Development of a Life-Cycle Cost Analysis Tool for Improved Maintenance and Management of Bridges

Final Report
June 2020

BRIDGE ENGINEERING CENTER

IOWA STATE UNIVERSITY
Institute for Transportation

Sponsored by
Iowa Highway Research Board
(IHRB Project TR-737)
Iowa Department of Transportation
(InTrans Project 18-632)

About the Bridge Engineering Center

The mission of the Bridge Engineering Center (BEC) is to conduct research on bridge technologies to help bridge designers/owners design, build, and maintain long-lasting bridges.

About the Institute for Transportation

The mission of the Institute for Transportation (InTrans) at Iowa State University is to develop and implement innovative methods, materials, and technologies for improving transportation efficiency, safety, reliability, and sustainability while improving the learning environment of students, faculty, and staff in transportation-related fields.

The preparation of this report was financed in part through funds provided by the Iowa Department of Transportation through its "Second Revised Agreement for the Management of Research Conducted by Iowa State University for the Iowa Department of Transportation" and its amendments.

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
IHRB Project TR-737		

4. Title and Subtitle Development of a Life-Cycle Cost Analysis Tool for Improved Maintenance and Management of Bridges	**5. Report Date** June 2020
	6. Performing Organization Code
7. Author(s) Alice Alipour (orcid.org/0000-0001-6893-9602), Behrouz Shafei (orcid.org/0000-0001-5677-6324), Andrew Mock (orcid.org/0000-0003-3120-4359), and Kanta Prajapat (orcid.org/0000-0001-8661-4369)	**8. Performing Organization Report No.** InTrans Project 18-632
9. Performing Organization Name and Address Bridge Engineering Center Iowa State University 2711 South Loop Drive, Suite 4700 Ames, IA 50010-8664	**10. Work Unit No. (TRAIS)**
	11. Contract or Grant No.
12. Sponsoring Organization Name and Address Iowa Highway Research Board Iowa Department of Transportation 800 Lincoln Way Ames, IA 50010	**13. Type of Report and Period Covered** Final Report
	14. Sponsoring Agency Code IHRB Project TR-737

15. Supplementary Notes

Visit https://intrans.iastate.edu/ for color pdfs of this and other research reports.

16. 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 respective portions of the National Highway System (NHS). Life-cycle cost and risk management analyses must be included in a state's TAMP. As defined in the 1998 Transportation Equity Act for the 21st Century (TEA-21), life-cycle cost analysis (LCCA) is "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, and reconstruction, rehabilitation, restoring, and resurfacing costs, over the life of the project segment."

The main objective of this research project was to develop a LCCA tool for Iowa's bridges based on survival analysis of condition ratings. This tool was designed to cover the most common types of bridges in Iowa while integrating historical data from maintenance crews, contractors, and past inspections into the predictive models that account for the costs of maintenance and repair during a bridge's service life.

The tool developed in this project provides a user friendly way to evaluate and compare maintenance costs for bridge decks over the lifetime of a bridge. With this information, transportation investment decisions can be made in consideration of all of the maintenance costs incurred during the period over which the maintenance alternatives are being compared.

17. Key Words	18. Distribution Statement
bridge condition ratings—bridge decks—bridge maintenance—life-cycle cost analysis	No restrictions.

19. Security Classification (of this report)	20. Security Classification (of this page)	21. No. of Pages	22. Price
Unclassified.	Unclassified.	93	NA

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

DEVELOPMENT OF A LIFE-CYCLE COST ANALYSIS TOOL FOR IMPROVED MAINTENANCE AND MANAGEMENT OF BRIDGES

Final Report
June 2020

Principal Investigator
Alice Alipour, Structure and Infrastructure Engineer
Bridge Engineering Center, Iowa State University

Co-Principal Investigators
Behrouz Shafei, Structural Engineer
Bridge Engineering Center
Institute for Transportation, Iowa State University

Research Assistants
Andrew Mock and Kanta Prajapat

Authors
Alice Alipour, Behrouz Shafei, Andrew Mock, and Kanta Prajapat

Sponsored by
Iowa Department of Transportation and
Iowa Highway Research Board
(IHRB Project TR-737)

Preparation of this report was financed in part
through funds provided by the Iowa Department of Transportation
through its Research Management Agreement with the
Institute for Transportation
(InTrans Project 18-632)

A report from
Bridge Engineering Center
Iowa State University
2711 South Loop Drive, Suite 4700
Ames, IA 50010-8664
Phone: 515-294-8103 / Fax: 515-294-0467
https://intrans.iastate.edu/

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGMENTS

The authors would like to thank the Iowa Highway Research Board and the Iowa Department of Transportation for sponsoring this research. The authors also would like to thank the technical advisory committee for their time and effort working on this project.

EXECUTIVE SUMMARY

Background

The 2012 Moving Ahead for Progress in the 21st Century (MAP-21) Act requires states to develop and implement a transportation asset management plan (TAMP) for their portions of the National Highway System (NHS). MAP-21 specifically mandates that each state's TAMP includes life-cycle cost (LCC) and risk management analyses.

To calculate the LCCs of its bridges, the Iowa Department of Transportation (DOT) currently uses a type of life-cycle cost analysis (LCCA) that involves determining the expected number of iterations of 10 typical maintenance activities over a bridge's lifetime. The number of iterations and their costs are fixed, but the model is tailored to the three main bridge types in Iowa: prestressed girder, steel girder, and reinforced concrete slab.

While the costs and iterations of these maintenance activities are based on experience, they are not directly tied to historical performance data. More importantly, the current model does not include uncertainty or risk in the input variables.

In contrast, risk-based, probabilistic LCCA relies heavily on historical bridge data to determine the probabilities of various costs that may occur throughout a bridge's lifetime and the potential uncertainties in those costs. Such a model can provide a more realistic understanding of the costs necessary to maintain a bridge and the ways different strategies may affect a bridge over its service life.

Problem Statement

To help the Iowa DOT comply with MAP-21's risk management requirements, risk must be integrated into Iowa's LCCA method to develop Iowa-specific deterioration models and thereby determine maintenance and repair needs.

Objective

The objective of this project was to develop a user friendly LCCA software tool for Iowa's bridges based on a survival analysis of bridges at various condition ratings.

The tool was to cover the most common types of bridges in Iowa while integrating historical data from various sources into predictive models that account for the maintenance and repair costs incurred during a bridge's service life.

Research Description

The LCCA tool developed in this project focuses on bridge decks, with the possibility of potential extensions in subsequent implementation phases. Bridge decks were chosen due to the relatively abundant amount of data available for this component.

Bridge data were sourced from experts in the field, Iowa's Structure Inventory and Inspection Management System (SIIMS) database, and the National Bridge Inventory (NBI) database.

To create the software tool, an LCCA methodology was first developed that considers the deterioration rates specific to Iowa bridge decks over two-year inspection intervals and aims to predict the agency and user costs associated with preservation, rehabilitation, and repair.

The LCCA methodology involved determining the probability that a given bridge component will transition from one condition state to another over a certain period. To obtain this probability, more than 10 years of historical data were used to determine the hazard rates associated with different condition states and estimate hazard functions. Survival or failure probability distributions for different condition states were then derived, which yielded the average ages of condition ratings.

The software tool developed in this project is a MATLAB-based application called LCCAM. The application is built around a deterioration curve for Iowa's bridges that was derived using the LCCA methodology described above and data from 24,000 bridges in Iowa. The deterioration curve shows bridge deck deterioration over a period of more than 100 years.

Possible ways that LCCAM can be utilized with other bridge management tools, such as SIIMS and AASHTOWare Bridge Management (BrM), were also investigated.

Key Findings

- LCCAM is a user-friendly software tool that allows a user to select the optimal maintenance activity for a given bridge deck by inputting the bridge deck's current condition rating and the threshold rating at which maintenance is required.

- Based on the condition rating inputs, LCCAM presents a menu of all available maintenance options, from which the user can either select a specific activity or compare different activities.

- LCCAM also allows the user to determine the optimal maintenance activity given a required service life improvement.

- The maintenance options in LCCAM are compared in terms of the cost of the maintenance activity, the extension in service life, and the improvement in condition rating.

- LCCAM is able to integrate Iowa's available data and adapt as more data are added over time. As the database grows, so will the calculated confidence levels of the tool's output, allowing Iowa DOT and county engineers and planners to select the most cost-effective alternatives.

- LCCAM allows the user to input the average age of each condition rating as a variable instead of using the deterioration curve included with the application, thereby allowing AASHTOWare BrM-based condition rating predictions to be integrated into LCCAM.

Recommendations for Future Research

Future work on LCCAM can involve determining project selection criteria that optimize maintenance schemes. Consultations with Iowa DOT representatives may provide greater insight into the deciding factors between similar alternatives and help LCCAM provide results in a preferable decision making context.

Close work and interviews with Iowa DOT representatives can also help refine LCCAM's user interface so that it best suits users and explore where the tool can complement AASHTOWare BrM.

Ultimately, a more self-explanatory graphical interface and manual of practice can be developed to help make the tool more user-friendly. Workshops can also help potential users implement the tool.

LCCAM can be extended through the development of degradation curves for all bridge components in addition to the curves developed for bridge decks in this phase of the research. Additionally, the impacts of exposure conditions on the degradation curves can be refined.

LCCAM can further be extended through the inclusion of varying inflation rates and a feature that allows a database of new condition states to be loaded annually.

Implementation Readiness and Benefits

LCCAM provides a user friendly way to thoroughly and realistically evaluate and compare maintenance costs for bridge decks over a bridge's lifetime. With this information, investment decisions can be made in consideration of all maintenance costs during the period over which alternatives are compared.

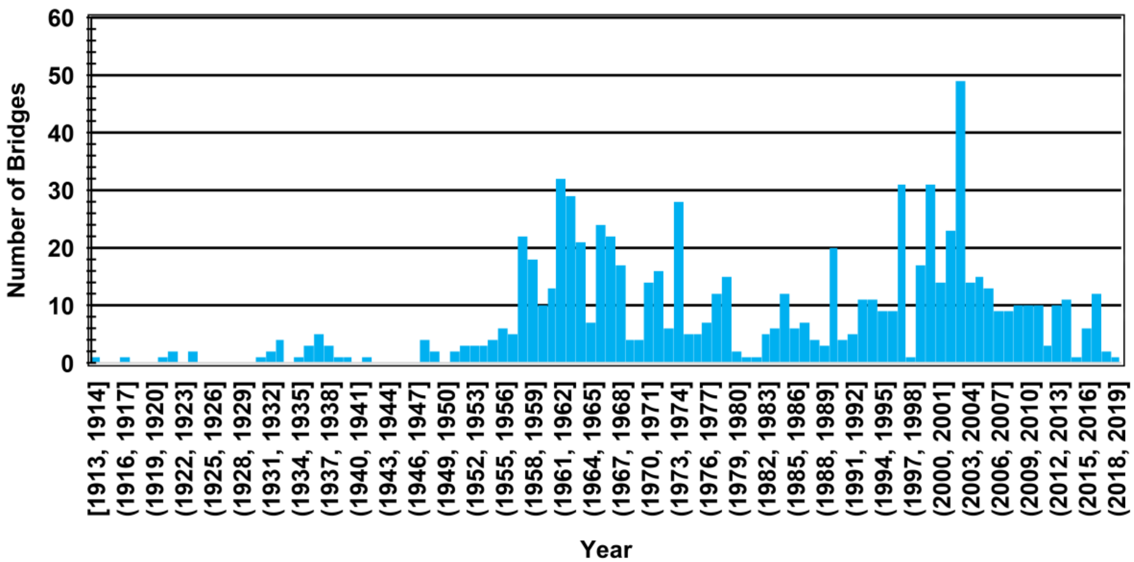
In its consideration of the variability of future infrastructure investments, LCCAM has an advantage over Iowa's current system, which is to select projects based on the lowest bid or estimated initial costs.

The Iowa DOT’s current plan for implementing LCCA in bridge management is to focus its efforts on bridge decks until sufficient data are available to expand the model to other bridge components.

Further efforts to integrate LCCAM with AASHTOWare BrM could lead to swifter and smoother assimilation of the tool among Iowa’s agency personnel. Additional inspection data requirements can also be mandated and then input into AASHTOWare BrM to provide a crucial data source for LCCAM.

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 Iowa, 35% of bridges are over 50 years old (Figure 1.1).



Source: Iowa DOT n.d. https://iowadot.gov/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 is able to 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 5.

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 actually 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 (personal communication with Scott Neubauer, Iowa DOT bridge maintenance engineer, 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). 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 as data became available (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 has the ability to 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. 2013, Shafei and Alipour 2015a and b, Cui and Alipour 2018, Cui et al. 2019, Zhang and Alipour 2020). This technique is widely used due to its robustness and its versatility (Alipour and Shafei 2016a and b). 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, Alipour and Shafei 2012). 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 tool that can be used with confidence.

