 5.5: Menu showing salient points of Sweeping/Washing option

Step 4.1.1: Proceeding with the users selected maintenance activity, the application requires additional data on the cost and the final service-life extension plan. These inputs cover the number of decks or deck area, the required number of maintenance actions, and the intended interest rate. Deck area and deck quantity are differentiated as some cost values are per unit deck while others are per deck area. As explained in prior chapters, the interest rate accounts for the monetary value of time in the cost analysis. The default interest rate is taken as 4% annually, unless otherwise stated by the user.

Step 4.2: If the user chose to select comparison data for multiple maintenance activities as mentioned in step 4, the application will next display the salient points of each maintenance option in tabular form to easily visualize key differences and similarities between those selected. Figure 5.6 demonstrates the comparison feature of the application. After reviewing this data, users can choose to continue with their selected activity data or return to the main menu and explore further maintenance activity comparisons as shown in Figure 5.7.

	Cost_LinearOrSquareFoot	Life_Extension	CR_Improve
Epoxy Crack Chasing	'10'	'5'	'No'
Ashpalt Patching	'10'	'2'	'No'
Concrete Patching	'60'	'5'	'may improve by one'
Epoxy injection	' 8'	'7'	'may improve by one'

Figure 5.6: Application display of salient points comparison

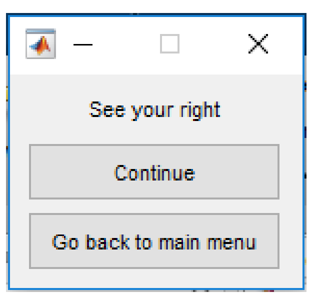


Figure 5.7: Menu to continue with current selection or return to main menu

Step 4.2.1: If the choice to move forward with the comparison option is selected from Step 4.2, the user will need to input information similar to that seen in step 4.1.1. This will allow for the application to output the results in terms of total cost, service life extension and condition rate improvement for each maintenance activity being compared, as seen in Figure 5.8.

	Total_CostinDollars	Life_Extension	CR_Improve
Epoxy Crack Chasing	' 19057.3081'	'10'	'No'
Ashpalt Patching	'39223.37562'	' 4'	'No'
Concrete Patching	'228687.6972'	'10'	'may improve by one'
Epoxy injection	'14964.48143'	'14'	'may improve by one'

Figure 5.8: Total cost comparison between different maintenance options

Note: Only select maintenance actions provide condition rate improvement and service life extension. These are then coupled with an outputted deterioration curve for the deck as seen in. Figure 5.9. The figure depicts a typical deterioration curve for two consecutive maintenance actions initiated as the deck reaches a condition rating of 5. The implementation of these 2 maintenance activities projects a condition rate improvement of 2 points.

