DISSERTATION

A STUDY ON BRIDGE INSPECTIONS:
IDENTIFYING BARRIERS TO NEW PRACTICES AND PROVIDING STRATEGIES FOR CHANGE

Submitted by

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In partial fulfillment of the requirements

For the Degree of Doctor of Philosophy

Colorado State University

Fort Collins, Colorado

Summer 2021

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ABSTRACT

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Bridge inspections are one of the key elements required for a successful bridge management process to ensure adequate bridge performance. Inspections significantly inform maintenance decisions and can help in managing maintenance activities to achieve a reliable bridge network. In the United States (U.S.) routine visual inspections are required for most bridges at a maximum interval of 24-months regardless of the bridge condition. However, limitations of current bridge inspection practices impact the quality of information provided about bridge condition and the subsequent decisions made based on that information. Accordingly, the overarching goal of this research project is to support bridge inspection practices by providing a systematic and rational framework for bridge inspection planning and identifying the factors that can facilitate innovation and research transfer in the bridge inspection field. To do so, this dissertation includes three separate yet related studies; each focusing on essential aspects of bridge inspection planning.

Much research in bridge inspection has been conducted to improve the inspection planning process. The first study provides an overview of current bridge inspection practices in the U.S. and conducts a systematic literature review on innovations in the field of bridge inspection planning to identify research gaps and future needs. This study provides a background on the history of bridge inspection in the U.S., including current bridge inspection practices and their limitations, and analyzes the connections between nondestructive evaluation techniques, deterioration models and bridge inspection management. The primary emphasis of the first study is a thorough analysis of research proposing and investigating different methodologies for inspection planning. Studies were analyzed and categorized into three main types of inspection planning approaches; methods that are based on: reliability, risk analysis, and optimization approaches. This study found that one of the main barriers that may be preventing the implementation of

new inspection planning frameworks in practice is that the approaches presented focus on a single bridge element or deterioration mechanism in the decision-making process. Additionally, it was concluded that approaches in the literature are either complex to apply or depend solely on expert judgement.

Limitations of the uniform calendar-based approach used to schedule routine inspections have been reported in the literature. Accordingly, the objective of the second study is to provide a new systematic approach for inspection planning that integrates information from bridge condition prediction models, inspection data, and expert opinion using Bayesian analysis to enhance inspection efficiency and maintenance activities. The proposed uncertainty-based inspection framework can help bridge owners avoid unnecessary or delayed inspections and repair actions, determine the inspection method, and consider more than one deterioration process or bridge component during the inspection planning process. The inspection time and method are determined based on the uncertainty and risks associated with the bridge condition. As uncertainty in the bridge condition reaches a defined threshold, an inspection is scheduled utilizing nondestructive techniques to reduce the uncertainty level. The framework was demonstrated on a new and on an existing reinforced concrete bridge deck impacted by corrosion deterioration. The results showed that the framework can reduce the number of inspections compared to conventional scheduling methods, while also reducing the uncertainty regarding the transition in the bridge deck condition and repair time.

As identified through the first study, over the last two decades many researchers have focused on providing new ideas to improve conventional bridge inspection practices, however, little guidance is provided for implementing these new research products in practice. This, along with resistance to change and complexity of the proposed ideas, resulted in a lack of consistency and success in applying new technologies in bridge inspection programs across state departments of transportation (DOTs). Accordingly, the third paper presents a qualitative study set out to identify the factors that can help improve research products and accelerate change and research transfer in bridge inspection departments. This study used semi-structured interviews, written interviews, and questionnaires for data collection and engaged

with twenty-six bridge staff members from different DOTs. The findings of this study are expected to be both specific to changes in bridge inspection practice and have some generalizability to other significant changes to engineering practice at DOTs. To improve research products, this study suggested that researchers need to collaborate more with DOT staff members and provide relevant research products that are not specific to certain bridge cases and can be applied on different bridges. Also, to facilitate change in transportation organizations, change leaders should focus on showing the need for change, gaining support from the FHWA, allocating the required resources, and enhancing the capacity of DOT staff members through training and effective communication. The investigation also presented participants' opinions on some of the aspects related to conventional inspection practices such as their support of a uniform inspection interval over a variable interval, and the main barriers limiting the use of NDE methods.

This study contributes to the body of knowledge in the bridge inspection field by providing a new inspection planning approach that depends on the uncertainty and the risks associated with the bridge condition and uses both computational methods and expert judgment allowing bridge owners select inspection time and method while considering more than one deterioration process or bridge element. In addition, this study presents some of the factors that can help reduce the gap between research and practice and facilitate innovation and change in transportation organizations.

ACKNOWLEDGMENTS

I would like to express my deepest gratitude for my advisors Dr. Rebecca A. Atadero and Dr. Mehmet E. Ozbek. In addition to their support and friendship over the past few years, they have provided the unwavering source of inspiration, determination, and leadership that was so essential for the successful execution of this research project. I would also like to thank my committee members Dr. Gaofeng Jia and Dr. DaeSeok Chai for their constructive comments and directions.

I am grateful to my family and friends for their continuous support and kindness. Special thanks to my wife, Nouran, whom I share with her this success, without her help and brave spirit we would not have been where we are today. Last but not least, I am grateful to Zein and Jaida for always putting a smile on my face, I hope I made you proud.

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CHAPTER 1: INTRODUCTION

Bridge inspection is one of the main components of the bridge management process that can help maintain a reliable and safe bridge network. Valuable and timely bridge inspections can help bridge owners monitor the damage modes affecting their bridge stock while optimizing the cost of repair activities, and reducing the overall expenditure on bridges (Kim, Frangopol, & Soliman, 2013). However bridge inspection management is a non-trivial process impacted by various uncertainties and contradicting objectives (Morcous, Lounis, & Cho, 2010). In the United States (U.S.), bridge inspections are conducted based on the National Bridge Inspection Standards (NBIS), which were developed by the Federal Highway Administration (FHWA) after the collapse of the Silver Bridge in 1967 (Dorafshan & Maguire, 2018). The NBIS requires that, for almost all bridges, a routine inspection should be conducted every two years using visual inspection, and for structurally deficient bridges, annual inspections should be conducted (FHWA, 2012b).

This uniform approach used to schedule inspections was established based on expert judgement 50 years ago without any quantitative justification (Washer, Connor, Nasrollahi, & Provines, 2016a). Also this approach does not consider the inspection requirements of a bridge based on its age and deterioration process, which can result in the same inspection interval and procedure for a new or aging bridge (Washer et al., 2014). Further, visual inspections are highly subjective, arduous, and depend mainly on the inspector's experience (Lin, Pan, Wang, & Li, 2019). Visual inspections, if not accompanied by a chain drag test, are limited to surface defects and can only locate subsurface deteriorations (i.e., rebar corrosion, delamination, and voids) that have reached a significant extent and have emerged to the surface of the bridge element (Phares et al., 2004). Given the limited information that can be collected from visual inspections, more in-depth inspections are to be conducted if the inspector suspects a problem with the bridge during routine inspections (Hearn, 2007). Repeating inspections with more sophisticated techniques can consume a lot of time and money. Moreover, bridge inspection methods commonly remain constant throughout the life span of the bridge despite the fact that bridge deterioration processes can change over time, which is another major limitation to current inspection practices (Agrawal & Alampalli, 2010).

Based on the limitations of current inspection practices a variety of researchers have focused on improving the inspection planning process and the tools used in evaluating the bridge performance and managing inspection results (Clarke-Sather, McConnell, & Masoud, 2021). However, despite the research efforts and their potential to improve bridge inspections, there still maintains a lag between research findings and implementation in the bridge inspection field and transportation agencies still depend on the conventional inspection methods (Zulifqar, Cabieses, Mikhail, & Khan, 2014).