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 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 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 (personal communication with Scott Neubauer, Iowa DOT bridge maintenance engineer, 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" (personal communication with Scott Neubauer, Iowa DOT bridge maintenance engineer, 2018). The expert judgement used in these decisions will be a valuable resource in the development of a LCCA program for 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.

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 (personal communication with Scott Neubauer, Iowa DOT bridge maintenance engineer, 2018 and Iowa DOT n.d.). Table 1.2 shows the quantity and type of each of these bridges and the various deck types in each of the Iowa DOT's six districts.

Table 1.2. 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

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 life-cycle cost analysis 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 organization of the remainder of this report is as follows:

- Chapter 2 of this report addresses and reviews current Iowa DOT maintenance and repair activities. The comprehensive 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 existed bridge management applications for better management and cost analysis.
- Chapter 7 provides the summary of the work described in this report.

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.

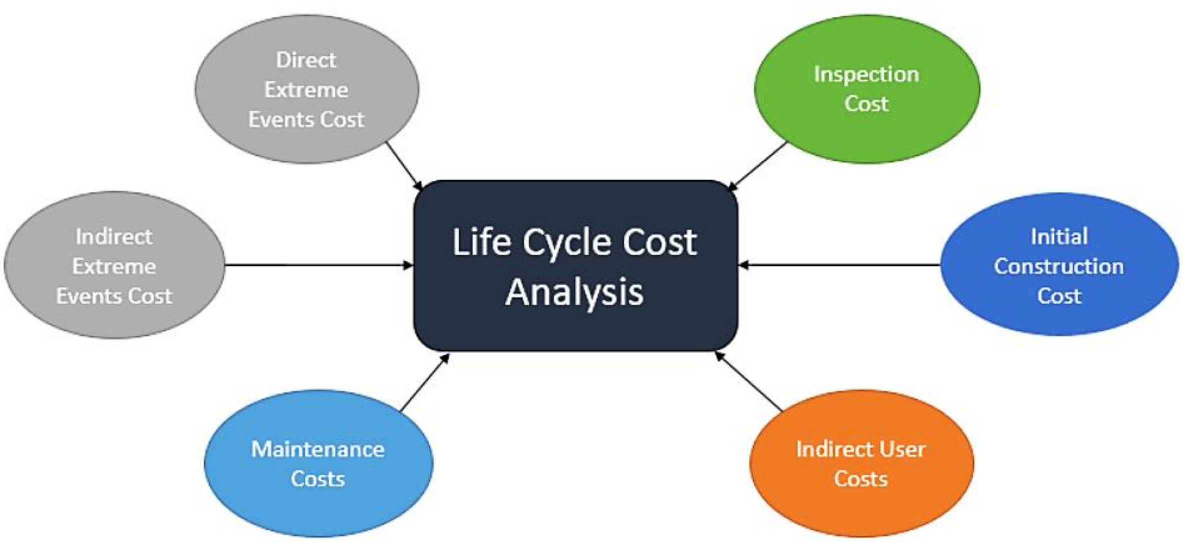


Figure 2.1. Life-cycle cost analysis cost inputs

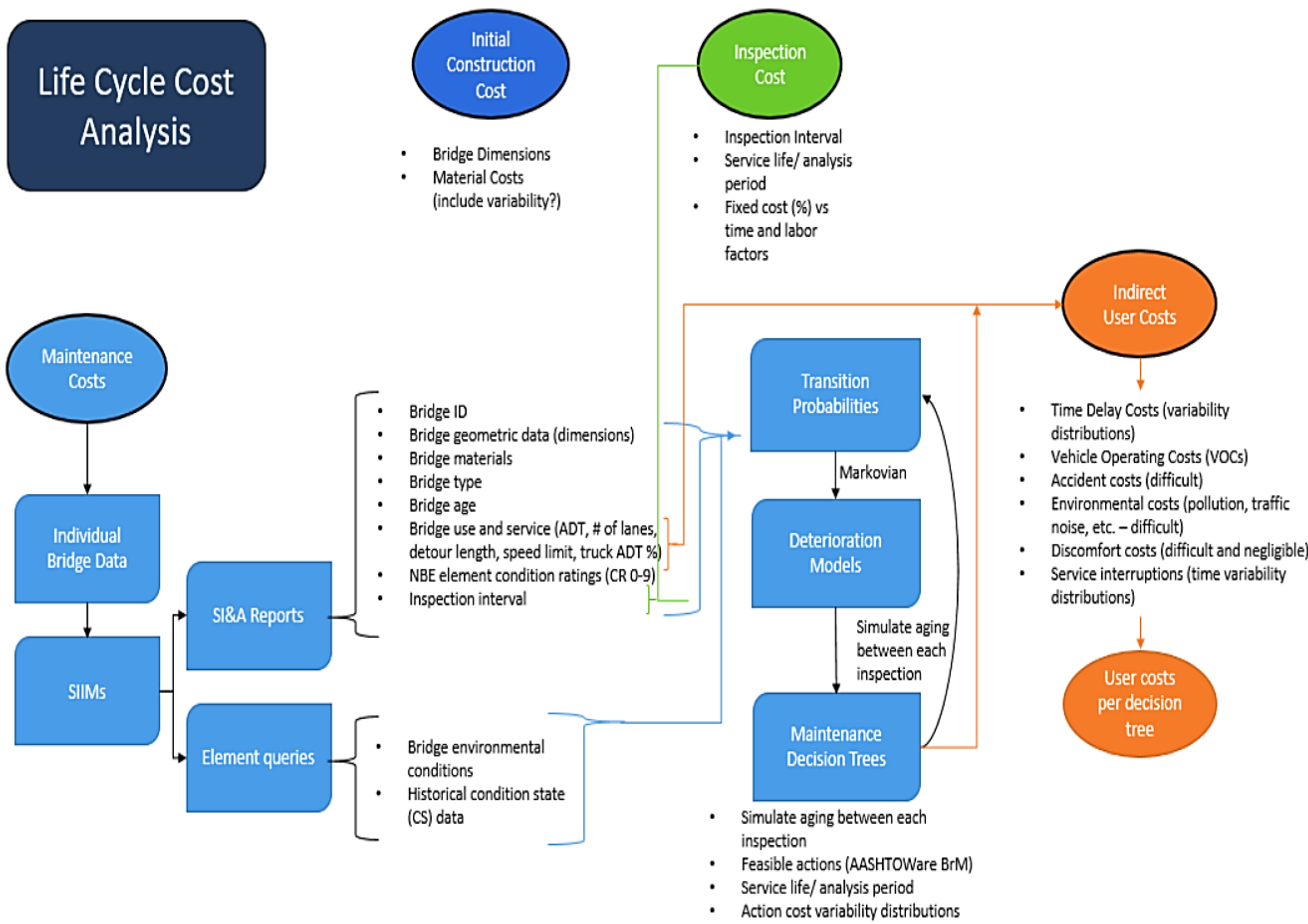


Figure 2.2. Flowchart of LCCA cost inputs

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:

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

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 a number of 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.

2.2.2 Inspection Costs

Inspection costs are often debatable in regards to 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), and 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.

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 repair or replacement.

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 (after the component reaches 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 are able to 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 absolutely 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 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).

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 a particular 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.

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

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

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

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

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

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).

LCCAM uses a single-payment present worth factor to calculate the money value of time in a life-cycle cost analysis.

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 be 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 (Washer et al. 2017) 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 a 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 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.

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 (Hopwood et al. 2018) 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 (Hopwood et al. 2018). 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.

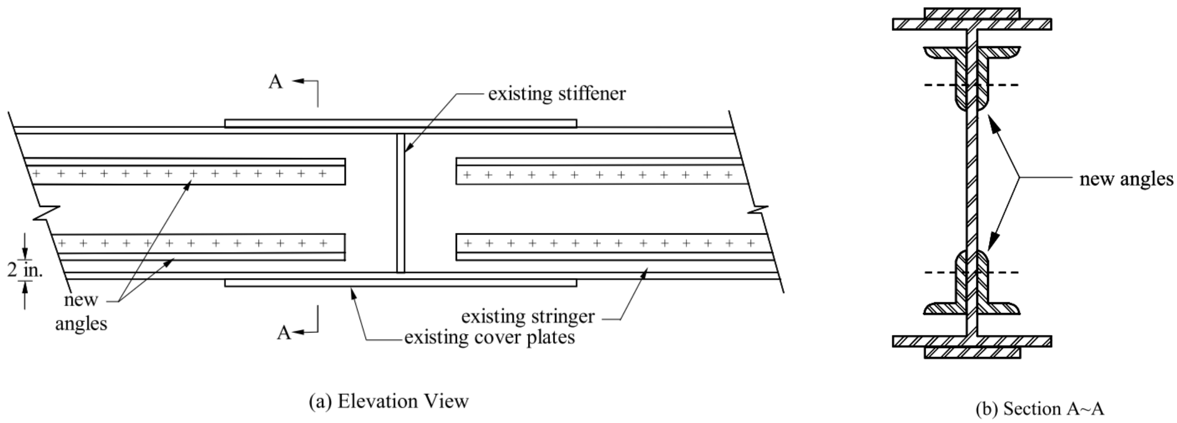
2.3.2.2 Zone Painting

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 (Auyeung and Alipour 2016, Auyeung et al. 2019, 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 2.3, 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 2.3. 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

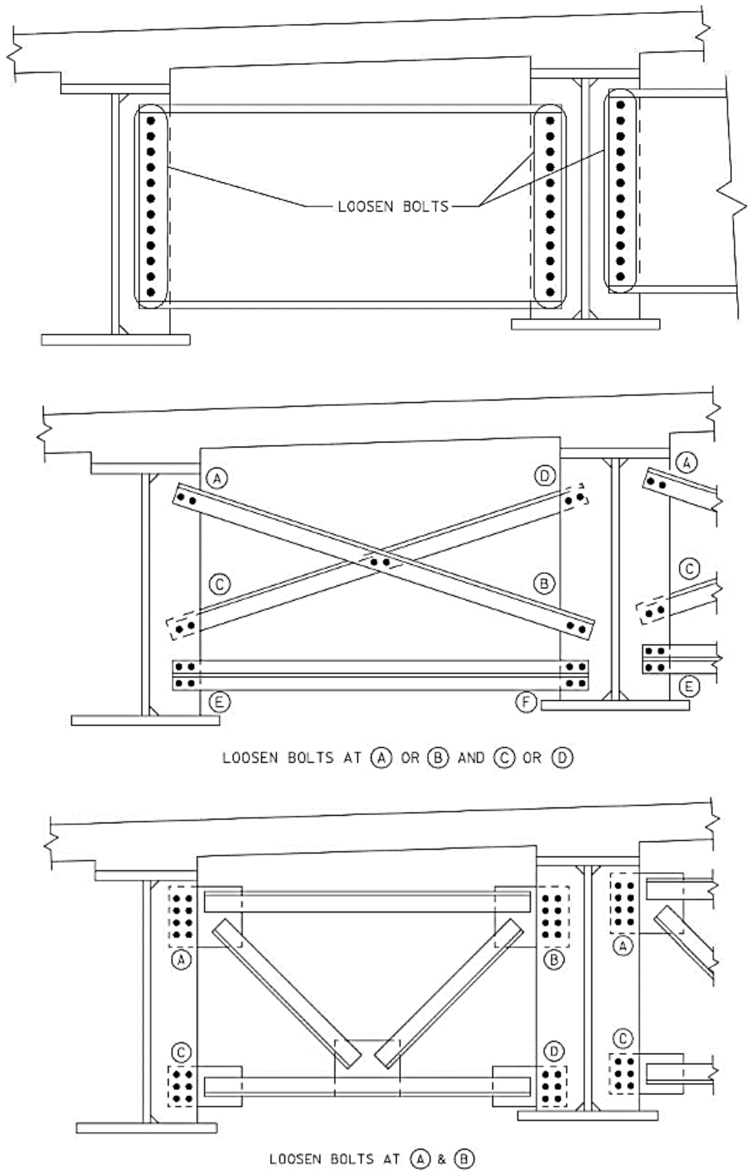
Years of gradual deterioration, collisions with vehicles, changes in required load ratings, or any combination of these factors can lead to the need for girder replacement. As opposed to girder repair and section replacement, the damage to or change intended for the structure in this situation is to 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 2.4 shows the selection of bolts to loosen.



Iowa DOT 2014

Figure 2.4. Fatigue prevention by loosening of bolts for bent plate or channel diaphragm (top), X-braced cross frame (middle), and K-braced cross frame (bottom)

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 (Wipf et al. 1998). 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 2.5.