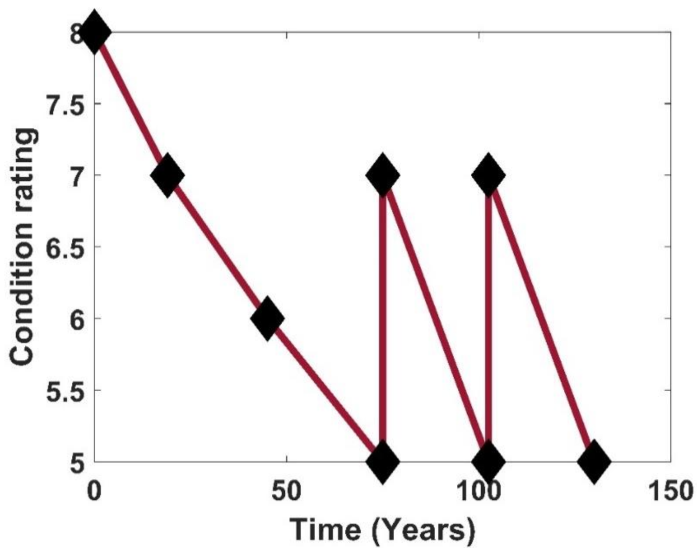


Figure 5.9: Deterioration curve with maintenance actions

5.4 Required service life option

The LCCAM application incorporates another feature per condition rating, seen in Figures 5.2-5.4 as the option "want to go according to required service life." This option's allows users to input the desired service life extension in years in order to project the most cost-optimal method to increase the service life by the desired number of years. Users can then assign specific maintenance materials for the analysis or allow the application to compare all associated materials to determine the best available options; see Figure 5.10. Selection of specific materials enables the user to exclude known unavailable or inapplicable materials from the analysis. If the user wishes to pick specific materials, a new menu will be displayed with a list of materials to choose from as shown in Figure 5.11. The user can select a singular material or, by depressing and holding the control key, multiple materials can be selected. Each will be considered when analyzing for the optimal solution for the set required service life.

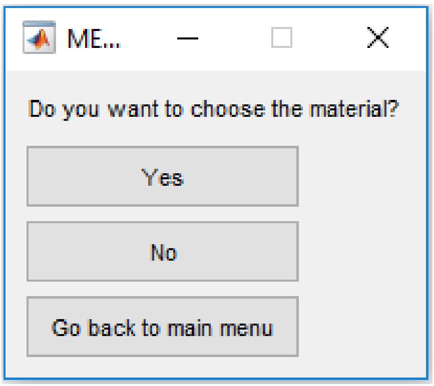


Figure 5.10: Menu for choice regarding materials to be used in analysis

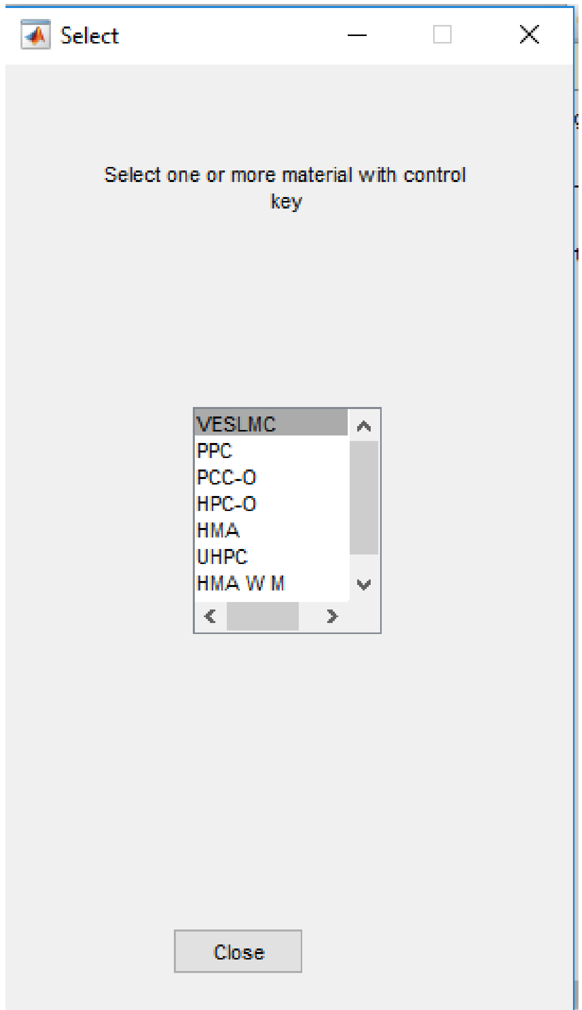


Figure 5.11: List of available materials

Results of the analysis are then presented to the user as 3 choices for the required service life extension. First, each material is considered as the only material in the analysis and an optimal solution for required service life extension is calculated for the individually selected material. An example of this first choice is shown in Figure 5.12. This choice is to determine if the use of a fixed material or maintenance activity may require the activity to be repeated multiple times to reach the required service life. The results given are within ±5 years of required service life extension years.