This dissertation consists of three separate yet related studies; each focusing on the field of bridge inspection. The research starts by conducting a literature review on the limitations of current inspection practices and prior research on bridge inspection planning (presented in the first study). Then the information found in the literature was used to develop a new framework for bridge inspection planning to overcome the limitations of current practices (presented in the second study). Finally, a qualitative study was conducted using questionnaires and interviews to help identify the barriers slowing the implementation of research into practice in the bridge inspection field (presented in the third study). With this introduction, the first chapter of this dissertation presents the research objectives and organization for the remainder of the dissertation.

1.1. Research Objectives

The primary purpose of this dissertation is to help improve bridge inspections by providing a systematic framework for bridge inspection planning and investigating the reasons behind the gap between researchers and practitioners in the field of bridge inspection. This study has been motivated by (1) the limitations of the fixed approach used to schedule bridge inspections, (2) the problems associated with visual inspections, (3) the uncertainty associated with the bridge deterioration process, and (4) the capabilities of new research products that can help improve inspection practices such as non-destructive evaluation (NDE) methods and deterioration prediction models.

The first study in this dissertation provides a comprehensive literature review on the research that has been conducted in the field of bridge inspection planning while identifying research gaps and needs. The objectives of this study are to :

1. Conduct an overview on the history of bridge inspection, current bridge inspection practices and their limitations in the U.S., and technologies available for evaluating bridge performance.
2. Analyze the connection between NDE techniques, deterioration models and bridge inspection.
3. Perform a systematic literature review on inspection planning frameworks that have been proposed in the literature.
4. Identify research gaps and needs for implementing new inspection planning frameworks in practice.

The second study presents a new uncertainty-based inspection planning framework that enables bridge inspection planners to determine the inspection time and technique based on the bridge condition, while minimizing unnecessary or delayed inspections and improving the quality of collected inspection data. This approach will help bridge owners move away from the costs and risks of the uniform inspection interval used in current practices. The objectives of the second study are:

1. Provide a systematic approach for integrating information from bridge condition prediction models, NDE inspection data, and expert judgement to enhance the understanding of bridge condition, allowing for a more efficient use of inspection resources and better decision making about maintenance activities.
2. Develop an inspection planning framework that can help bridge owners choose inspection time while considering more than one deterioration mechanism or bridge component.
3. Provide a quantitative measurement that bridge inspectors can use to report the condition of the bridge more accurately than the conventional methods.

4. Provide a clear procedure that can help bridge inspection planners choose the inspection method while considering the bridge deterioration stage, model parameters that need to be updated, and inspection accuracy.
5. Incorporate new inspection data in the decision process to improve the future selection of inspection time and method and reduce uncertainty regarding the bridge condition.

The third study presents the results of a qualitative analysis conducted to provide supporting information that can help improve research products and facilitate change and research transfer in departments of transportation (DOTs). The study involved bridge staff members from different DOTs in the U.S., and information was gathered using questionnaires and interviews. The objectives of this study are :

1. Analyze current inspection practices and the participants' opinions on some of the approaches related to bridge inspection such as the uniform approach used to schedule inspections, visual inspection and NDE methods.
2. Identify the actions that can be taken by researchers and DOTs to help improve the effectiveness of research products in the transportation field and promote their utilization.
3. Identify the factors that should be considered from an organizational change perspective that can help accelerate change and research implementation in bridge inspection practices.

1.2. Research Organization

To address our research objectives the dissertation is presented in three separate, yet related studies organized as follows:

Chapter 2: A State-of-the-Art Review of Bridge Inspection Planning: Current Situation and Future Needs: This chapter presents the first study which focuses on conducting a literature review on current bridge inspection practices, associated limitations, and inspection planning frameworks presented by other researchers. The first study was submitted to the ASCE Journal of Bridge Engineering and is still under review.

Chapter 3: A Comprehensive Uncertainty-Based Framework for Inspection Planning of Highway Bridges: This chapter presents the second study which provides a systematic and rational approach for choosing the inspection time and method. This second study has been published in MPDI Infrastructures Journal.

Chapter 4: Transferring Research Innovations in Bridge Inspection Planning to Bridge Inspection Practice: This chapter presents the third study that shows the results of a qualitative analysis involving different staff members from state DOTs, to identify the gap between research and practice and help facilitate research implementation in the bridge inspection field. The goal is to submit the third study as a research report to the Mountain-Plains Consortium (MPC) and then submit it to the Transportation Research Record (TRR) Journal after adjusting it according to the journal's requirements.

Chapter 5: Conclusion and Future research recommendation: The last chapter of this dissertation highlights the main conclusions of the three studies, research contributions and the recommendations for future researchers in the field.

CHAPTER 2: A STATE-OF-THE-ART REVIEW OF BRIDGE INSPECTION PLANNING: CURRENT SITUATION AND FUTURE NEEDS

2.1. Introduction and Purpose

Bridges are one of the main components of a community's infrastructure and have significant impact on the community's traffic flow and economy. In 2019, about 7.5% of bridges in the United States (U.S.) were considered structurally deficient and many bridges require rehabilitation projects with an estimated cost of $125 billion, which represents a significant backlog given current funding levels (ASCE, 2021). In the near future many additional bridges will require major rehabilitation projects, as most of the bridges in the U.S. were designed for a lifespan of 50 years while currently 42% of the bridges in the U.S. are at least 50 years old (ASCE, 2021). Thus, maintenance activities need to be economically conducted and prioritized depending on the bridge condition (Abdelkhalek & Zayed, 2020). Since maintenance activities mainly depend on the information collected during inspection, accurate and timely inspection of bridges is important in optimizing bridge maintenance strategies and avoiding unnecessary repair activities, which can help lighten the burden on limited budgets available for bridge rehabilitation.

Moreover, constrained budgets lead to delayed maintenance actions and repairing bridges that have reached a poor condition is more expensive than conducting maintenance on a bridge while deterioration is in its early stages (ASCE, 2020). Valuable and timely bridge inspections can help bridge owners monitor the damage modes that affect their bridge stock throughout its service life and capture early stages of deterioration. Catching damage early allows preserving and prompt maintenance actions to be performed, improving the bridge management process and reducing the overall bridge life cycle cost (Soliman, Frangopol, & Kim, 2013). In the U.S., bridge inspections are conducted based on the National Bridge Inspection Standards (NBIS). The NBIS requires that, for almost all bridges, a routine inspection should be conducted at least every 24 months (FHWA, 2012b). Routine inspections are the most common type of inspections conducted on bridges and usually completed using visual inspection (Graybeal et al., 2001). In this study we focus on routine bridge inspections and the different approaches presented in the literature that can be used in inspection planning.

Due to the importance of bridge inspections and how they can affect the decision process of bridge owners, there has been a significant amount of research about inspection planning. To improve bridge inspections in the U.S., in 2008 a team of bridge inspection scholars was formed to study bridge inspections in European countries, specifically the aspects related to quality assurance, and provide bridge owners and the Federal Highway Administration (FHWA) with ideas that can help refine bridge inspection programs in the U.S. The study provided several recommendations; one of the recommendations was the need to develop a rational approach or alternative for determining the frequency of inspections based on the scope of the inspection, bridge condition and engineering judgement (Everett et al., 2008). Also, the FHWA is starting to encourage new approaches for inspection planning that are based on the bridge condition and can enhance inspection efficiency (FHWA, 2019). Accordingly, the purpose of this study is to review different bridge inspection planning frameworks that have been proposed in the literature to provide the reader with an update on different perspectives in the field of bridge inspection planning and help bridge owners develop new methodologies for planning inspections. This review will start by reviewing the history of bridge inspection, current bridge inspection practices and their limitations in the U.S., and technologies available for evaluating bridge performance. Then, a systematic review of studies that present innovative methods and frameworks for bridge inspection planning will be presented. The findings of this review will help in characterizing the current state of bridge inspection programs and future needs to enhance inspection programs and reduce the gap between inspection practice and research. It should be noted that although maintenance actions and inspections are strongly related, the focus of this paper is on bridge inspection planning and scheduling, not maintenance decision making.