Iowa DOT 2014

Figure 2.5. 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

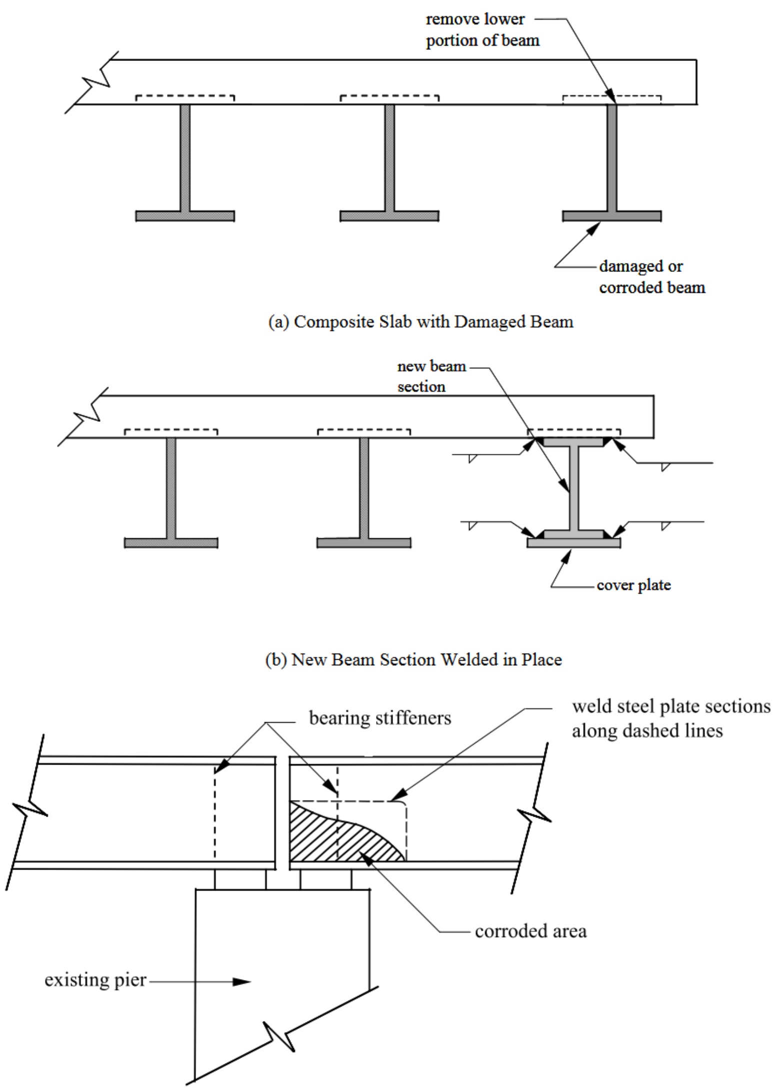
As with reinforced concrete, the depth of spalling is a main factor in deciding the degree of maintenance to be performed on prestressed concrete beams. All underlying steel, including prestressed or flexural reinforcement, must be inspected, cleaned, and, if necessary, reset or replaced; any damaged 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 2.6) can be costly.



Wipf et al. 2003, Iowa State University

Figure 2.6. Repair of damaged steel beam ends

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 performance of the beam 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 (Iowa DOT 2014). 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 2.7).

NYSDOT 2008

Figure 2.7. Shooting material for shotcrete repair

2.3.5 Joints

2.3.5.1 Expansion Joints

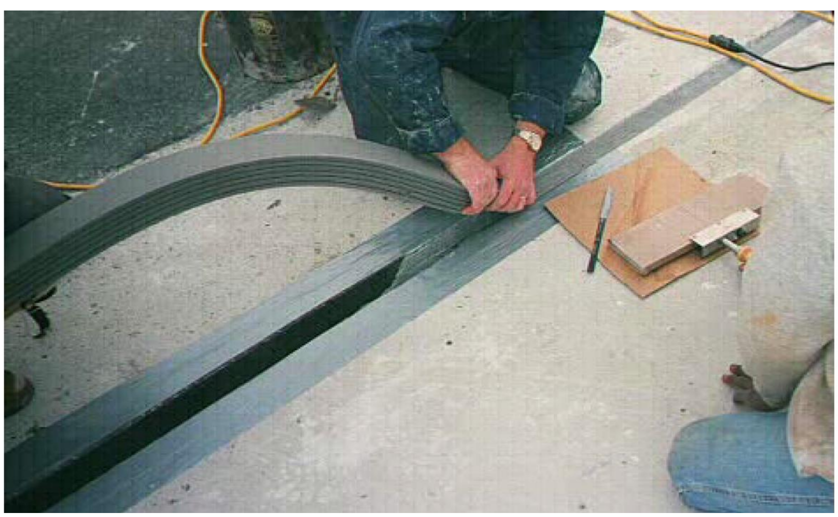
The Iowa DOT incorporates a range of expansion joint types in its bridge designs, ranging from simple gaps for small bridges to a variety of sealed joints, with a preference for the latter. The specific types of expansion joints and descriptions and diagrams of each can be found in the Iowa DOT's *Bridge 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, 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, with two hours of traffic control for each joint, which adds two years to the service life of the joint.

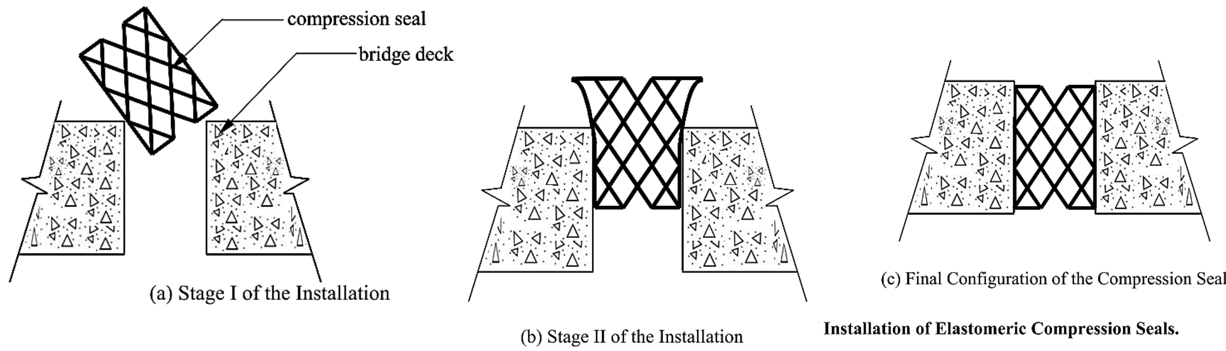
2.3.5.3 Replacing Joint Seals or Glands

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 2.8 and 2.9 demonstrate how seals are replaced.



NYSDOT 2008

Figure 2.8. Installing joint seal



Wipf et al. 2003, Iowa State University

Figure 2.9. 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 because they help to 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

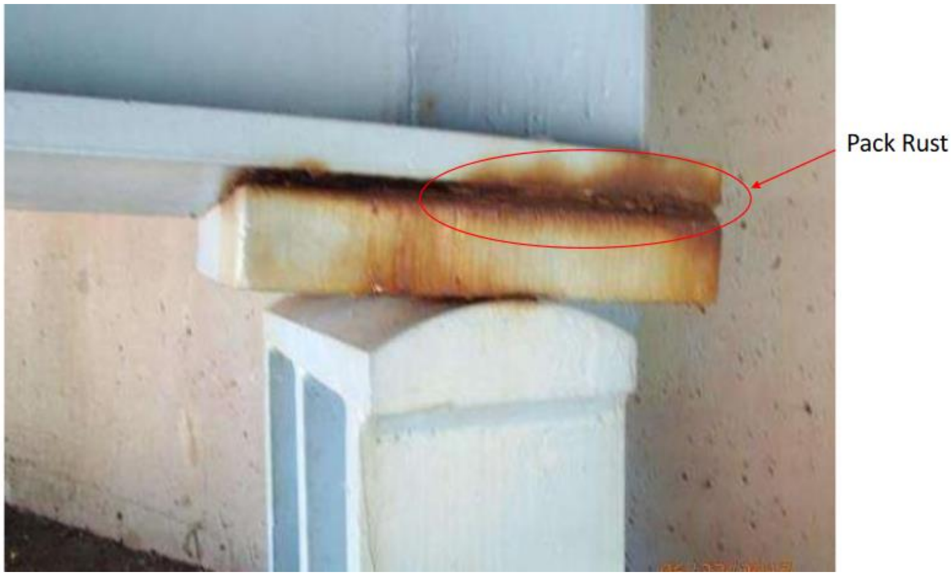
Bridge bearings are under immense loads. Friction between any components can quickly cause deterioration and failure of the bearings and ultimately the bridge. Additionally, a seized bearing can fail to transfer lateral loads and can cause changes in the loading of the structure, leading to the deterioration 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 2.10.

NYSDOT 2008

Figure 2.10. 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 2.11.



Patel and Bowman 2018

Figure 2.11. 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. The 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 mechanically removed (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 2.12).

NYSDOT 2008

Figure 2.12. 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).

3. DATA GATHERING AND ANALYSIS

3.1 Introduction

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

Iowa stores its inspection information in its SIIMS database. All NBI data required by federal regulations, as well as condition data for both NBI and NBE and BME elements, are stored in SIIMS and can be queried based on requested criteria. This chapter provides a detailed explanation of and background information on the SIIMS database and NBI, NBE, and BME components.

3.2 SIIMS

Iowa's inspection database has been referenced in previous chapters. SIIMS is a crucial component of Iowa's implementation of LCCA. SIIMS contains all NBI and element-level data that the Iowa DOT records for each bridge. The following section elaborates on these NBI and element-level data. For probabilistic LCCA, the historical data stored in SIIMS are necessary to create the transition probabilities to be discussed in Chapter 4. Reinforced concrete decks were found to be the most common deck type across the state.

3.3 NBI versus 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 brief 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 (Federal Register 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*.

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 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 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 3.1.

Table 3.1. General condition ratings for deck, superstructure, and substructure

Rating	Description
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.

Source: Iowa DOT 2015

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 were 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 (Iowa DOT 2015). 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.

3.4 NBI Data Sources for this Study

NBI deck data were used for this study. These data seemed to be consistent and provided a larger range of data, dating back to 1983. 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. These were used to develop the deterioration curve for bridge decks in Iowa.

4. EVALUATION OF AVERAGE AGE OF CONDITION RATINGS FOR BRIDGE DECKS BASED ON DATA

4.1 Introduction

This chapter provides a detailed investigation into evaluating the average age of a condition rating for a bridge deck. The average age is evaluated by evaluating the appropriate hazard rate for a condition rating. These hazard rates are evaluated by employing more than 10 years of visual inspection data. The chapter discusses the commonly adopted survival distributions to evaluate the hazard rate and then the data-based methodology adopted in this study.

4.2 Condition States and Deterioration Process

As soon as a bridge is opened for traffic, it starts to deteriorate. The main factors that contribute to bridge deterioration are environmental stressors, traffic conditions, lack of proper maintenance, and any unnoticed initial defects that may worsen with time. Most of these factors are unavoidable, and a bridge is inevitably subjected to deterioration throughout its lifetime. From the intact state to the complete collapse state of the bridge, this deterioration process is divided into several condition states that serve as a quick measure of bridge's health. Different agencies all over the world have different numbers of divisions to describe the deterioration process based on their requirements. Each division is then given a definition in terms of some visual measures indicating the bridge's health, such as crack width, crack number, area of spalling, joint defects, scoring, settlement, and similar measures. Each of these divisions is referred to as a condition state. For a more systematic categorization of condition states, these condition states are defined separately for each critical component of the bridge, for example deck, piers, and bearings. The NBI employs 10 condition ratings, where a rating of 9 represents excellent structural integrity and a rating of 4 or below reflects the fact that the structure needs repair or replacement (FHWA 1995). The condition of each bridge element is determined by visual observation, or if necessary, by non-destructive or destructive testing.

In order to predict the future condition state of a bridge component, it is important to understand the deterioration process and the time that a bridge component spends in one condition state before moving to next condition state. For this purpose, let us assume that the inspection data for a bridge component is available at two subsequent time instants t_A and t_B for an inspection interval z, where $z = t_B - t_A$. Further, the condition states are defined for $i = 1$ to I, an intact to a complete collapse state. If at time t_A the observed state is i, then at time t_B the state can be observed as any state between $i = 1$ to I (assuming that only deterioration is possible for a component and neglecting the possibility of achieving a better condition due to repair). Figure 4.1 shows a schematic representation of deterioration process.