	Row_Num	Total_Activities	Dollars_Cost	Life_Extension
VESLMC	1	2	1248	60
PPC	2	2	1405	60
PCC-O	3	2	1462	55
HPC-O	4	2	1666	55
HMA	5	10	3352	50
HMA W M	6	5	4115	50
UHPC	7	2	5462	60

Figure 5.12: Results for required service life extension with one material

The second option considers two materials or maintenance activities to be repeated as necessary to provide the required service life extension; see Figure 5.13.

	Row_Num	Total_Activities	Dollars_Cost	Life_Extension
VESLMC and PPC	1	2	1304	60
VESLMC and PCC-O	2	2	1315	58
VESLMC and HPC-O	3	2	1387	58
PPC and PCC-O	4	2	1416	58
PPC and HPC-O	5	2	1488	58
PCC-O and HPC-O	6	2	1537	55
PCC-O and HMA and PCC-O	7	3	1703	60
VESLMC and UHPC	8	2	2747	60
PPC and UHPC	9	2	2848	60
PCC-O and UHPC	10	2	2967	58
HPC-O and UHPC	11	2	3089	58
HMA and UHPC and HMA	12	3	3942	40

Figure 5.13: Results for required service life extension with two materials

Finally, choice three considers three materials or maintenance activities to be repeated as necessary to provide the required service life extension; see Figure 5.13.

	Row_Num	Total_Activities	Dollars_Cost	Life_Extension
VESLMC and HMA and HMA W M	1	3	1670	45
PPC and HMA and HMA W M	2	3	1771	45
PCC-O and HMA and HMA W M	3	3	1835	43
HPC-O and HMA and HMA W M	4	3	1962	43
HMA and UHPC and HMA W M	5	3	4278	45

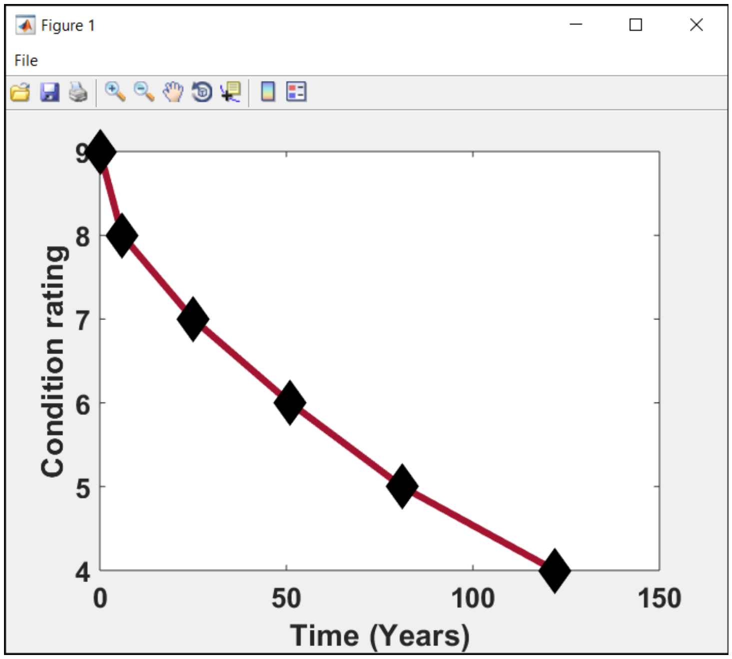
Figure 5.14: Results for required service life extension with three materials

The results presented in Figures 5.12-5.14 are projected based upon the goal of extending the service life for 50 years. If the required service life extension has the ability to be achieved with less than 3 maintenance actions, the application will output only two choices using one to two material options. The final input required of the user for the application is whether the user would like to generate deterioration curves for their maintenance activity. Again, the user can select multiple inputs for the deterioration curve.

5.5 Summary

This chapter was included to inform users how to execute the MATLAB based application LCCAM. As the first version of the next generation life cycle cost analysis tool, the program was centered around bridge decks. As data gathering continues, the application will grow in time and constantly evolve to meet the ever-changing needs of Iowa DOT. The following appendix section has another brief example to display the user interface of the application prompt.