2.2. Background

2.2.1. Brief History of Bridge Inspection in the United States

During the 1950's and the early 1960's as the U.S. significantly expanded its roadway infrastructure, including the interstate highway system, the focus of bridge programs was mainly on constructing new bridges; and inspections and maintenance of bridges were very limited (Shiraki et al., 2007). In 1968 the National Bridge Inspection Program was introduced as a result of the collapse of the Silver Bridge in 1967 killing 46 people (Lee & Kalos, 2014). Accordingly, the NBIS were established in 1971 to provide guidance on the frequency of bridge inspections, bridge rating system, report formats and qualifications of bridge inspectors (Dorafshan & Maguire, 2018). To support bridge inspections further, three bridge inspection manuals were introduced in the early 1970s: 1) The FHWA Bridge inspector Training Manual 70, 2) the American Association of State Highway Officials (AASHO) Manual for Maintenance Inspection of Bridges, and 3) The FHWA Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges (Ryan, Mann, Chill, & Ott, 2012). By 1979 the Manual for Maintenance Inspection of Bridges, and the FHWA Recording and Coding Guide were revised to help state Departments of Transportation (DOTs) in following the NBIS requirements (Ryan et al., 2012). After the collapse of the Mianus River Bridge and the Schoharie Creek Bridge in the 1980s due to hanger failure and pier scour, respectively, new policy memorandums for inspecting fracture critical details and underwater components were provided by the federal authority (Swenson & Ingraffea, 1991). Also in 1988 the FHWA issued one of the most important revisions for the Recording and Coding guide, the helped in shaping the NBIS in the next decade (Ryan et al., 2012).

In 1990, the FHWA introduced the Bridge Inspector's Reference Manual (BIRM) as a revision of the FHWA Bridge Inspector Training Manual. The BIRM has been revised in 2006, 2012 and is still under continuous improvement and development (Ryan et al., 2012). The BIRM and the NBIS were the main reference for bridge inspections and training programs for bridge inspectors until 1991, when the federal government mandated every state DOT to develop a bridge management system (BMS) specific for every state bridge inventory (Tarighat & Miyamoto, 2009). From this new era, a comprehensive bridge management software package named "PONTIS" currently known as "AASHTOWare Bridge"; emerged in 1998 to help bridge owners manage bridge inspections, and develop a database of inspection records with up to date and organized bridge inspection reports, and pictures (Thompson, Small, Johnson, & Marshall, 1998). During the same decade, another software named "BRIDGIT" was developed by the National Cooperative Highway Research Program (NCHRP), which was used as a guide for decision making process for local bridge inspection agencies (Khan, 2000).

In 1995, the FHWA updated the revised Recording and Coding Guide, and required that bridge conditions reported on the National Bridge Inventory (NBI) database should follow the FHWA Recording and Coding guide (FHWA, 1995; Ryan et al., 2012). This guide required reporting the condition of the bridge's main components, which were the bridge deck, superstructure, and substructure. The condition was reported on a scale from 0 to 9, in which 0 and 9 described a failing and a new component respectively (FHWA, 1995). A component with condition rating less than 4 was considered structurally deficient. According to several studies, this wide scale of condition ratings and only focusing on the overall bridge components resulted in many uncertainties and reduced knowledge of the specific bridge elements, which made it hard to use the collected information for maintenance decision making (Phares et al., 2004; Thompson & Shepard, 2000). Therefore, around 1997, the American Association of State Highway and Transportation Officials (AASHTO) presented the AASHTO Guide to Commonly Recognized (CoRe) Structural Elements (AASHTO, 1997), which provided a system for rating specific bridge elements using a smaller rating scale of three to five condition states, depending on the bridge element.

The AASHTO CoRe guide did not only address the limitations of the NBI rating system but was also considered as the basis for a new edition to the Manual for Condition Evaluation of Bridges (MCE) developed by AASHTO in 1994. The MCE was intended to help identify the bridge condition and load capacity, but did not have a clear procedure for rating the bridge condition (AASHTO, 1994). To reduce the gap between the NBI and the AASHTO rating systems, in 1997 the FHWA promoted a new software program that helped in translating CoRe element data to the NBI rating system (FHWA, 2012a). This software helped in unifying the inspection reports uploaded on the NBI database which currently contains bridge inspection data for more than 600,000 bridges in the U.S (Hasan & Elwakil, 2020).

After the collapse of the I-35W bridge in 2007 several studies and reviews were conducted by the American Society for Civil Engineers (ASCE) and AASHTO to revise highway bridge inspection standards and evaluation programs used across the U.S. (ASCE/SEI-AASHTO-Ad-hoc, 2009). In 2010, the AASHTO Guide Manual for Bridge Element Inspection (GMBEI) was provided (AASHTO, 2011a) replacing the AASHTO CoRe guide to improve the quality of the data collected during inspection and expand element level inspection. In 2013, the first edition of the AASHTO Manual for Bridge Element Inspection (MBEI) was provided (AASHTO, 2013) as a refinement for the GMBEI (Farrar & Newton, 2014). While in 2019, a second edition for the MBEI was released to supersede the first edition and is currently used by most DOTs (AASHTO, 2019). The AASHTO MBEI includes some significant improvements and provides different elements and element units than the CoRe guide (AASHTO, 2019). Also, the MBEI discusses the different distress paths associated with bridge condition state. The multiple distress approach provides bridge owners with the opportunity to consider different damage modes during the condition assessment process (Farrar & Newton, 2014).

In 2012, The Moving Ahead for Progress in the 21st Century Act (MAP-21) was introduced as an effort to improve the nations highway system (MAP-21, 2012). Among other aspects, MAP-21 required that after October 1st 2014 element level data must be collected during any inspections on the National Highway System (NHS) (Campbell, Perry, Connor, & Lloyd, 2016). Currently, the FHWA plans on updating the NBIS through the Notice of Proposed Rule Making (NPRM). This new edition of the NBIS was required by MAP-21 and will focus on: updating the training approaches and required certifications for bridge inspectors, update the frequency of inspections and establishing a uniform procedure for reporting and monitoring critical findings during inspections (FHWA, 2019). Table 2.1 provides a timeline of bridge inspection history in the U.S.

Table 2.1. A timeline of bridge inspection in the U.S.