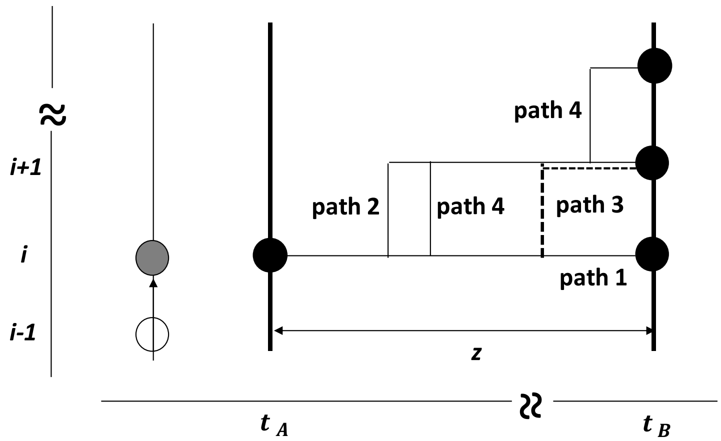


Figure 4.1. Schematic diagram of deterioration process

As shown in Figure 4.1, in an inspection interval of $z = t_B - t_A$ a bridge component can deteriorate more than just to an adjacent condition state. Although the condition state at time instant t_B is observable in inspection data, the actual time the bridge component spends in the previous observed state is not observable. Figure 4.1 also shows that there is more than one possible way to transition between states. Therefore, it can be concluded that by employing discontinuous inspection data, the time a bridge component spends in a particular condition state, also known as the sojourn time for that condition state, cannot be determined accurately using a deterministic analysis. Further, predicting the state of a bridge component in the future depends on the time the component spent in all of the previous states, which cannot be obtained deterministically using the available data from inspection reports.

A probabilistic approach is therefore needed to resolve the problem of determining transitions between condition states. There are many probabilistic approaches available in the literature, most of which assume an exponential distribution for the sojourn time, which is associated with the basic assumption that the failure of a state can occur at any instant in time and the mean occurrence rate of failure is constant over time. These assumptions further make the deterioration process of a condition state independent of the history of the deterioration process or the age of the component and dependent only on the current state. In other words, the deterioration process becomes a memoryless process and can be modeled as a Markov process. A few other probabilistic approaches have also been used that have developed a semi-Markov or a non-Markov model for predicting the future condition state of a bridge component by considering the history of the deterioration process or making the process age dependent. The underlying idea behind these approaches is to observe the hazard rate associated with different condition states indicated in the inspection data, develop hazard functions for different condition states, and finally derive the survival or failure probability distribution for different condition states. The following section explains the hazard and survival functions in detail.

4.3 Hazard Rate Function

A hazard rate function, or simply a hazard rate, for a condition state is defined as the conditional probability of failure of a condition state at time instant *t* conditioned on the survival of that condition state until time ***t*.** In other words, it is the instantaneous rate of occurrence of the event and is defined as follows:

$$\lambda(\mathrm{t}) = \lim_{dt \to 0} \frac{\Pr(\mathrm{t} \le \mathrm{T} < \mathrm{t} + \mathrm{dt} \mid \mathrm{T} \ge \mathrm{t})}{dt} = \frac{f(\mathrm{t})}{S(\mathrm{t})} \tag{4.1}$$

where, *T* is the time until failure, *f*(t) is the probability of failure at *t*, and S(t) is the cumulative probability of survival of a condition state until time *t*. The failure probability density function *f*(t) and the survival distribution function S(t) can be written as follows:

$$\mathrm{S(t)} = \Pr\{\mathrm{T} \ge \mathrm{t}\} = 1 - \mathrm{F(t)} = \int_t^{\infty} f(\mathrm{x})dx \tag{4.2}$$

where, F(t) is the failure cumulative distribution function. Using Equation 4.2, an alternative form of Equation 4.1 can be written as follows:

$$\lambda(\mathrm{t}) = -\frac{d}{dt} \log \ \mathrm{S(t)} \tag{4.3}$$

Further, a function $\lambda(\mathrm{t})$ can be called a hazard rate function if and only if it satisfies the following properties:

1. $\forall \mathrm{t} \ge 0 \ (\lambda(\mathrm{t}) \ge 0)$
2. $\int_0^{\infty} \lambda(\mathrm{t})dt = \infty$

(4.4)

On integrating Equation 4.3 from 0 to *t*, the expression for the survival probability distribution can be obtained as follows:

$$\mathrm{S(t)} = \exp\{-\int_0^{t} \lambda(\mathrm{x})\,\mathrm{dx}\} \tag{4.5}$$

Assuming that the hazard rate is constant over the time, i.e., $\lambda(\mathrm{t}) = \lambda$, the survival distribution function S(t) and the failure probability density function *f*(t) can be written as follows:

$$\mathrm{S(t)} = \exp\{-\lambda t\} \tag{4.6}$$

$$\mathrm{f(t)} = \lambda \exp\{-\lambda t\} \tag{4.7}$$

The life expectancy or the mean age of a condition state can be obtained as follows:

$$\mu = \int_0^\infty t f(\mathrm{t}) dt \tag{4.8}$$

Integrating by parts in Equation 4.8 and considering -*f*(t) as the derivative of S(t), the average life of a condition state can be written as follows:

$$\mu = \int_0^\infty S(\mathrm{t}) dt \tag{4.9}$$

4.4 Transition Probabilities

The data gathered through visual inspections contain the condition state ratings for the bridge components evaluated at some regular interval, such as every one or two years or at longer inspection intervals. From these data, the transition probabilities (i.e., the conditional probability of transitioning from a given state to another state within a given inspection interval) for a component type can be evaluated. For this purpose, let us assume that the data for component type k are available for time instants t_B and t_A ($t_B > t_A$) for inspection interval $z = t_B - t_A$. If the total number of condition states is denoted by I, then the transition probability between state i(i = 1 to I - 1) and j(j = i to I) for component type k can be given as follows (assuming I is an absorbing state $\mathrm{p}_{II}^k = 1$):

$$p_{ij}^k = \frac{\text{number of samples in state } j \text{ at time } t_B}{\text{total number of samples in state } i \text{ at time } t_A} \tag{4.10}$$

It is assumed here that data reflecting the repair of a component and thus the possibility of transitioning to a better condition state are ignored. Therefore, the transition matrix is only an upper triangular matrix instead of a full matrix. These obtained transition probabilities from the data are then used to evaluate the failure and survival probability distributions of different condition states. For this purpose, these transition probabilities are expressed in the form of failure and survival probability distributions and, in turn, in the form of hazard rate functions using theorems and axioms of conditional and total probability. This is achieved by assuming a standard survival distribution with unknown parameters, or, alternatively, a hazard rate function with unknown parameters, and then evaluating these unknown parameters given the available transition probabilities from the inspection data. An objective function based on the error between the available transition probabilities from the inspection data and the derived transition probabilities in terms of the unknown parameters of the hazard functions is minimized to get the optimal values of these unknown parameters. This can be achieved by employing any optimization algorithm.

The following section describes a few standard survival distributions and their associated hazard rate functions. A brief description of transition probabilities in terms of assumed survival distributions and thus hazard rate functions is also presented.

4.5 Standard Survival Distributions, Associated Hazard Functions, and Transition Probabilities

The widely adopted standard survival distributions in the literature on bridge condition assessment are exponential and Weibull distributions. The associated hazard rate function can be obtained from Equation 4.3. For an exponential survival distribution, the hazard rate function becomes a constant, as discussed in Section 4.3 of this report, whereas the hazard rate function associated with a Weibull survival distribution is given in Table 4.1. Table 4.1 also summarizes a few other families of standard distributions and their associated hazard functions.

Table 4.1. Standard distributions and associated hazard functions

Distribution	Probability density function	Parameters	Hazard function
Normal	$f(t)=\dfrac{e^{-(t-\mu^2)/2\sigma^2}}{\sigma\sqrt{2\pi}}$	μ,σ	$\lambda(t)=\dfrac{\phi(\mathrm{t})}{\Phi(-\mathrm{t})}$
Uniform	$f(t)=\dfrac{1}{B-A}$ for $\mathrm{A}\le \mathrm{t}\le \mathrm{B}$	$A,B-A$	$\lambda(t)=\dfrac{1}{1-t}$
Cauchy	$f(t)=\dfrac{1}{s\pi(1+((\mathrm{t-m})/\mathrm{s})^2)}$	m,s	$\lambda(t)=\dfrac{1}{(1+\mathrm{t}^2)(0.5\pi-\arctan t)}$
Exponential	$f(t)=\mu \mathrm{e}^{-\mu \mathrm{t}}$	μ	$\lambda(t)=\mu$
Weibull	$f(t)=\dfrac{\gamma}{\alpha}\left(\dfrac{t-\mu}{\alpha}\right)^{(\gamma-1)}\mathrm{e}^{(-((\mathrm{t}-\mu)/\alpha)^{\gamma})}$ $\mathrm{t}\ge\mu;\ \alpha>0$	μ,α,γ	$\lambda(t)=\gamma t^{(\gamma-1)}$ $\mathrm{t}\ge 0;\ \gamma>0$
Lognormal	$f(t)=\dfrac{e^{-((\ln((\mathrm{t}-\theta)/\mathrm{m}))^2/(2\sigma^2))}}{(t-\theta)\sigma\sqrt{2\pi}}$ t>θ; $\mathrm{m},\sigma>0$	θ,m,σ	$\lambda(t,\sigma)=\dfrac{\left(\dfrac{1}{t\sigma}\right)\phi\left(\dfrac{\ln\ \mathrm{t}}{\sigma}\right)}{\Phi\left(\dfrac{-\ln\ \mathrm{t}}{\sigma}\right)}$ t>0; $\sigma>0$
Gamma	$f(t)=\dfrac{\left(\dfrac{t-\mu}{\beta}\right)^{\gamma-1}e^{\left(-\frac{t-\mu}{\beta}\right)}}{\beta\Gamma(\gamma)}$ t>μ; $\gamma,\beta>0$	μ,β,γ	$\lambda(t)=\dfrac{t^{\gamma-1}e^{-t}}{\Gamma(\gamma)-\Gamma_t(\gamma)}$ t>0; $\gamma>0$
Double exponential	$f(t)=\dfrac{e^{\left(-\frac{t-\mu}{\beta}\right)}}{2\beta}$	μ,β	$\lambda(t)=\dfrac{e^t}{2-e^t}$ for t<0 1 for $\mathrm{t}\ge 0$

ϕ is the probability density function for the standard normal distribution.
Φ is the cumulative density function for the standard normal distribution.

Figure 4.2 shows plots of hazard rate variations for exponential and Weibull distributions.

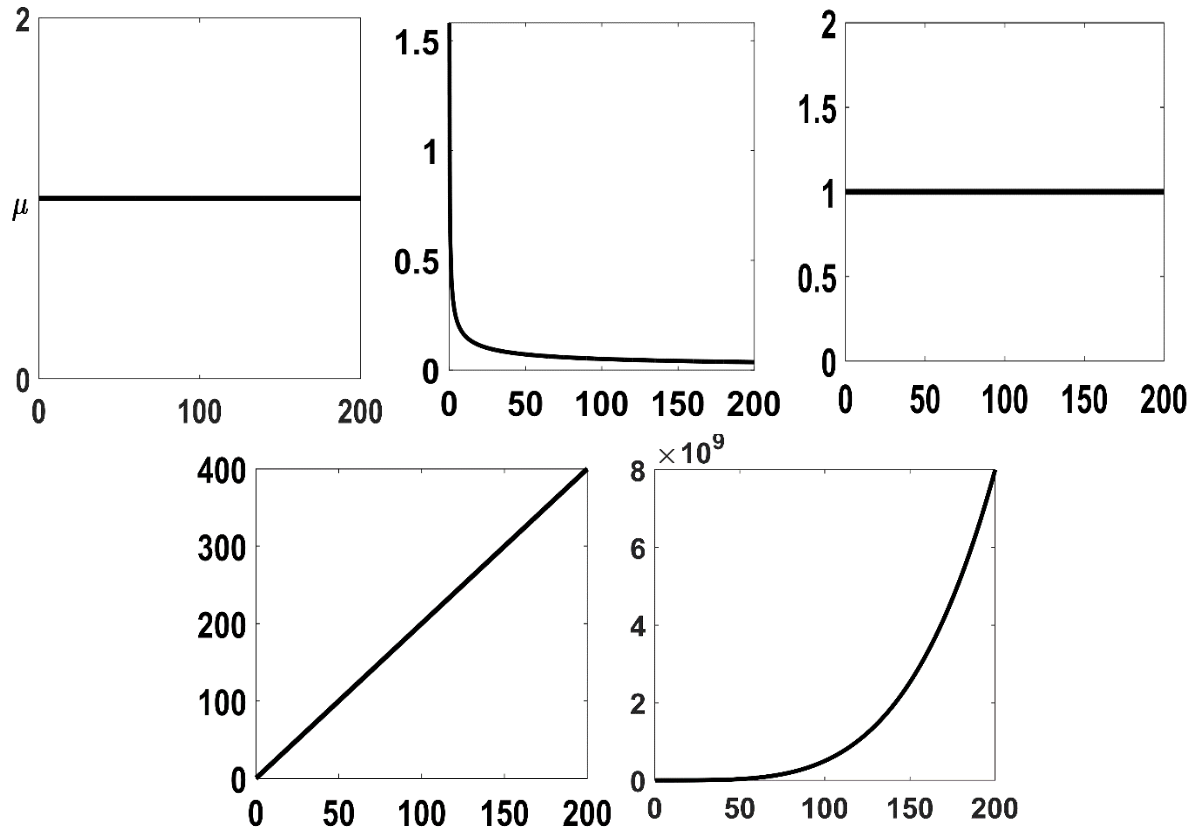


Figure 4.2. Hazard functions: Exponential distribution (top left), Weibull γ=0.5 (top middle), Weibull γ=1.0 (top right), Weibull γ=2.0 (bottom left), Weibull γ=5.0 (bottom right)