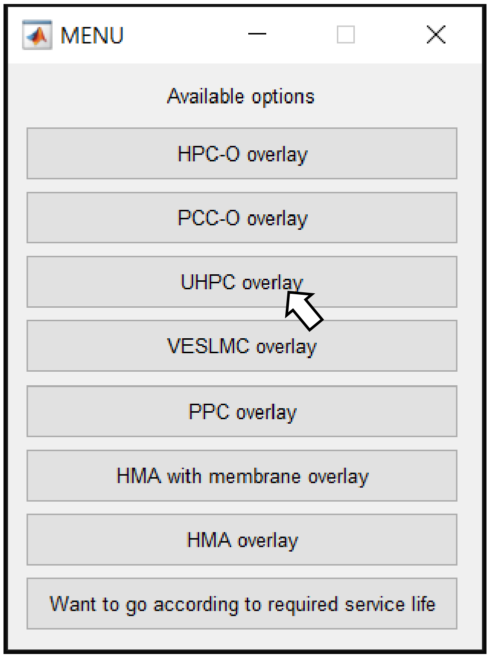
5.6 Appendix




```
This is the deterioaration curve obtained for IOWA bridges, press enter once you have gone through it:

Please enter current condition rating of deck between 4-9:
6
Please enter condition rating after which you want maintenance (should not be more than current conidtion rating)
4
Please enter total area in square yard
24000
Please enter total number of maintenance actions
2
Default interest rate is chosen as 4% annually,
 enter new interest rate if you want to change it otherwise enter 0
0
Total cost will be $678619 with an annual interset of 4 percent
Total service life extension will be 55 to 65 years

 Thank you
```


MENU
Available options
HPC-O overlay
PCC-O overlay
UHPC overlay
VESLMC overlay
PPC overlay
HMA with membrane overlay
HMA overlay
Want to go according to required service life


MENU
$350 per square yard, service life extension--> >=30 years
Continue
Go back to main menu

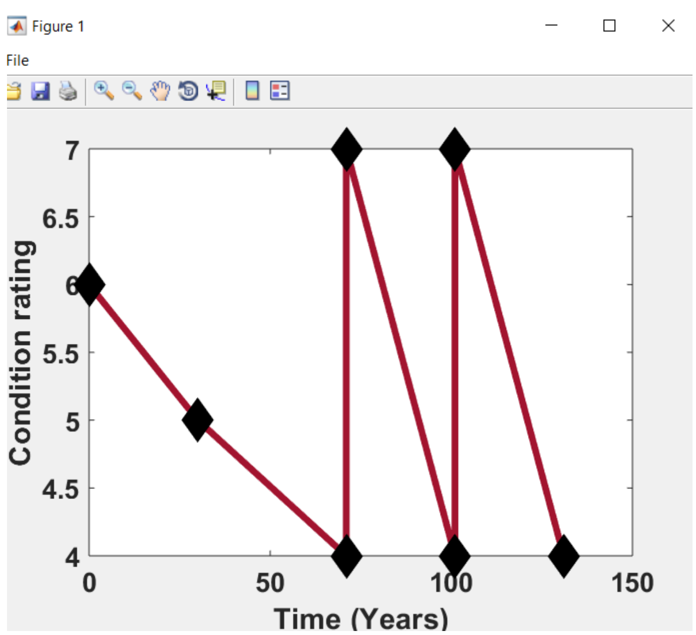


Figure 1
File
Condition rating
7
6.5
6
5.5
5
4.5
4
0
50
100
150
Time (Years)

CHAPTER 6. SUMMARY, FUTURE RECOMMENDATIONS AND CLOSING THOUGHTS

The purpose of this report is to provide background and direction in the steps of implementing a comprehensive Life Cycle Cost Analysis tool for bridges in Iowa. It was established that the lowest initial cost does not necessarily represent the lowest LCC and the lowest LCC is not always a realistic expectation. LCCA provides those tasked with asset management critical information to aid in their decision making for maintenance and repair schemes.