Year	Main events
1967	Collapse of the Silver Bridge killing 46 people
1968	National Bridge Inspection Program introduced
1970	The American Association of State Highway Officials (AASHO) Manual for Maintenance Inspection of Bridges was released
1971	National Bridge Inspection Standards (NBIS) established, and the FHWA Bridge Inspector Training Manual 70 was released
1972	The FHWA Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges was released.
1978	The American Association of State Highway and Transportation Officials (AASHTO) Manual for Maintenance Inspection of Bridges was revised
1979	The FHWA Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges was revised
1983	Collapse of the Mianus River Bridge due the failure of fracture critical details
1987	Collapse the Schoharie Creek Bridge due to pier scour
1988	-Introduction of the policy memorandum for inspecting scoured bridge elements and fracture critical details by FHWA -The FHWA issued one of the most important revisions for the Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges
1990	FHWA introduced the BIRM as a revision of the FHWA Bridge Inspector Training Manual
1991	Federal government mandated every DOT to develop a BMS
1994	AASHTO developed the Manual for Condition Evaluation of Bridges (MCE)
1995	The FHWA required that bridge conditions reported on the NBI should follow the FHWA Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges
1997	- AASHTO presented the guide to (CoRe) which provided a system for rating specific bridge elements -FHWA promoted a new software program that translates CoRe element data to the NBI rating system
1998	Emergence of PONITS (AASHTOWare) and BRIDGIT
2005	NBIS was revised to reduce ambiguity and add the inspection guidelines for scoured bridge elements and fracture critical details.
2006	BIRM was revised to provide new guidelines for qualifications of bridge inspectors
2007	Collapse of the I-35W bridge
2010	AASHTO Guide Manual for Bridge Element Inspection (GMBEI) published
2012	-BIRM was revised to include new technologies in bridge inspections and updated training programs -The Moving Ahead for Progress in the 21st Century Act (MAP-21) was passed.
2013	The AASHTO Manual for Bridge Element Inspection (MBEI) was published
2014	Element level inspections were mandated by MAP-21 for any inspections on the NHS
2019	The second edition of the AASHTO (MBEI) was released
Expected Future	Updating the NBIS, inspection techniques and planning programs

2.2.2. Current Bridge Inspection Practices

There are different types of bridge inspections in the U.S.: initial, routine, in-depth, damage, fracture critical, underwater, and special inspection (AASHTO, 2011b, 2016). The inspection frequency and detail depend on the inspection type and bridge complexity. Table 2.2 provides a brief description of each inspection type based on the information provided in (Hearn, 2007). Routine inspection is the most common type of inspection and is mainly based on visual evaluation. Simple inspection methods like chain drag or hammering can also be used during routine inspections to locate cracks on bridge decks. In some special cases when deficiencies are not detected using visual inspection or when severe deterioration is found, more in-depth inspections using more advanced inspection tools are required (Hearn, 2007).

Table 2.2. U.S. Bridge Inspection types (Hearn, 2007)

Inspection	Description
Initial	First inspection to be conducted on a bridge as the bridge becomes part of the bridge inventory, to determine all baseline structural conditions.
Routine	Regular bridge inspection to evaluate bridge physical and functional condition and to identify any changes from previous inspections.
In-depth	A more detailed inspection for one or more members of the bridge, to identify deteriorations that were clearly identified during routine inspection.
Damage	An unscheduled inspection to evaluate bridge condition after a natural hazard or human actions
Fracture Critical	An inspection on fracture critical details that may include visual or another nondestructive evaluation method
Under water	Inspection of the underwater substructure and which generally requires diving or other techniques
Special	A scheduled inspection to evaluate a specific deterioration or suspected deficiency

The FHWA requires a routine inspection for almost all bridges at regular intervals not to exceed 24 months so that inspectors can monitor defects and deterioration (FHWA, 2012b). However certain bridges require inspections at shorter intervals; so based on the bridge age, traffic characteristics and known deficiencies, bridge owners can reduce inspection intervals and conduct inspections on a frequency less than 24 months. (FHWA, 2012b). For some cases, with express approval from the FHWA, routine inspections can be conducted over longer periods not exceeding 48 months (AASHTO, 2016). During routine inspections, a qualified bridge inspector is responsible for reporting the degree of damage for each bridge element within reach following an element numbering system and a checklist (AASHTO, 2019). Then all inspected elements are rated and documented using standard inspection reports (FHWA, 1995), which are uploaded to the state Bridge Management System (BMS) and NBI database, to be accessible for other bridge inspectors (Farrar & Newton, 2014).

Due to the previously discussed limitations of the NBI rating system and for more precise condition assessment, the standard inspection report currently used by almost every DOT is a combination of the NBI rating system (FHWA, 1995) and the AASHTO element-level rating system (AASHTO, 2019) . The

AASHTO element level rating system is only required for inspections conducted on the NHS (MAP-21, 2012) and consists of mainly four condition states (CSs); good (CS1), fair (CS2), poor (CS3), and severe (CS4) (AASHTO, 2019). In the AASHTO element level rating system the primary bridge components such as the bridge deck, super-structure and sub-structure are divided into a group of minor elements. For example, a steel bridge superstructure can be divided into main girders, stringers, and splices. These minor elements are rated according to the element level system. Then based on the rating of the elements, load path, and bridge management elements (e.g., coatings and protective systems) the primary bridge component such as the steel superstructure is assigned an overall score from 0 to 9 according to the NBI rating system and the FHWA requirements. This conversion from the element level system to the NBI system can be conducted using a specific FHWA translator program as mentioned earlier (FHWA, 2012a) and is necessary to maintain a reliable NBI database (Lin et al., 2019). Further, a load rating of the bridge capacity is estimated to determine the suitable actions that should be conducted for the bridge (AASHTO, 2019).

To help state agencies in managing their reporting system and to have a nationwide standardized system, the new AASHTO (MBEI) divides the bridge elements in two main categories; the national bridge elements (NBEs) and bridge management elements (BMEs) (AASHTO, 2019). The NBEs are the primary bridge components and the elements that form these major components. The NBEs should be consistent among state agencies to standardize the national rating system (Farrar & Newton, 2014). The BMEs are elements such as the coating and protective systems, that depend on the agencies bridge management system. The BMEs rating system are left general and can be modified according to the materials and designs used by the local bridge managers (Farrar & Newton, 2014) .

2.2.3. Identified Limitations of Current Bridge Inspection Practices

There are a variety of physical and process constraints that affect current bridge inspection practices. According to Hallermann and Morgenthal (2014), bridge inspectors are exposed to risks and potential injuries during routine visual inspections when attempting to reach areas with limited accessibility. Some inspectors revealed that the factors that affected their inspections were the fear of traffic and height, lack of accessibility to some bridge locations, and bridge complexity (Graybeal et al., 2001). Also, equipment and access vehicles used during visual inspection such as ladders, man-lifts and scaffolding are expensive, in many cases can disturb the flow of traffic, are hard to schedule, add load on the bridge and might require skilled workers to operate. These additional costs can form a budget constraint on a bridge owner (Zink & Lovelace, 2015).

Bridge inspection practices and the quality of the data collected during inspections can be significantly affected by the inspectors' training and qualifications, and the number of inspectors conducting the inspection (Ahamdi, 2017; Dietrich, Inkala, & Männistö, 2005; Graybeal et al., 2001). Therefore, the NBIS are very specific in stating the minimum qualifications and training required by each staff member in a state bridge inspection program. For example, a program manager needs to be registered as a professional engineer (PE) and is required to complete an FHWA approved comprehensive training course which covers all aspects of bridge inspection and enables inspectors to evaluate bridge condition. Similarly, team leaders need to complete the same course and attain other NBIS requirements if they are not registered as professional engineers (FHWA, 2012b). As for other bridge inspectors assisting the team leader there are no specific federal requirements (FHWA, 2012b). However these NBIS requirements are the minimum standards and other National Highway Institute and DOT in-house courses are available to improve inspectors' knowledge (Ryan et al., 2012). Also, most DOTs conduct refresher training courses for bridge inspectors, although Hearn (2007) found that there is a variability in the rate DOTs conduct refresher courses. Some DOTs conduct refresher training annually while other DOTs can reach five years without conducting a refresher training for staff members (Hearn, 2007).