As shown in Figure 4.2, an exponential distribution is associated with a constant hazard rate, whereas a Weibull distribution allows only a monotonically increasing or decreasing hazard rate. However, the actual hazard rate associated with the deterioration of a bridge component can vary with time in an entirely different pattern, and the assumed standard distribution may not be a good choice to represent deterioration. In addition, the transition probabilities, when expressed in terms of an assumed distribution, contain high-dimensional integrals, and evaluating the unknown parameters of the assumed distribution becomes a significant computational challenge. This is particularly true when the hazard function associated with an assumed distribution is time dependent. Transition probabilities in terms of assumed standard survival distribution *S* and associated failure probability density function *f* are derived in Kobayashi et. al. (2010), which can be written as follows:

$$p_{ij}(\mathrm{s_A}, s_\mathrm{B}) = \mathrm{Prob}[h(s_A) = i, h(s_A + s_B) = j] = \int_0^{t_A} \eta_i(\mathrm{s}_A, y_i)\kappa_{ij}(s_B \mid y_i)dy_i \tag{4.11}$$

In Equation 4.11, it is assumed that inspection data are available at time t_A and t_B, and further $t_A = s_A$ and $t_B = s_A + s_B$. The time at which the actual transition occurs between state *i* - 1 and *i* is denoted as y_i, which belongs to domain $0 \le y_i \ge s_A$. However, note that this transition is observed at time t_A only. The probability density $\eta_i(s_A, y_i)$ defines the probability of the occurrence of condition *i* at time $t_{i-1} = t_A - y_i$ and can be given as follows:

$$\eta_i(s_A, y_i) = \left\{ \int_0^{s_A - y_i} f_1(\zeta_1) \int_0^{s_A - y_i - \zeta_1} f_2(\zeta_2) \ldots \int_0^{s_A - y_i - \ldots - \zeta_{i-3}} f_{i-1}(\zeta_{i-1}) d\zeta_i \ldots d\zeta_{i-2} \right\} S_i(y_i)$$
$$= \left\{ \int_0^{s_A - y_i} \int_0^{s_A - y_i - \zeta_1} \cdots \int_0^{s_A - y_i - \sum_{m'=1}^{i-3} \zeta_{m'}} \prod_{m'=1}^{i=1} f_{m'}(\zeta_{m'}) \, d\zeta_1 \ldots d\zeta_{i-2} \right\} S_i(y_i) \quad (4.12)$$

In deriving Equation 4.12, it is assumed that condition state *i* advances to *i* + 1 at time $t_i = t_A + z_i$ and that the lifespan of the condition state is defined by the variable $\zeta_i = y_i + z_i$. Further, $k_{ij}(s_B \mid y_i)$ in Equation 4.11 defines the probability of observing condition state *j* at inspection time $t_B = t_A + s_B$, given that condition state *i* occurred at y_i and was observed at t_A and can be written as follows:

$$\kappa_{ij}(s_B \mid y_i) = \int_0^{s_B} \int_0^{s_B - z_i} \cdots \int_0^{s_B - z_i - \sum_{m'=i+1}^{i-2} \zeta_m} \frac{f_i(y_i + z_i)}{S(y_i)} \prod_{m=i+1}^{j-1} f_m(\zeta_m) S_j\left(s_B - z_i - \sum_{m=i+1}^{j-1} \zeta_m \right) dz_i d\zeta_{i+1} \ldots d\zeta_{i-1} \quad (4.13)$$

It is clear from the above expressions that an assumed survival distribution provides a significant challenge in terms of computational costs, especially when the deterioration process is categorized into a large number of condition states (for example, 10). These computational costs increase by several factors when an iterative optimization approach is used to find the optimal values of the unknown parameters of the assumed survival distributions. Furthermore, the integral involved in Equation 4.13 becomes difficult to evaluate with conventional numerical methods for most of the standard distributions, and Monte Carlo methods may need to be used. The large sample size needed for Monte Carlo simulations to yield a fairly accurate prediction poses another challenge in terms of computational efficiency.

4.6 Average Age of Deck Based on Data

To overcome the challenges discussed in the previous section, this study adopts a data-based method for hazard function prediction without any prior assumption of survival distribution. Two salient points regarding the proposed approach are as follows:

1. The proposed approach is free from any prior assumption and can therefore capture the actual variation in hazard rate over time for bridge elements.
2. The proposed approach provides a huge advantage in terms of computational efficiency.

To determine the actual hazard rate variation over time, in this study bridges are first categorized according to their age in each available set of inspection data collected at two-year intervals. Small age ranges are then chosen with a constant gap. For example, with a five-year gap, the ranges become 0 through 5 years, 6 through 10 years, 11 through 15 years, and so on. The bridges falling into each of these age ranges are then extracted from each inspection data set. Within each of these age ranges, the hazard rate is assumed to be constant. Although it is not valid to assume that the hazard rate does not vary over time, for a small age range the hazard rate can reasonably be assumed to be constant. The reasoning behind this decision is that the actual deterioration process is complex, and although it is age dependent, within a small age range the assumption of a random failure (a constant hazard rate) is more reasonable than the assumption of an age-dependent failure.

Data for a total of 4,000 bridges in Iowa were obtained for the years 1993 to 2017, with an inspection interval of two years. Any data that indicated repair and therefore a probability of returning to a better condition state were eliminated. The average ages of bridges that exhibited the respective condition ratings are tabulated in Table 4.2.

Table 4.2. Average age of bridges in different condition states

Condition state	Average age (years)
1	5.3397
2	11.7200
3	23.8592
4	13.2802
5	11.6702

This average age for each condition rating is used for the life-cycle cost analysis tool discussed in the next chapter. Due to lack of data, only the first three condition states' or condition ratings' (9–7) average age can be reliably evaluated. Although, condition ratings 4 and 5 are included in the table, a good convergence for the parameters of survival distribution of these condition states are not obtained.

5. MATLAB-BASED APPLICATION (LCCAM) DEVELOPED FOR CHOOSING OPTIMAL MAINTENANCE ACTIVITIES

5.1 Introduction

This chapter provides a detailed explanation of the MATLAB-based application developed for choosing the optimal maintenance activity for a given bridge deck. The application allows the user to choose a certain maintenance activity or to compare different activities. The options are compared in terms of the money required for maintenance, the service life extension provided by the maintenance activity, and the condition rating improvement provided by the maintenance activity. In addition, the application provides a solution for the optimal maintenance activity for a required service life improvement.

This chapter discusses each aspect of the application in detail to demonstrate how the different features of the application work. The chapter begins with the installation process for the application and concludes with guidelines for using the application to evaluate optimal maintenance activities for bridge decks.

5.2 Installation Guidelines

5.2.1 Files to Deploy and Package

The following files must be packaged and deployed to install the standalone application:

- LCCAM.exe
- MyAppInstaller_web.exe

5.2.2 Installation

The user will need administrator rights to run the MATLAB Runtime installer MyAppInstaller_web.exe. Once the runtime installer is installed, the LCCAM application can be used. For more information about MATLAB Runtime and the MATLAB Runtime installer, see Package and Distribute in the MATLAB Compiler documentation in the MathWorks Documentation Center.

5.3 Input Guidelines and Step-by-Step Execution

5.3.1 Step 1

On execution of the LCCAM application, the application shows the deterioration curve for Iowa's bridges. This deterioration curve is evaluated in a stochastic environment based on data from 24,000 bridges in Iowa. The transition of a bridge deck from one condition rating to another is evaluated based on the average age of a condition rating. This average age of a condition rating is evaluated using survival functions, as explained in Chapter 5 of this report. From this deterioration curve, the user of this application can get an idea about the average time the bridge will take to reach a particular condition rating from the current rating, which can help the user plan the optimal maintenance strategy for the bridge deck.

5.3.2 Step 2

In Step 2, the application asks for user input on the current condition rating of the bridge deck. The user is advised to input a current condition rating that does not exceed 9 and is not below 4.

5.3.3 Step 3

In Step 3, the application asks for user input on the condition rating of the bridge deck below which some maintenance activity should be performed. For example, if the current condition rating is 8, the user indicates in this step that maintenance should be performed only after the bridge deck reaches a condition rating of 6. In this case, the input value for this step is 6 and for the previous step is 8.

5.3.4 Step 4

In Step 4, the application shows a menu of all available maintenance options for the condition rating entered in Step 3. The user can choose any one of the maintenance options shown in the menu (described in Step 4.1) or compare different maintenance options (described in Step 4.2). The items in this menu are selected by the application based on all available maintenance options for a particular threshold condition rating. Figures 5.1 through 5.4 show the menus of possible maintenance actions for different condition ratings.