Bridge data was sourced from experts in the field, Iowa's inspection database system SIIMS, and the National Bridge Inventory Database to paint a clear perspective of Iowa's ability to supply the necessary data for a stochastic approach to LCCA. This approach is intended to include risk-analysis in asset management that is required of the MAP-21 Act of 2012. The use of Monte Carlo simulations and Markov-Chain models is suggested for preparing the Iowa-specific deterioration and decision-making models. Iowa DOT's current implementation plan is to focus efforts of LCCA on bridge decks across the state until sufficient data is available to expand the model to the remaining bridge components. Decks were chosen due to their comparatively abundant amount of data and information. This methodology takes into consideration the deterioration rates specific to Iowa bridge decks on a two-year interval and aims to predict the agency and user costs associated with preserving, rehabilitating, and repairing the bridges. Markov-chains will be used to model the deterioration and create decision trees that will provide LCCs for each alternative as well as the respective ranges and probabilities of their occurrence as opposed to singular values. Monte Carlo simulations will apply the uncertainties in maintenance and repair costs, with the potential to add other uncertainties as data evolves.

Understanding of the variability of future investments will give the system an advantage over Iowa's current system of relying on project selection through the lowest bid or estimated initial costs. The proposed method is a tried and proven system among existing literature and has the capability to produce clear and realistic results. The system must be tailored to adapt to Iowa's needs and information. After significant data searching and observation of Iowa's resources, future recommendations and needs for proper implementation will be addressed in the remainder of this chapter.

6.1. Cost Data: Crew vs Bids

Chapter Two and Three address the need to gather cost data for projects and their alternatives. Through expert elicitation this study was able to gather some cost figures, however for probabilistic LCCA this fails to provide any insight on uncertainties within these costs. We propose the following steps in obtaining further cost information.

District maintenance crews and maintenance engineers can be individually interviewed in regard to their best estimates of maintenance unit costs. These guesses can be arranged to create probability distributions and integrated in the Monte Carlo simulations as a parameter of uncertainty for activities that are expected to be performed in-house. Each of Iowa's six districts should be interviewed.

Iowa DOT documents all project bid cost estimations. This historical bid data can be sorted and used to create probabilistic distributions for each specific maintenance and rehabilitation activity's expected costs. This will provide cost insight to projects that are expected to be contracted out as opposed to performed in-house, increasing the accuracy of the model. Costs of bids will need to be converted to represent a common year. A benefit to this can be the potential to compare the costs imposed by contractor's vs in-house crews per maintenance and repair activity which may lead to more efficient delegation of these tasks.

Additionally, the study can look outwards and broaden their range by conducting interviews and bid data analysis of surrounding states. The obtained cost information could enhance cost distribution data as well as benefit both states in their efforts of project cost estimation.

6.2. Project Scaling

This section is to suggest the probable scaling abilities of the proposed LCCA tool. We see the chance to expand the tools future capabilities and versatility by using data types to scale the tool to the intended user. As will be explained, day to day maintenance can be categorized separate from large rehabilitation projects. District maintenance engineers and crews can choose when to address basic preservation and maintenance work whereas large rehabilitation and rebuilding projects must go through a rigorous process before implementation. A tool that can provide results applicable to both state level and maintenance garage level would be beneficial to those at all levels and may simplify bridge management.

Chapter Three discussed available data and data sources. SIIMS gives us access to a plethora of inspection information for Iowa bridges. The FWHA mandated NBI data available will be analyzed and observed trends can be determined to improve the LCCA tool and understand the effects of maintenance activities. NBI item 58, Deck Condition Rating is one of the main focuses of this study and provides an overall assessment of the bridge component as a whole. With NBI item 58, we can understand the type of damage present on the deck, but not necessarily the amount. We believe this overall assessment can be utilized for larger scale maintenance and rehabilitation project planning as it removes more of the minute variables that may arise when considering bridge condition, and also can be used to determine the overall bridge sufficiency rating. These sufficiency ratings are used by Iowa DOT to rank and prioritize bridge maintenance and rehabilitation projects fir their (5) year budget planning. Therefore, by using Iowa's bridge inventory database we can create trends of ratings for the hundreds of bridges in each of the six districts. These trends will display the effects that aging, environmental conditions and use have upon the structure. These can then be used to create the transition probability matrices seen in Chapter Four to predict deterioration and create Markov-Chain decision trees. This then can be expanded to the remaining main structural components of the bridges, NBI items 59-62.