In addition, visual inspection can lead to limitations in the quality of data that is collected during routine bridge inspections. In many occasions visual inspection and element level evaluation are subjective and mainly depend on the inspector's experience (Bu et al., 2014; Lin et al., 2019). A study reported in Pines and Aktan (2002), found that until 2002, 56% of condition ratings for concrete bridges in the NBI were inaccurately reported and about 95% of these bridges were inspected using only visual inspection. A trial bridge was used in a study by the FHWA to assess the variability in inspection reports based on different inspectors' qualifications, the bridge was skew with some support deterioration and fracture critical details. Only 25% of inspectors were able to detect the defects in the support conditions and 50% of inspectors were able to identify the fatigue critical details. Also, only half of the inspectors took photos of the deteriorated locations. There was a significant variability in the time inspectors predicted will be suitable to conduct the inspection, the predicted times ranged from a few minutes to several hours. It was noticed that 95% of condition ratings for a specific element assigned by inspectors varied within approximately ± 2 rating points from the average inspector rating and 68% of the condition ratings were within ± 1 rating points of the mean (Graybeal et al., 2001). Moreover, visual inspections are limited to surface defects, and can only locate subsurface deteriorations (i.e., rebar corrosion, delamination and voids) that have reached a significant level and have emerged to the surface of the bridge element (Kim, Gucunski, & Dinh, 2019; Morcous et al., 2010). A recent study conducted by Campbell, Connor, Whitehead, and Washer (2020) evaluated the performance of 30 bridge inspectors in conducting hands on visual inspection for 147 bridge specimens with fatigue cracks. The results showed substantial variability and the average detection rate was 65%.

An additional challenge facing current bridge inspection practice and subsequent management decision making is how bridge inspection results are documented and recorded. Many current BMSs don't facilitate the coordination process between management of all stages of the entire bridge life cycle, since they contain only bridge inventory and inspection data which do not identify the standard information needed for future bridge repairs (Shirolé, 2010). For optimum maintenance decisions other data such as design drawings, photographs, deterioration rates, bridge layouts and bridge visualization models are required for better maintenance decisions and for identifying the bridge probability of failure at a certain time (McGuire, Atadero, Clevenger, & Ozbek, 2016; Sacks et al., 2018). In addition, the collected inspection data is associated with several uncertainties and inconsistencies because every state DOT has its own recording procedures. Although each state manages its bridge network within the standards of the NBIS, for complex bridges or fatigue sensitive bridges each state has its own management system, leading to a lot of inconsistencies in the reported bridge ratings (Phares et al., 2004).

One of the major concerns about the current bridge inspection program is the timing and frequency of inspection as was addressed in (ASCE/SEI-AASHTO-Ad-hoc, 2009). The fixed two year interval was decided based on engineering judgement 50 years ago (Washer et al., 2016a) and does not have any quantitative engineering justification (Parr, Connor, & Bowman, 2010). Many studies do not consider the fixed interval the most efficient scheduling strategy for some bridges and sometimes unnecessary and a waste of resources (Atadero, Jia, Abdallah, & Ozbek, 2019; Nasrollahi & Washer, 2015; Soliman & Frangopol, 2014). For instance, some bridges that have been in service for many years and have been exposed to several deterioration cycles are inspected on a 2-year interval such as newly constructed bridges (Emal, 2017; Parr et al., 2010). A variable inspection interval depending on the age and condition of the bridge might be more cost effective and able to capture the deterioration process more accurately (Nasrollahi & Washer, 2015; Parr et al., 2010; Sanders, Atadero, & Ozbek, 2018; Soliman & Frangopol, 2014). According to a survey conducted by Lin et al. (2019), more the 40% of the surveyed bridge managers and inspectors agreed that inspection intervals can be extended to 5 years and even 10 years depending on the bridge condition and properties. In fact, in Japan routine bridge inspections are done every 5 years and in Germany every 3 years (Lin et al., 2019). Also, the short inspection intervals will lead to more frequent inspections causing more traffic disturbance and site visits by inspectors which may present unnecessary risk on the travelling public and the bridge inspectors (Washer et al., 2014). Furthermore, the technologies available for bridge inspection and condition evaluation have significantly improved over the past 50 years, and it is appropriate to consider the type of inspection that will be conducted when determining inspection intervals.

2.2.4. Nondestructive Evaluation Methods and their Significance in Bridge Inspection

In the 1990s bridge managers and scholars realized the limitations of visual inspection and suggested the need to enhance bridge inspections to be able to provide accurate, cost effective evaluations of bridge performance (Rens, Wipf, & Klaiber, 1997). Several studies suggested the use of nondestructive evaluation (NDE) methods in bridge inspections to reduce the subjectivity of visual inspection, improve inspection speed, increase the probability of detecting subsurface cracks and avoid disturbing the traffic flow during inspections (Alampalli & Jalinoos, 2009; NCHRP, 2006; Ryan et al., 2012; Vaghefi et al., 2012). Also, due to the increasing cost of late repairs, aging infrastructure and accelerated bridge construction methods, NDE has received increased attention recently to maintain a reliable bridge network performance (Akgul, 2020; Farhangdoust, Mehrabi, & Mowsavi, 2018).

According to the bridge construction material, appropriate NDE methods can be assigned, for example Electrical Resistivity (ER), Ground Penetrating Radar (GPR), Chloride Ion Penetration Test (CIP), Impact Echo (IE), Infrared Thermography (IT), Radiography Testing (RT), Linear Polarization (LP) and Half-Cell Potential (HCP) can be used for reinforced and prestressed concrete bridges. As for steel bridges, NDE methods such as Acoustic Emission (AE), Ultrasonic Testing (UT), Liquid Penetrant Testing (PT), Magnetic Particle Testing (MT), Computed Tomography (CT) and Eddy current testing (ET) can be considered (ASNT, 2020; Gucunski et al., 2013; Lee & Kalos, 2014; Yehia, Abudayyeh, Nabulsi, & Abdelqader, 2007). The FHWA developed an NDE web manual that can help bridge inspectors choose the appropriate NDE method based on the type of the bridge, material, and bridge element to be inspected. The web manual provides the inspector with several methods to choose from, and the description of each method (FHWA, 2015). Also, the American Society for Nondestructive Testing (ASNT) promotes the discipline of NDE by providing technical information on different NDE methods, educational materials, and services for training and certifying NDE inspectors (ASNT, 2020). More concepts and limitations of the different NDE techniques can be found in (Gucunski et al., 2013; Omar, Nehdi, & Zayed, 2017; Yehia et al., 2007).

In 2001, when NDE was still on the rise in the field of bridge inspection, a survey was conducted by Rolander et al. (2001) to analyze the usage of NDE methods in bridge inspection by forty-one DOTs. The study found that ten DOTs used IE, GPR, pachometers, and HCP for concrete bridge inspection, and that NDE methods were more widely used for fatigue sensitive details in steel bridges. According to Rolander et al. (2001), visual inspection is the most frequent method used in routine bridge inspection by DOTs; and for in-depth inspections the most commonly used techniques are UT, MT, radio graphic testing and PT. By 2015, NDE started to gain more interest but still was not widely used in routine bridge inspection, during this time Lee and Kalos (2015) investigated how NDE technologies were being utilized in the U.S. bridge inspection programs. The study found that NDE methods were rarely or never used by state governments when conducting initial or routine inspection, while almost 80% of states considered NDE methods when conducting in-depth inspections or inspecting fatigue critical components. It was concluded that about 76% of state agencies conduct NDE using in house inspectors and that NDE methods were frequently used to inspect superstructure bridge components and rarely used to inspect substructure elements. However, some state DOTs such as Pennsylvania DOT have been using borehole-based NDE methods to evaluate and measure bridge foundations and soil properties (Coe, Nyquist, Kermani, & Sybrandy, 2013; Olson, Jalinoos, & Aouad, 1995). Also, a study conducted by Lee and Kalos (2014) found that out of thirty states only eight had local bridge inspection manuals that suggested using NDE as of the year 2014 .