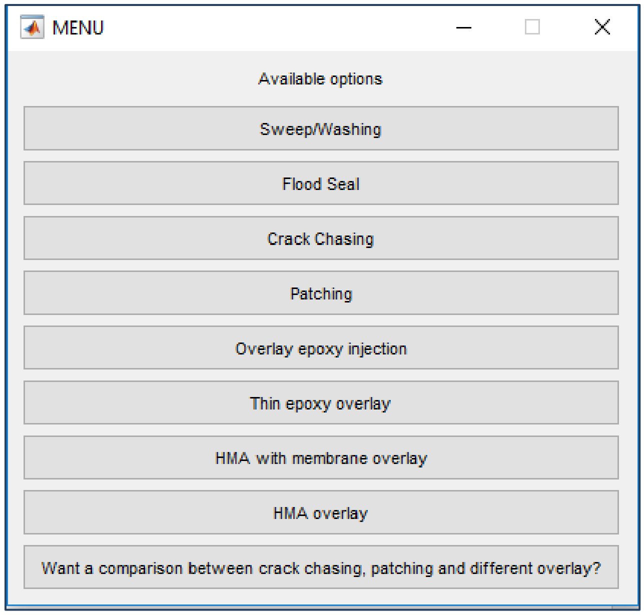


Figure 5.1. Menu for condition ratings 7 through 9

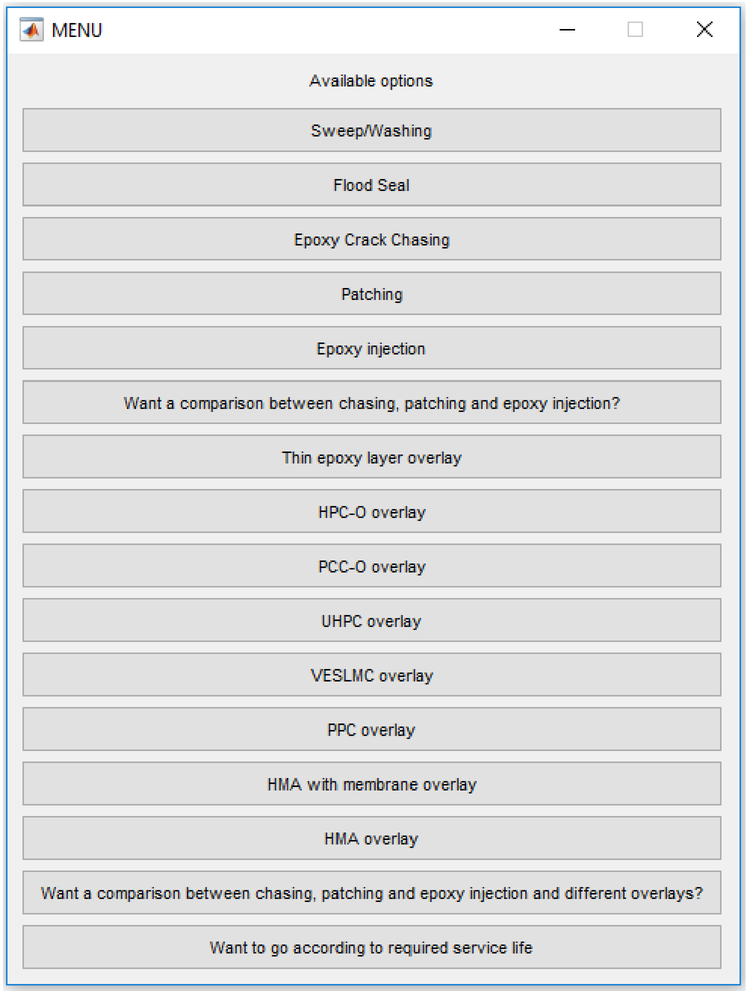


Figure 5.2. Menu for condition rating 6

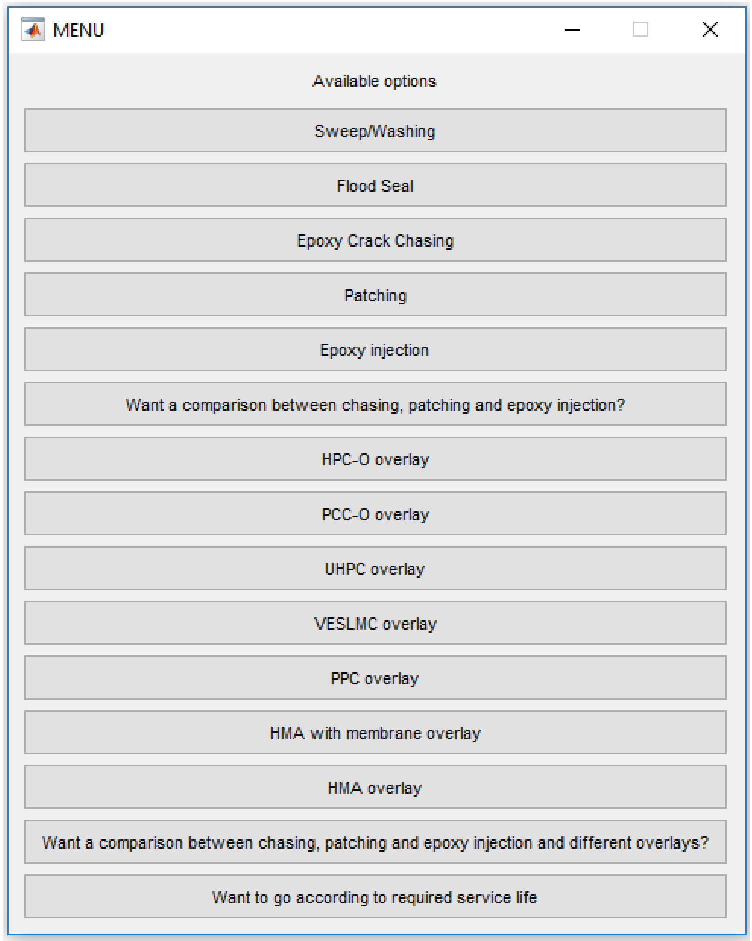


Figure 5.3. Menu for condition rating 5

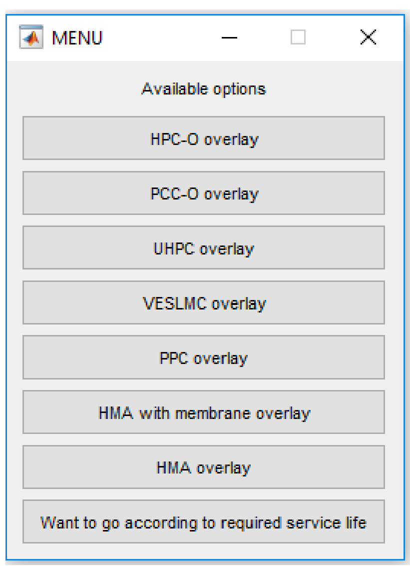


Figure 5.4. Menu for condition rating 4

5.3.4.1 Step 4.1

In Step 4.1, the user has chosen a single maintenance activity from the menu of possible maintenance actions. After choosing the option, the application presents another menu that shows the salient features of the chosen option, such as the associated cost and the service life extension provided by the option. Figure 5.5 shows this menu for the Sweep/Washing option.

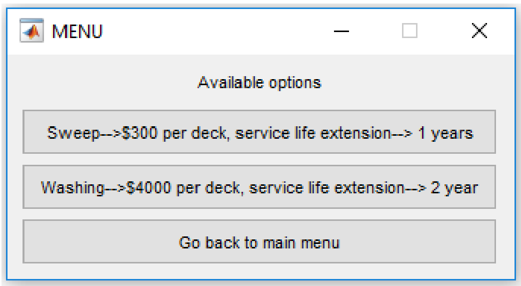


Figure 5.5. Menu showing the salient features of the selected option

If after reviewing the salient features of the selected option the user does not want to continue with that option, the menu also provides a button to return to the main menu and select another option. If the user wishes to continue with the selected option, then he/she can proceed by clicking on the details of selected option.

Once the user is certain about the chosen maintenance activity, the application asks the user to input the additional information required to execute the selected option and evaluate the associated cost and service life extension. These inputs include the number of decks or size of the deck area (depending on whether the unit cost is defined as per unit deck or per unit area of the deck), the required number of maintenance actions, and the interest rate. The interest rate is included to account for the money value of time in the cost analysis. The default interest rate is set at 4% annually. However, the application allows this interest rate to be changed and can take a different interest rate as user input.

5.3.4.2 Step 4.2

As shown in Figures 5.1 through 5.3, this application also allows the user to compare different maintenance activates. In Step 4.2, the user has selected the comparison option from the menu. The application then shows the salient features of multiple maintenance options that will be compared in terms of their total maintenance costs and service life extensions, as shown in Figure 5.6.

	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. Screenshot showing salient features of different maintenance options to be compared

After reviewing these details, the user can choose to either proceed with the comparison or return to the main menu using the menu shown in Figure 5.7.

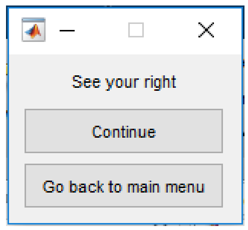


Figure 5.7. Menu showing the option to proceed with the comparison or return to the main menu

If the user chooses to continue with the comparison, then, in a similar process to that described in Step 4.1, the application asks the user to input the details required to execute the comparison and provides the results in terms of total cost, service life extension, and condition rate improvement. Figure 5.8 shows the results of an example comparison.

	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. Screenshot showing the results of a comparison between different maintenance options

5.3.5 Effects of Maintenance Actions

For maintenance actions that provide a condition rate improvement in addition to a service life extension, the application shows the complete deterioration curve for the deck, including the changes resulting from the maintenance action. Figure 5.9 shows a typical deterioration curve when two consecutive maintenance actions are undertaken after the deck reaches a condition rating of 5 (both of the maintenance actions shown in this plot improve the deck condition rating by 2).

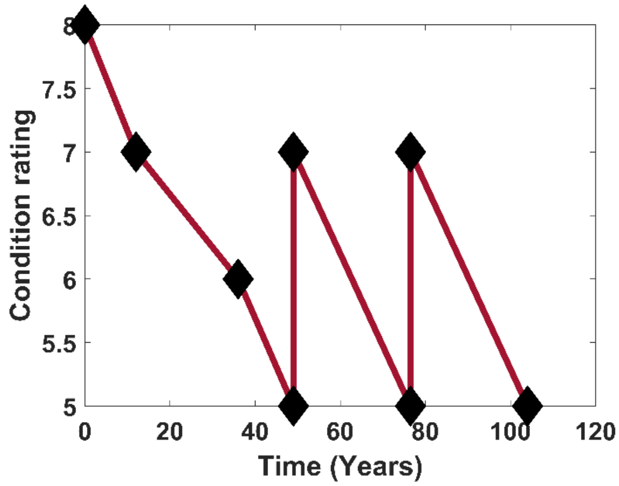


Figure 5.9. Deterioration curve showing the effects of maintenance actions

5.4 Required Service Life Option

In addition to the options discussed above, the application also provides a feature that allows the user to forgo the choice of any specific maintenance option and instead direct the application to increase the service life by a certain number of years. This feature is available through the "Want to go according to required service life" button shown in Figures 5.2 through 5.4. With this option, the application provides the optimal solution in terms of cost that provides the required service life extension specified by the user.

When the user chooses this option from the main menu, the application first asks the user to input the required service life extension in years. Once this input is entered, the application asks whether the user wants to choose the specific materials to be considered in the analysis, as shown in Figure 5.10.

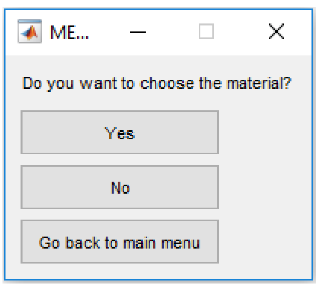


Figure 5.10. Menu showing the choice to specify the materials to be used in the analysis

This option is included for cases where only certain materials are available for maintenance activities, that is, when materials that are not available should be excluded from the analysis. If the user does not have any preference in terms of material, the optimal solution is calculated considering all materials. If the user chooses “Yes” in the menu shown in Figure 5.10, then the application shows the list of all available materials, as shown in Figure 5.11. The user can select any number of materials using the control key. All chosen materials will then be considered in the analysis to obtain the optimal solution given the required service life. The list shown in Figure 5.11 also provides the option to return to the previous menu.

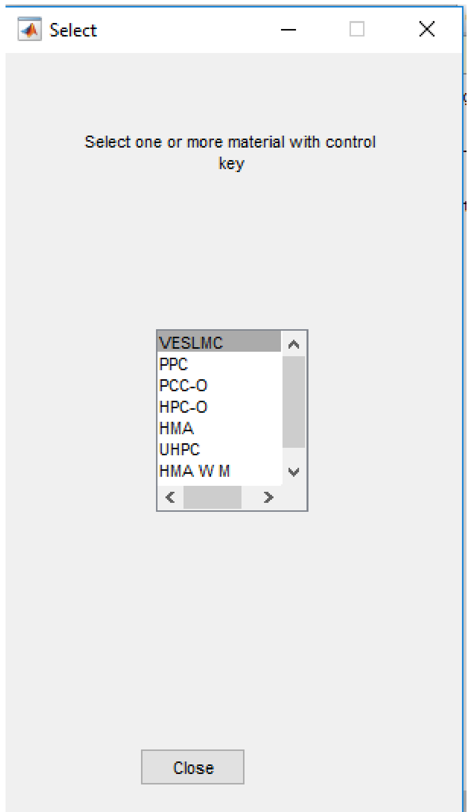


Figure 5.11. Menu showing a list of all available materials for analysis

After the user provides his/her input regarding the choice of material, the application asks the user for the additional input required to execute the analysis, as discussed under Steps 4.1 and 4.2. The results of the analysis are then presented as three choices for the user to achieve the required service life extension. In the first choice, the analysis considers only one material at a time to provide the optimal solution for the required service life extension, as shown in Figure 5.12.

	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. Screenshot showing the results of the required service life extension analysis with one material

As shown in this figure, when a single material or maintenance activity is used to provide the required service life extension, the activity may need to be repeated multiple times. All solutions that will extend service life within ±5 years of the user-specified service life extension are presented.

In the second choice, the analysis considers two materials or maintenance activities to provide the required service life extension, as shown in 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. Screenshot showing the results of the required service life extension analysis with two materials

In the third choice, the analysis considers three materials or maintenance activities to provide the required service life extension, as shown in Figure 5.14.

	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. Screenshot showing the results of the required service life extension analysis with three materials

Note that the results presented in Figures 5.12 through 5.14 are for a service life extension of 50 years. If the required service life extension can be achieved with less than three maintenance actions, then the application will present only two choices (for one and two materials).

Finally, the application asks whether the user wants to see the deterioration curve for any of the solutions from any of the three choices. If the user does, the application generates the selected deterioration curve. The application also allows users to give multiple choices to produce the deterioration curve.

5.5 Summary

This chapter provided detailed step-by-step execution guidelines for the MATLAB-based LCCAM application developed as a next-generation life-cycle cost analysis tool.

6. ENHANCEMENT FOR RELEVANT BRIDGE MANAGEMENT TOOLS

6.1 Introduction

This chapter discusses possible ways the next-generation tool for life-cycle cost analysis developed in this study, LCCAM, can be utilized with other existing bridge management tools like SIIMS and AASHTOWare BrM. Integrating LCCAM with these existing bridge management tools will provide a more efficient way to deal with bridge management and life-cycle cost analysis.

This chapter first briefly discusses the features of these bridge management tools and then provides solutions for integrating these bridge management tools with LCCAM for the efficient management and life-cycle cost analysis of bridges in Iowa.