SIIMS stores element level condition states. The elements, as explained in Chapter Three consist of the NBE and BME lists. Tracking of element level condition states has only been part of Iowa's inspection procedure since 2004 for Iowa and therefore sufficient Iowan data to produce accurate trends and transition probabilities over the lifespan of a bridge does not exist at the present moment at the element level. We believe that it is necessary for Iowa to continue recording this data so that it can be implemented in the tool in the future. Using element level data will increase the accuracy of predictions and provide more realistic inspection-based maintenance decisions. The element level condition ratings have the standard number of condition states (1-4) with associated qualities of the total quantity present for that individual bridge. The potential transition probabilities produced with sufficient data would be valuable for DOT district maintenance crews that must make daily decisions on which maintenance, and preservation activities to perform, and the effects of these decisions. Timing with such decisions is a large factor in final LCCs. A LCCA tool that provides insight on minor work, accounting for timing within the bridge's lifespan would greatly benefit crews as they can then plan their work accordingly.

6.3. Salt Use among Districts

Briefly touched upon in Chapter Four was the difference in the extent of salt and chemical de-icers in the Iowa DOT districts. Use of these salts have increased considerably in the recent decade, from a statewide total of 627 kiloton in 2010, to 810 kiloton in 2017, and with that so has the amount reaching Iowa's bridges (Khatami et. al. 2016). Through our research we obtained de-icing figures for Iowa, breaking them down by district for comparison. We propose future efforts to compare district-based transition probabilities with the district-based salt use to understand potential correlations with salt use or de-icer types, environmental exposure conditions and the deterioration of bridge components. Previous studies have sectionalized state areas into specific exposure regions, grouping areas with similar environmental stressors ((Ertekin et. al. 2008), (Bales et. al. 2018)). Ertekin et al. divided the United States into nine climatic regions using the National Climatic Data Center's information. They further subdivided these regions by producing individual models based on different bridge superstructure types that represented the majority of bridges in that region and this resulted in a total of 18 usable deterioration models for the nations bridges (Ertekin et. al. 2008). Similar work can be accomplished with Iowa's six districts. This would produce area specific predictions, increasing the models' accuracy. Future analysis of the district-based transition probabilities can then help teach more effective maintenance techniques and aid in budget allocation across the state.

6.4. Criteria for Project Selection

Future continuation of this work will have to address project selection for optimization of maintenance schemes. Interviews with Iowa DOT representatives may provide greater insight as to what could be the deciding factor between two similar alternatives. We understand timing of costs can be a large influence on the final decision as agencies must understand the potential cost occurred each year by a bridge to properly sort budgets. Studies have proposed the use of not only net present value through discounting but also equivalent uniform annual costs to depict expected annual costs over the lifetime of a bridge (Hawk 2003). Again, due to budget restraints, this may be the deciding factor in choosing maintenance schemes. Future consultation with Iowa DOT bridge maintenance engineers could then sculpt the tool to provide results in preferable context that allows for the most effective and efficient final decision making.

6.5. Integration with AASHTOWare BrM

Lastly, this report and common to those reference believe in the importance of integration of LCCA with BMS. The mating of the two systems could benefit agencies and lead to swifter and smoother assimilation of the system within Iowa DOT personnel. Close work and interviews with DOT representatives can aid in future provisions of this project as they can establish the user-interface that would best suit them and where it can be added to the BMS software, AASHTOWare BrM that they currently use. Additional inspection data requirements can be dictated and that then inputted to AASHTOWare to act as a crucial data source for the proposed LCCA tool.

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