According to the survey conducted by Lee and Kalos (2015), the more complex and expensive the NDE method the less likely agencies will use it or even consider it, and that the main reason NDE is not utilized actively is because state agencies believe that NDE methods are difficult to use and require a high initial capital cost to obtain (Lee & Kalos, 2015). However, a study conducted by the Indiana Department of Transportation (INDOT) found that using NDE methods to detect delamination and maintain only the parts of a bridge that need repair can help in reducing the expected annual cost of managing the bridge network by 50% (Taylor, Qiao, Bowman, & Labi, 2016). Also, NDE-based inspection can help predict the performance of a bridge more accurately and precisely, thus optimizing bridge management strategies (Gucunski, Maher, Ghasemi, & Ibrahim, 2012). However, NDE methods are accompanied by inaccuracies or limitations and cost (Hesse, Atadero, & Ozbek, 2015; Taylor et al., 2016), meaning they should be deliberately deployed.

Unfortunately, all NDE methods are associated with certain limitations and a single method cannot be used independently to capture all deterioration mechanisms (Abdelkhalek & Zayed, 2020). Therefore recently, hybrid integrated systems and automated unmanned inspections (AUI) have been suggested for improving bridge evaluations and enhancing NDE methods (Jung et al., 2019; Omer et al., 2019). An example of these assessment tools is a multi-sensor robot that has an ER, IE, UT , GPR and a visualizing screen attached to it (Gucunski, Pailes, et al., 2017). The robotic assisted bridge inspection tool (RABIT) has been designed for detecting rebar corrosion, delamination, and concrete degradation. Test results showed that the RABIT can help reduce inspection time and exposure of inspection crew to traffic (Gucunski, Basily, et al., 2017), however the accuracy of the data collected still requires further validation.

Also, unmanned aerial systems (UASs) and drones are being tested for bridge inspection (Hallermann & Morgenthal, 2014; Hubbard & Hubbard, 2020; Seo, Wacker, & Duque, 2018; Wells & Lovelace, 2018; Xu & Turkan, 2019). A survey conducted in 2016 by AASHTO found that almost seventeen DOTs have investigated the use of UASs in managing their transportation system and infrastructure inspections (Dorafshan & Maguire, 2018). Two studies conducted by Georgia DOT and Michigan DOT found that UASs can be time efficient and cost effective for bridge inspection and traffic monitoring (Brooks et al., 2015; Irizarry & Johnson, 2014). Minnesota DOT has been very active in researching the use of UAS for inspection, for example Minnesota DOT researchers found that UAS can also be used for planning inspections and helping to locate the safest way to access the bridge leading to faster inspections and less traffic disturbance (Wells & Lovelace, 2018).

Also, Perry, Guo, Atadero, and van de Lindt (2020), have proposed a bridge inspection system that helps bridge inspectors monitor and document the progression of damage in a bridge element using information from UASs and machine learning techniques. Overall, NDE methods and hybrid inspection systems have enhanced throughout the years and still are improving due to the developments in artificial intelligence and visualization methods such as augmented reality and photogrammetry (Emal, 2017). However, more efforts are still required to facilitate their implementation by state DOTs.

2.2.5. Bridge Deterioration Modelling for Inspection Planning

Agrawal and Alampalli (2010) stated that one of the main limitations of bridge inspections, is that inspection methods remain constant throughout the bridge's service life, and that if bridge inspection planners were able to understand the deterioration phases in a bridge service life, they would be able to select inspection methods more accurately. Modelling and forecasting of bridge performance and deterioration is important for bridge asset management. In addition to adopting new methods for inspection, predicting the deterioration process of a bridge can help in inspection planning and determining the appropriate time for intervention, saving a significant amount of resources while still providing necessary information. Deterioration models are commonly used to predict the condition of a bridge; and to plan and optimize the timing of bridge maintenance, repair and replacement decisions (Kim et al., 2013; Soliman & Frangopol, 2013). However, they can also be used to provide information that could be useful for planning inspections (Morcous et al., 2010). For example, using deterioration models to consider the likelihood of significant reduction in bridge condition during a 2-year inspection cycle might allow for longer inspection intervals reducing costs and risks associated with the current uniform inspection program (Nasrollahi & Washer, 2015). However, predicting the performance level of a bridge is affected by many uncertainties including the material properties of the bridge and environmental loads surrounding the bridge, therefore probabilistic deterioration models should be used (Biondini & Frangopol, 2016; Morcous et al., 2010).

Deterioration models can be deterministic, stochastic, mechanistic, or artificial intelligence models. Deterministic models are mainly used for short term predictions and to deterministically describe the relation between the factors affecting the bridge performance and condition of the bridge elements using regression models. Deterministic models are developed using historical data that describe the condition of the considered bridge element under the same analyzed stresses (Chen, 1987; Shahin, 1994). Unlike deterministic models, stochastic models consider the uncertainty in the bridge deterioration process by representing the factors affecting the bridge condition using probabilistic distributions. Stochastic models can be state-based, predicting the probability of deterioration based on the bridge properties or environmental conditions; or can be time-based models predicting the time for a bridge to deteriorate in performance (Mauch & Madanat, 2001). Examples of stochastic models are Markov Chains or Weibull models that can be used to predict the time of transition from one condition state to another (Agrawal, Kawaguchi, & Chen, 2010; Gamerman & Lopes, 2006; Lethanh, Hackl, & Adey, 2017; Li & Jia, 2020; Morcous et al., 2010; Nasrollahi & Washer, 2015; Scherer & Glagola, 1994; Tao & Wang, 2019; Thompson et al., 1998). Mainly, deterministic and stochastic deterioration models are developed using the information provided in the NBI database (Morcous et al., 2010) and bridge management tools such as AASHTOWare Bridge and BRIDGIT incorporate the use of stochastic models to determine the bridge condition at a certain time.

Mechanistic models seek to predict the future condition of the bridge by modeling the physical deterioration mechanism such as fatigue cracking or corrosion using physical variables that describe the materials and loading or exposure conditions of the bridge (Ben-Akiva & Gopinath, 1995; Enright & Frangopol, 1999a; Irwin & Paris, 1971; Paris & Erdogan, 1963; Stewart, 2004; Vu & Stewart, 2005). Mechanistic models mainly describe specific bridge elements such as the bridge deck, and the parameters used in these models can be deterministic or probabilistic representing the factors affecting bridge deterioration (Nickless & Atadero, 2018). Artificial intelligence models are recently utilized to analyze complex data and detect patterns and relations between bridge conditions and different factors such as the in-service environment or bridge age. Artificial intelligence models can predict the condition state of a bridge at a defined time in the future using supervised and unsupervised machine learning techniques, neural networks, or case based reasoning (Mohamed, Abd El Halim, & Razaqpur, 1995; Morcous et al., 2010; Morcous, Rivard, & Hanna, 2002; Nguyen & Dinh, 2019; Straub & Der Kiureghian, 2010; Tokdemir, Ayvalik, & Mohammadi, 2000; Yang & Frangopol, 2018a).

In 2006, the FHWA launched the Long-Term Bridge Performance (LTBP) program to collect high quality bridge inspection data using detailed forensic analysis, visual inspection, destructive testing and NDE methods for more than 2000 bridges in the US for a period of almost 20 years (Friedland, Ghasemi, & Chase, 2007). The information collected will help bridge managers in developing more realistic deterioration and life cycle models that could capture the deterioration process of a bridge during its service life and to report actual and up to date performance data on deterioration and degradation of bridges; and structural impacts from overloads (Ajegba, 2020; Ghasemi, 2008; Petroff, Halling, & Barr, 2011; Sorel, 2019). Although many transportation agencies have adopted deterioration models in their bridge management system, there are still gaps in knowledge regarding the structure life cycle performance, and how effective various repair strategies are for a given bridge element or system. Moreover, the materials being used for bridge construction are in continuous enhancement and innovation, and deterioration models still cannot capture all the uncertainty in the factors affecting the performance of the bridge.