6.2 Current Practice of the Iowa DOT

SIIMS and AASHTOWare BrM are the two primary bridge management tools used by the Iowa DOT. SIIMS serves as the inspection management system and repository of a variety of data items, such as design documents, historic condition data, NBI data items, and program recommendations, whereas AASHTOWare is a sophisticated bridge management system. The following sections briefly describe SIIMS and AASHTOWare BrM.

6.2.1 SIIMS

Currently, Iowa bridges are inspected following the maximum required interval of every 24 months, as mandated by the FHWA. When necessary, certain bridges are inspected more frequently, usually for a more in-depth inspection preceding project decisions or after any concerning accidents. The data from these inspections are logged into Iowa’s central inspection database, SIIMS. All NBI data required by the FHWA are recorded here, as well as any additional information Iowa chooses to log. This process is explained in Chapter 3 of this report. The data recorded are used by the Quality Control Team of the Iowa DOT Office of Bridges and Structures to suggest maintenance and repair activities to appropriate staff engineers, who then make the necessary decisions for programming.

6.2.2 AASHTOWare BrM

AASHTOWare BrM, previously Pontis, is a sophisticated BMS that has been used in Iowa for several years. It was first developed under an NCHRP project sponsored by the FHWA in the early 1990s and soon thereafter was transferred to AASHTO for further development, maintenance, and support. For over 20 years, BrM has seen dramatic improvements due to technological changes, product innovations, and, most importantly, direct user feedback. As a key product in the AASHTOWare software suite, BrM continues to be widely used as the primary bridge management software application by transportation agencies across the US and internationally. Although BrM has its own detailed element-level modeling framework, some of the models developed during this project can provide inputs for BrM models.

The potential interactions between LCCAM and other BrM tools like AASHTOWare were identified to guide efforts to produce enhancements/input for other in-house tools when feasible and applicable.

6.3 Integration of LCCAM and BMS

Most bridge management systems contain some form of life-cycle cost analysis. According to the results of a three-stage survey of 39 state DOTs, 68% of participants indicated that LCCA is used in their transportation management systems (Rangaraju et al. 2008). Most respondents indicated that LCCA is used in pavement management, whereas the lowest percentage of respondents, about 12.5%, indicated that LCCA is used in bridge management. About 60% of state DOTs mentioned that they have LCC guidelines and that these guidelines focus on LCCA in a way that mainly addresses the needs of the state. For example, the Colorado DOT's guidelines contain the definition and parameters of LCCA and recommend the use of previously collected information in their databases. The results of the survey indicated that 50% of agencies use a software package to perform LCCA. The current BrM software uses a utility function to capture the combination of risk, life-cycle cost, and other significant criteria for the agency.

LCCAM can be directly linked with existing bridge management tools like AASHTOWare BrM. In a way, AASHTOWare BrM predicts the condition rating of a bridge at a future time based on the data provided to the software, or, in other words, it predicts the deterioration curve for the bridge. LCCAM also performs its analysis based on predicted future condition ratings or deterioration curves. In the very first step, LCCAM shows the average deterioration curve for bridges in Iowa, which has been estimated based on SIIMS data. The methodology to develop this curve is discussed in Chapter 4, and the curve itself is shown in Figure 6.1

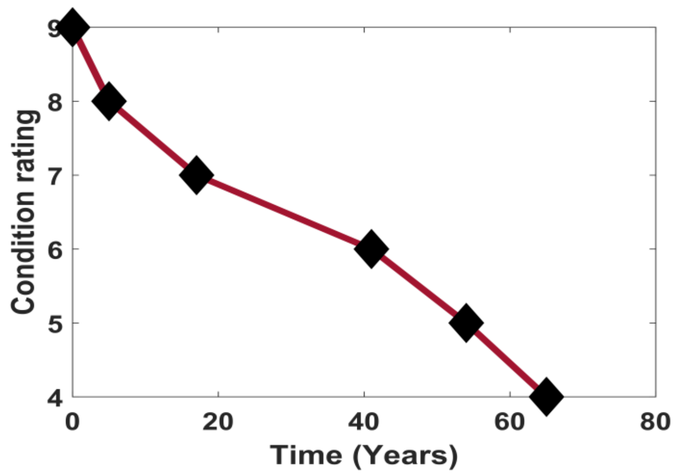


Figure 6.1. Deterioration curve for bridge decks in Iowa

Note that this curve is estimated based on the data available to date. However, this deterioration curve can be updated when new data become available. In this way, AASHTOWare-based condition rating predictions can be incorporated into the LCCAM application for a better life-cycle cost analysis. To do so, LCCAM allows the user to input the average age of each condition rating as a variable instead of using the non-varying deterioration curve and thereby taking the average ages as constants. Before the user inputs these average ages into LCCAM, they can first be evaluated using AASHTOWare BrM. Figure 6.2 shows the case where the average ages are input by the user.

```
Input the average age (in years) of condition rating 9: 20
Input the average age (in years) of condition rating 8: 15
Input the average age (in years) of condition rating 7: 30
Input the average age (in years) of condition rating 6: 15
Input the average age (in years) of condition rating 5: 20
```

Figure 6.2. Screenshot of average ages of condition ratings being input by a user

In this figure, arbitrary inputs for the average ages are given, for example, 20 years for condition rating 9, 15 years for condition rating 8, 30 years for condition rating 7, 15 years for condition rating 6, and 20 years for condition rating 5. The user is always able to input the average ages based on predictions obtained from AASHTOWare BrM. The deterioration curve for this age input is shown in Figure 6.3. The LCCAM application will then use this generated deterioration curve for the life-cycle cost analysis.

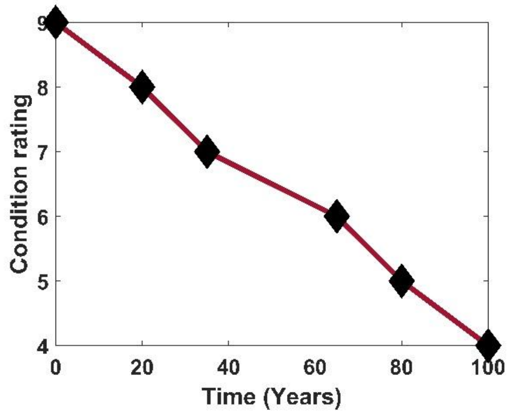


Figure 6.3. Deterioration curve based on input of Figure 6.2

6.4 Summary

In this chapter, a way to integrate existing bridge management systems to the developed next generation tool, LCCAM, is demonstrated. Integrating all available BMS tools can provide a more effective and efficient bridge management tool. In this chapter, it is shown how the AASHTOWare-generated condition rate prediction can be integrated with LCCAM for a better life-cycle cost estimation.

7. SUMMARY, FUTURE RECOMMENDATIONS, AND CLOSING THOUGHTS

The purpose of this report was to provide background information on LCCA and bridge asset management practices and to describe the development and implementation of a preliminary life-cycle cost analysis tool for bridges in Iowa resulting from this research.

Bridge data were sourced from experts in the field, Iowa's SIIMS database, and the National Bridge Inventory database to demonstrate Iowa's ability to supply the data necessary for a stochastic LCCA approach. This approach includes risk analysis in asset management, which has been required by MAP-21 since its enactment in 2012. Monte Carlo simulations and Markov-Chain models were used to prepare the Iowa-specific deterioration models. Survival analysis was used to evaluate the average ages for the different condition ratings based on the available data.

The Iowa DOT's current plan for implementing LCCA in bridge management is to focus its efforts on bridge decks across the state until sufficient data are available to expand the model to the remaining bridge components. Decks were chosen due to the comparatively abundant amount of data and information available for this component. The methodology developed in this study takes into consideration the deterioration rates specific to Iowa bridge decks at two-year intervals and aims to predict the agency and user costs associated with preserving, rehabilitating, and repairing the bridges. Understanding the variability of future investments gives the system an advantage over Iowa's current system, which selects projects based on the lowest bid or estimated initial costs. Instead of a non-varying inflation rate, it is considered as a user input, and other costs are then evaluated using the user-provided inflation rate. In addition, the developed tool is easily extendable for bridge elements other than decks with a few modifications.

Future implementation of the developed preliminary tool requires the following steps:

- Development of degradation curves for all components of the bridge (in addition to the decks as developed in the first phase of the project)
- Refinement of the exposure conditions and their impacts on the degradation curves
- Inclusion of varying inflation rates
- Possibility to load database of new condition states on an annual basis
- A user friendly graphical interface for the tool that is self-explanatory, together with a manual of practice
- Potential workshops for implementation for users

7.1 Criteria for Project Selection

Future continuation of this work will involve determining the project selection criteria that can optimize maintenance schemes. Interviews with Iowa DOT representatives may provide greater insight into the deciding factor(s) between two similar alternatives. Based on this information, different weight factors can be assigned to different activities to take into account the human judgement factor.

The timing of costs can have a significant influence on the final decision, because agencies must understand the potential costs that a bridge may incur each year to properly manage budgets. Studies have proposed the use of not only net present value through discounting but also equivalent uniform annual maintenance costs to determine the expected annual maintenance costs over the lifetime of a bridge (Hawk 2003). Again, due to budget constraints, a bridge's annual maintenance costs may be the deciding factor in choosing a particular maintenance scheme.

Future consultation with Iowa DOT bridge maintenance engineers could help refine the tool so that it can provide results in a preferable context that allows for the most effective and efficient final decisions to be made.

7.2 Integration with AASHTOWare BrM

Lastly, this report, as well as other sources, emphasize the importance of integrating LCCA with BMS. The integration of the two systems could benefit agencies and lead to swifter and smoother assimilation of the system among Iowa DOT personnel. Close work and interviews with Iowa DOT representatives can help future phases of this project establish a user interface that would best suit Iowa DOT users and determine where the tool can be added to the BMS software, AASHTOWare BrM, that Iowa DOT staff currently use. Additional inspection data requirements can be mandated and then input into AASHTOWare BrM to provide a crucial data source for the proposed LCCA tool.

REFERENCES

AASHTO. 2003. *User Benefit Analysis for Highways Manual*. American Association of State Highway and Transportation Officials, Washington, DC.

——. 2010. *AASHTO Bridge Element Inspection Guide Manual*. American Association of State Highway and Transportation Officials, Washington, DC.

ACI Committee 224. 2007. *224.1R-07: Causes, Evaluation, and Repair of Cracks in Concrete Structures*. American Concrete Institute, Farmington Hills, MI.

Abu al-Eis, K. and I. K. LaBarca. 2007. *Evaluation of the Uretek Method of Pavement Lifting*. Wisconsin Department of Transportation, Madison, WI.

Alipour, A. 2010. Life-Cycle Performance Assessment of Highway Bridges under Multi-Hazard Conditions and Environmental Stressors. Dissertation Abstracts International, Vol. 71, No. 6.

Alipour, A. and B. Shafei. 2012. Performance Assessment of Highway Bridges Under Earthquake and Scour Effects. *Proceedings of the 15th World Conference on Earthquake Engineering*. September 24–28, Lisbon, Portugal.

——. 2016a. Seismic Resilience of Transportation Networks with Deteriorating Components. *Journal of Structural Engineering*, Vol. 142, No. 8, pp. C4015015-1–12.

——. 2016b. Assessment of Postearthquake Losses in a Network of Aging Bridges. *Journal of Infrastructure Systems*, Vol. 22, No. 2, pp. 04015023-1–12.

Alipour, A., B. Shafei, and M. Shinozuka. 2011. Performance Evaluation of Deteriorating Highway Bridges Located in High Seismic Areas. *Journal of Bridge Engineering*, Vol. 16, No. 5, pp. 597–611.

——. 2013. Capacity Loss Evaluation of Reinforced Concrete Bridges Located in Extreme Chloride-Laden Environments. *Structure and Infrastructure Engineering*, Vol. 9, No. 1, pp. 8–27.

——. 2012. Prediction of Corrosion Initiation in Reinforced Concrete Members Subjected to Environmental Stressors: A Finite-Element Framework. *Cement and Concrete Research*, Vol. 42, No. 2, pp. 365–376.

Auyeung S. and A. Alipour. 2016. Evaluation of AASHTO Suggested Design Values for Reinforced Concrete Bridge Piers Under Vehicle Collisions. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2592, pp. 1–8.

Auyeung S., A. Alipour, and D. Saini. 2019. Performance-Based Design of Bridge Piers Under Vehicle Collision. *Engineering Structures*, Vol. 191, pp. 752–765.

Azizinamini, A., E. H. Power, G. F. Myers, H. C. Ozyildirim, E. Kline, D. W. Whitmore, and D. R. Mertz. 2014. *SHRP 2 Report S2-R19A-RW-2: Design Guide for Bridges for Service Life*. Second Strategic Highway Research Program, Washington, DC.

Baird, D. C., L. Fotherby, C. C. Klumpp, and S. M. Sculock. 2015. *Reclamation Managing Water in the West: Bank Stabilization Design Guidelines*. SRH-2015-25. U.S. Department of the Interior, Bureau of Reclamation, Denver, CO.