2.3. Methodology for Analyzing Proposed Studies in Inspection Planning

The limitations of current bridge inspections impact the quality of information provided and the decisions that are based on this information. Based on the previous discussion, determining the inspection time and technique is a non-trivial problem with several uncertainties and contradicting objectives. Therefore, the research community has sought to address these limitations in inspection planning and the remainder of the paper reviews those efforts and identifies research gaps and needs.

The research method focused on developing a comprehensive review of literature that specifically discussed new methodologies and frameworks for inspection planning, group those frameworks that utilize similar general approaches, and identify research gaps and provide a path for future research. A systematic review protocol was designed to ensure an objective selection of literature related to the topic under consideration (Liberati et al., 2009).

2.3.1. Inclusion Criteria

Based on the objectives of this paper, we initially defined that the studies included in this review must meet the following inclusion criteria:

1. The article represents a framework for choosing inspection time and/or technique not only maintenance time.
2. The article provides an application example to clearly demonstrate the presented framework.
3. The article is written in English.

2.3.2. Search Protocol

In this study the following bibliometric databases were utilized: Compendex, Web of Science, IEEE-Xplore, Scopus, Science Direct and Google Scholar, since they provide sufficient coverage for a systematic review (Harzing & Alakangas, 2016). The search started by searching the keywords: *Bridge inspection time*, *Bridge inspection interval, Bridge inspection cycle*, *Bridge inspection Scheduling*, *Bridge inspection Planning*, and *Bridge inspection management* in the title, abstract and keyword. The last search ended on the 29th of December 2020, and no date restrictions were imposed and only peer reviewed journal articles were initially included. This resulted in a total of 690 papers after excluding duplicates.

First the titles of the retrieved articles were scanned to eliminate irrelevant studies. This resulted in excluding 433 papers. Then the abstracts of the remaining papers were read to include only the articles that provide a framework for selecting bridge inspection time and/or method and provides an example to clearly explain the presented framework. This resulted in removing 214 papers. Eventually a total of 43 papers were selected for full text screening based on the inclusion criteria. A large number of studies were excluded in the screening phase because most of the founded studies focused on innovation in NDE and unmanned inspections, integrating inspection information, and deterioration modelling, but a fewer number of articles focused on choosing inspection time and method. Further, missing, or unclear information in the papers was requested from the authors by email.

After reviewing the full text of the 43 journal articles, to make sure that no relevant studies were excluded an additional manual search was performed using the reference list of the examined papers, Google scholar profiles of the top authors, and additional key words on Google scholar such as risk-based inspection, value of information inspection, reliability-based inspection, lifetime functions, optimization-based inspection, and probability of detection. This time conference articles, reports and book chapters that were referenced by more than one study were considered. As a result, 9 journal articles, 3 conference articles, 2 reports and 2 book chapters were added to the full text screening process. Finally based on the full text screening 26 articles (23 journal articles, 1 report and 2 conference articles) were synthesized, categorized, and reported in this study. Figure 2.1 summarizes the search protocol.

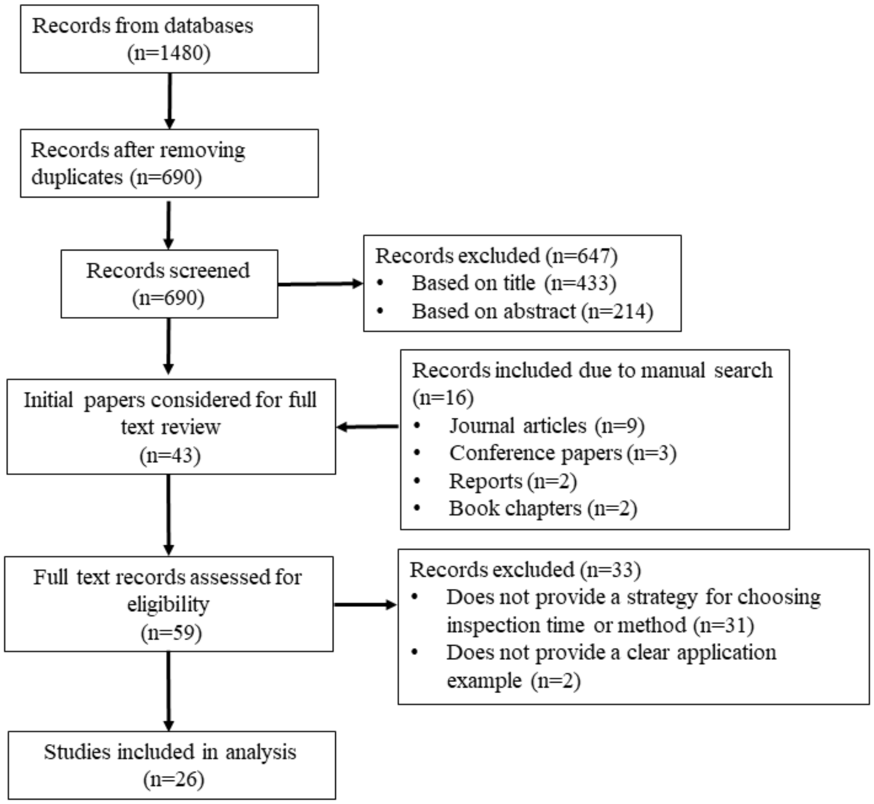


Figure 2.1. Flowchart for search protocol

2.3.3. Categorizing the studies

After reviewing the articles and the different methodologies used for inspection planning, the studies analyzed were grouped into three main categories based on their general approach: (1) inspection planning methods based on reliability theory and lifetime functions, (2) risk-based inspection methods based on expert judgement or the value of information, and (3) optimization-based inspection planning methods. Papers that included reliability index or lifetime functions were considered in category 1. Papers that considered the consequence of failure using expert judgment or the value of information and did not use any optimization algorithms were considered in category 2. Finally, frameworks that used optimization algorithms to decide on the inspection time and methods while minimizing or maximizing a set of objectives and did not consider a reliability index or lifetime functions were considered in category 3.

2.4. Findings

The literature review indicated that in the last few decades research in the field of bridge inspection scheduling and planning has been performed extensively, and different approaches have been proposed by different scholars. Table 2.3 summarizes the studies that were analyzed in chronological order, their objectives, the category of the planning approach described, and the application example used in each article.