Barlow, P. 1993. Epoxy Injection of Cracked Slabs. *Concrete Construction*. The Aberdeen Group.

Basim, M. C. and H. E. Estekanchi. 2015. Application of Endurance Time Method in Performance-Based Optimum Design of Structures. *Structural Safety*, Vol. 56, pp. 52–67.

Bucher, C. and D. M. Frangopol. 2006. Optimization of Lifetime Maintenance Strategies for Deteriorating Structures Considering Probabilities of Violating Safety, Condition, and Cost Thresholds. *Probabilistic Engineering Mechanics*, Vol. 21, No. 1, pp. 1–8.

Cimline. 2003. *The Guide to Cracksealing*. Cimline, Inc., Plymouth, MN. http://cimline.com/files/education/GuideToCrackSealing-CPMG.pdf.

Cui, Z. and A. Alipour. 2018. Concrete Cover Cracking and Service Life Prediction of Reinforced Concrete Structures in Corrosive Environments. *Construction and Building Materials*, Vol. 159, pp. 652–667.

Cui, Z., A. Alipour, and B. Shafei. 2019. Structural Performance of Deteriorating Reinforced Concrete Columns Under Multiple Earthquake Events. *Engineering Structures*, Vol. 194, pp. 460–468.

DeRuyver, J. and P. Schiefer. 2016. *Thin Epoxy Overlay/Healer Sealer Treatments on Bridge Decks*. Michigan Department of Transportation, Bridge Field Services, Lansing, MI.

Ertekin, A. O., H. H. Nassif, and K. Ozbay. 2008. An LCCA Algorithm for Bridges : A Comprehensive Approach. 87th Annual Meeting of the Transportation Research Board, January 13–17, Washington, DC.

FHWA. 1995. *Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges*. Federal Highway Administration, Washington, DC.

——. 2012. *Risk-Based Asset Management: Examining Risk-Based Approaches to Transportation Asset Management. Report 2: Managing Asset Risks at Multiple Levels in a Transportation Agency*. Federal Highway Administration, Office of Asset Management, Washington, DC.

——. 2019. LTBP InfoBridge: Data. Federal Highway Administration, Long-Term Bridge Performance (LTBP) Program. https://infobridge.fhwa.dot.gov/Data/Dashboard.

Federal Register. 2004. Vol. 69, No. 239 / Tuesday, December 14, 2004 / Rules and Regulations. https://www.govinfo.gov/content/pkg/FR-2004-12-14/pdf/04-27355.pdf.

Furuta, H., T. Kameda, K. Nakahara, Y. Takahashi, and D. M. Frangopol. 2005. Optimal Bridge Maintenance Planning Using Improved Multi-Objective Genetic Algorithm. *Structure and Infrastructure Engineering*, Vol. 2, No. 1, pp. 33–41.

Goh, K. C. and J. Yang. 2014. Managing Cost Implications for Highway Infrastructure Sustainability. International Journal of Environmental Science and Technology, Vol. 11, No. 8, pp. 2271–2280.

Harries, K. A., J. Kasan, and C. J. Aktas. 2009. *Repair Method for Prestressed Girder Bridges*. Pennsylvania Department of Transportation, Bureau of Planning and Research, Harrisburg, PA.

Hatami A. and G. Morcous. 2013. *Life-Cycle Assessment of Nebraska Bridges*. Nebraska Department of Roads, Bridge Division, Lincoln, NE.

Hawk, H. 2003. *NCHRP Report 483: Bridge Life-Cycle Cost Analysis*. National Cooperative Highway Research Program, Washington, DC.

Hearn, G. 2012. *Deterioration and Cost Information for Bridge Management*. Colorado Department of Transportation, Denver, CO.

Hegazy, T., E. Elbeltagi, and H. El-Behairy. 2004. Bridge Deck Management System with Integrated Life-Cycle Cost Optimization. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1866, pp. 44–50.

Helmerich, R., E. Niederleithinger, D. Algernon, D. Streicher, and H. Wiggenhauser. 2008. Bridge Inspection and Condition Assessment in Europe. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2044, pp. 31–38.

Hopwood II, T., II; S. Palle; B. Meade; R. Younce; D. Wells; and C. Goff. 2018. *NCHRP Web-Only Document 251: Spot Painting to Extend Highway Bridge Coating Life: Volume 2: Research Overview*. National Cooperative Highway Research Program, Washington, DC.

Husain, I. and D. Bagnariol. 1999. *Semi-Integral Abutment Bridges Manual*. Ontario Ministry of Transportation, Bridge Office, St. Catharines, ON.

Ilg, P., C. Scope, S. Muench, and E. Guenther. 2017. Uncertainty in Life Cycle Costing for Long-Range Infrastructure. Part I: Leveling the Playing Field to Address Uncertainties. *International Journal of Life Cycle Assessment*, Vol. 22, No. 2, pp. 277–292.

Illinois DOT. 2018. *Deck Slab Repair*. Illinois Department of Transportation. http://www.idot.illinois.gov/Assets/uploads/files/Doing-Business/Manuals-Guides-&-Handbooks/Highways/Bridges/Bridge-Special-Provisions/gbsp28.pdf.

Iowa DOT. n.d. Structure Inventory and Inspection Management System (SIIMS). https://iowadot.gov/siims.

——. 2014. *Bridge Maintenance Manual*. Iowa Department of Transportation, Office of Bridges and Structures, Ames, IA. https://siims.iowadot.gov/IowaDOT_BridgeMaintenanceManual_01JAN2014_FINAL.pdf.

——. 2015. *Bridge Inspection Manual*. Iowa Department of Transportation, Office of Bridges and Structures, Ames, IA. https://siims.iowadot.gov/IowaDOT_BridgeInspectionManual.pdf.

Kang, J., S. Lee, T. Hong, K. J. Koo, C. T. Hyun, and D. Lee. 2007. Life-Cycle Cost Analysis in Bridge Structures: Focused on Superstructure. Life-Cycle Cost and Performance of Civil Infrastructure Systems - Proceedings of the 5th International Workshop on Life-Cycle Cost Analysis and Design of Civil Infrastructure Systems, October 16–18, Seoul, Korea, pp. 191–198.

Khatami, D., B. Shafei, and O. Smadi. 2016. Management of Bridges Under Aging Mechanisms and Extreme Events: Risk-Based Approach. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2550, pp. 89–95.

Kobayashi, K., K. Kaito, and N. Lethanh. 2010. Deterioration Forecasting Model with Multistage Weibull Hazard Functions. *Journal of Infrastructure Systems*, Vol. 16, No. 4, pp. 282–291.

Liu, C., A. Hammad, and Y. Itoh. 1997. Multiobjective Optimization of Bridge Deck Rehabilitation Using a Genetic Algorithm. *Computer-Aided Civil and Infrastructure Engineering*, Vol. 12, No. 6, pp. 431–443.

Liu, M. and D. M. Frangopol. 2004. Optimal Bridge Maintenance Planning Based on Probabilistic Performance Prediction. *Engineering Structures*, Vol. 26, No. 7, pp. 991–1002.

Lund, M. and A.-M. Langlois. 2019. *A Briefing on Life-Cycle Cost Analysis of New Bridge Design Alternatives*. Second Strategic Highway Research Program, Washington, DC.

Mahmoud, H., R. Atadero, K. Rager, and A. L. H. Smith. 2018. *Joint Removal Implications – Thermal Analysis and Life-Cycle Cost*. Colorado Department of Transportation, Denver, CO.

Mao, I.-S. and R.-Y. Huang. 2015. Lifecycle Assessment of Maintenance, Repair and Rehabilitation Costs: A Deterioration Modeling Approach for Bridge Components. *Journal of the Chinese Institute of Civil and Hydraulic Engineering*, Vol. 27, No. 1, pp. 47–57.

Morcous, G. and Z. Lounis. 2005. Maintenance Optimization of Infrastructure Networks Using Genetic Algorithms. *Automation in Construction*, Vol. 14, pp. 129–142.

NYSDOT. 2008. *Fundamentals of Bridge Maintenance and Inspection*. New York State Department of Transportation, Office of Operations, Office of Transportation Maintenance. https://www.yumpu.com/en/document/read/31768775/fundamentals-of-bridge-maintenance-and-inspectionpdf-odot-ftp.

Oman, M. S. 2014. *Concrete Bridge Deck Crack Sealant Evaluation and Implementation*. Minnesota Department of Transportation, St. Paul, MN.

Osman, H. 2005. Risk-Based Life-Cycle Cost Analysis of Privatized Infrastructure. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1924, pp. 192–196.

Patel, C. H. and M. D. Bowman. 2018. *Pack Rust Identification and Mitigation Strategies for Steel Bridges*. Joint Transportation Research Program, Indiana Department of Transportation and Purdue University, West Lafayette, IN.

Pritzl, M. D., H. Tabatabai, and A. Ghorbanpoor. 2015. Long-Term Chloride Profiles in Bridge Decks Treated with Penetrating Sealer or Corrosion Inhibitors. *Construction and Building Materials*, Vol. 101, Part 1, pp. 1037-1046.

Rangaraju, P. R., S. Amirkhanian, and Z. Guven. 2008. *Life Cycle Cost Analysis for Pavement Type Selection*. Clemson University, Clemson, SC.

Reigle, J. A. and J. P. Zaniewski. 2002. Risk-Based Life-Cycle Cost Analysis for Project-Level Pavement Management. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1816, pp. 34–42.

Safi, M., H. Sundquist, and R. Karoumi. 2015. Cost-Efficient Procurement of Bridge Infrastructures by Incorporating Life-Cycle Cost Analysis with Bridge Management Systems. *Journal of Bridge Engineering*, Vol. 20, No. 6, pp. 1–12.

Saassouh, B. and Z. Lounis. 2012. Probabilistic Modeling of Chloride-Induced Corrosion in Concrete Structures Using First- and Second-Order Reliability Methods. *Cement and Concrete Composites*, Vol. 34, No. 9, pp. 1082–1093.

Shafei, B. and A. Alipour. 2015a. Application of Large-Scale Non-Gaussian Stochastic Fields for the Study of Corrosion-Induced Structural Deterioration. *Engineering Structures*, Vol. 88, pp. 262–276

——. 2015b. Estimation of Corrosion Initiation Time in Reinforced Concrete Bridge Columns: How to Incorporate Spatial and Temporal Uncertainties. *Journal of Engineering Mechanics*, Vol, 141, No. 10, pp. 04015037-x–xx

Shafei, B., A. Alipour, and M. Shinozuka, 2013. A Stochastic Computational Framework to Investigate the Initial Stage of Corrosion in Reinforced Concrete Superstructures. *Computer‐Aided Civil and Infrastructure Engineering*, Vol. 28, No. 7, pp. 482–494

Stallings, J. M., T. E. Cousins, and T. E. Stafford. 1996. Effects of Removing Diaphragms from Steel Girder Bridge. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1541, pp. 183–188.

Thompson, P. D. and R. W. Shepard. 2000. *AASHTO Commonly-Recognized Bridge Elements: Successful Applications and Lessons Learned*. Prepared for the National Workshop on Commonly Recognized Measures for Maintenance.

United Professional Caulking & Restoration. n.d. *Crack Chasing Concrete Walls*. United Professional Caulking & Restoration, Inc., Seahurst, WA. http://www.masonryinstitute.com/wp-content/uploads/Crack-Chasing-Concrete-Walls.pdf.

Washer, G., M. Hammed, and H. Brown H. 2017. *Bridge Maintenance Program for the City of Columbia, Missouri*. Midwest Transportation Center, Iowa State University, Ames, IA. https://intrans.iastate.edu/app/uploads/2018/03/columbia_mo_bridge-_mtc_program_w_cvr-1.pdf.

Walls III, J. and M. R. Smith. 1998. *Life-Cycle Cost Analysis in Pavement Design-Interim Technical Bulletin*. Federal Highway Administration Office of Engineering, Washington, DC.

Wipf, T. J., F. S. Fanous, F. W. Klaiber, and A. S. Eapen. 2003. *Evaluation of Appropriate Maintenance, Repair, and Rehabilitation Methods for Iowa Bridges*. Department of Civil and Construction Engineering, Iowa State University, Ames, IA.

Wipf, T. J., L. F. Greimann, A. H. Khalil, and D. Wood. 1998. *Preventing Cracking at Diaphragm/Plate Girder Connections in Steel Bridges*. Center for Transportation Research and Education, Iowa State University, Ames, IA.

Zhang, M. and A. Alipour. 2020. A Two-Level Mixed-Integer Programming Model for Bridge Replacement Prioritization. *Computer-Aided Civil and Infrastructure Engineering*, Vol. 35, No. 2, pp. 116–133.