Table 2.3. Summary of analyzed articles in chronological order

Method category	Article	Main objective of the inspection framework	Application
Reliability based methods	Straub and Faber (2004)	Reduce the number of components being inspected at inspection time depending on the outcomes of already conducted inspections	A general system with damaged elements
	Kwon and Frangopol (2011)	Predict fatigue crack growth propagation with time and corresponding inspection and repair schedules based on the Probability of Detection (PoD) and repair method	A steel bridge with a fatigue sensitive detail
	Orcesi and Frangopol (2011)	Find the appropriate inspection time and method to inspect specific bridge girders, and not inspect the whole bridge at every inspection time	Composite bridge
	Soliman and Frangopol (2013)	Finding the appropriate inspection time for fatigue sensitive structures based on pre-defined threshold values for the probability of failure	A steel bridge with a fatigue sensitive detail
	Dong and Frangopol (2015)	Find the appropriate time for inspecting and repairing each component in the analyzed structure	Ship structure with fatigue and corrosion deterioration

Risk based methods	Parr et al. (2010)	Find inspection intervals for fracture critical bridges to prevent delayed or too frequent inspections	Fracture critical bridges in the NBI
	Washer et al. (2014)	Find the inspection interval considering the probability and consequences of failure	Different types of bridges
	Nasrollahi and Washer (2015)	Find the inspection interval that will guarantee the bridge is inspected before its condition drops	Prestressed Concrete bridge deck
	Agusta, Thöns, and Leira (2017)	Find the inspection time and method with highest value of information (VoI)	Offshore structure
	Haladuick and Dann (2018)	Find the inspection method with highest VoI considering only the next inspection	Pipeline under corrosion
	Yang and Frangopol (2018a)	Find the appropriate inspection strategy that will have the highest VoI using dynamic Bayesian networks and pre-posterior analysis	A ship with fatigue sensitive detail
	Liu and Frangopol (2019)	Find the inspection time and method that will have the highest utility to the bridge owner.	A fatigue sensitive detail
Optimization based methods	Chung, Manuel, and Frank (2006)	Find the NDE method and its corresponding inspection interval that will reduce the total inspection cost and increase the PoD	Steel box girder bridge
	Kim and Frangopol (2011b)	Find inspection time and method that will minimize damage detection delay	RC bridge deck exposed to corrosion
	Kim and Frangopol (2011c)	Find inspection time and method that will minimize damage detection delay and inspection cost	Ship hull structure with fatigue sensitive detail
	Kim and Frangopol (2011a)	Find inspection time and method that will minimize damage detection delay and total cost including inspection cost and failure cost	Ship hull structure with fatigue sensitive detail
	Kim, Frangopol and Zhu (2011)	Find inspection time and method and repair time that will minimize damage detection delay, extend service life, and reduce total cost including inspection cost and repair cost	RC deck under pitting corrosion
	Kim and Frangopol (2012)	Find the optimum inspection strategy and structural health monitoring plan to minimize damage detection delay and inspection and monitoring cost	A steel bridge with fatigue sensitive details
	Kim et al. (2013)	Find optimum inspection and repair time and method that will minimize damage detection delay, extend service life, and reduce total cost including inspection cost, failure cost and repair cost	RC bridge deck exposed to corrosion and fatigue sensitive ship structure
	Soliman et al. (2013)	Find the inspection schedule and NDE method that will minimize the inspection cost and maximize the probability of damage detection before fatigue failure for multiple details at the same time	A steel bridge with multiple fatigue sensitive details
	Kim et al. (2013)	Find optimum inspection and repair time and method that will minimize damage detection delay, extend service life, and reduce total cost including inspection cost, failure cost and repair cost	RC bridge deck exposed to corrosion and fatigue sensitive ship structure
	Soliman and Frangopol (2014)	Find the optimum inspection and repair schedule that will minimize the probability of failure and life cycle cost while incorporating the data collected from inspection using Bayesian updating	Ship hull structure with fatigue sensitive detail

	Soliman, Frangopol, and Mondoro (2016)	Find the inspection and structural health monitoring method and time that will minimize the probability of failure and life cycle cost while incorporating information from the monitoring process	Naval ship with fatigue sensitive detail
	Kim and Frangopol (2017)	Determine the optimum inspection time and method that will minimize the expected damage detection delay, probability of failure, maximize the extended service life, and minimize the expected total life-cycle cost	RC bridge deck exposed to corrosion
	Kim and Frangopol (2018)	Determine the optimum inspection times while considering maximizing the probability of fatigue crack damage detection, minimizing the expected fatigue crack damage detection delay, minimizing the expected repair delay, minimizing the damage detection time-based probability of failure, maximizing the expected extended service life, and minimizing the expected life cycle cost. Multi-attribute decision making techniques were used to choose between the pareto front solution	A steel bridge with fatigue sensitive detail
	Kim, Ge, and Frangopol (2019)	Explore how Bayesian updating and inspection outcomes can enhance the multi-attribute decision process presented in (Kim & Frangopol, 2017, 2018) and assist in choosing the optimum inspection and repair time and method, while minimizing the expected maintenance delay and expected total inspection cost	A steel bridge with fatigue sensitive detail

The frameworks studied focused on providing bridge inspection planners with a guide on how to select bridge inspection times, inspection methods or both. The frameworks analyzed herein consider two main deterioration modes: corrosion of reinforced concrete structures and fatigue damage propagation in steel structures, although other damage modes and probabilistic deterioration models can be found in other structure and infrastructure management and maintenance literature (Jia & Gardoni, 2018; Soltangharaei et al., 2020; Sultana et al., 2018; Ullidtz, 1993, 1999). The Probability of Detection (PoD), which can be described as the probability of detecting a flaw with a certain size, was used in various papers to describe the reliability of the inspection method and find the appropriate NDE method that can be used to increase the PoD at time of inspection, the higher the PoD associated with an NDE, the higher its reliability (Chung et al., 2006).

2.4.1. Inspection Planning Frameworks Based on Reliability Theory and Lifetime Functions

In reliability theory the performance of a structure is represented using the probability of reaching a certain limit state which in many studies is the probability of failure. The probability of failure is defined as the probability that the stresses applied on a structure exceed or equal structural capacity. The factors controlling the structure behavior in terms of capacity and stresses are considered as random variables to incorporate the uncertainty associated with such parameters (Onoufriou & Frangopol, 2002). The probability of reaching a certain limit state can be evaluated using numerical methods or sampling techniques depending on the number of variables considered in the analysis (Melchers & Beck, 2018). Reliability concepts have been proposed in many studies as an approach for *maintenance* planning, where a maintenance action should be considered when the structure reaches a defined limit state, or the probability of structural failure exceeds a certain threshold. However, many fewer studies have proposed inspection planning frameworks using reliability theory, where an inspection should be considered to avoid structural failure and/or delayed maintenance. In the reviewed studies deterioration models were used to estimate the time of the structural failure and obtain the probability density function (PDF) of failure time using Monte Carlo Simulation.

Kwon and Frangopol (2011) proposed a combined approach that integrates a fatigue reliability model (FRM), crack growth model curves (CGM) and a PoD model, to predict fatigue crack growth propagation with time and to schedule inspections and repair actions. Based on the FRM model and the inspection data the probability of failure of an existing steel bridge was calculated and updated. The effect of different repair actions for fatigue cracking on the performance of the structure and the inspection schedule were analyzed. The study concluded that reliability-based frameworks that combine information from NDE methods and deterioration models can help in scheduling inspection and repair for fatigue sensitive structures, while maintaining an adequate reliability index of the bridge until the end of its service life. Using a similar reliability approach Dong and Frangopol (2015), presented a probabilistic framework for reliability based inspection and maintenance planning for ship structures. A reliability analysis was conducted to determine the probability of flexure failure, while considering the effect of corrosion and fatigue on the thickness of the ship hull elements. The structure was divided into different components and the objective of the framework was to find the appropriate time for inspecting and repairing each component. The study suggested that inspections or repairs do not have to be done on the whole structure at one time but can focus on a specific component to reduce inspection cost and improve inspection quality. To the authors knowledge, Straub and Faber (2004) were among the first researchers to present an adaptive inspection strategy that can help bridge owners reduce the number of components being inspected at inspection time depending on the outcomes of previously conducted inspections.

The probability of failure or the probability of reaching a certain limit state can also be illustrated using lifetime reliability functions, such as cumulative probability of failure, or the survivor function which is the reciprocal of the cumulative probability of failure (Okasha & Frangopol, 2010). The cumulative probability of failure as shown in Figure 2.2, represents the probability that a structure component is failing at a certain time. While the survivor function represents the likelihood that the structure will not fail before a certain time.

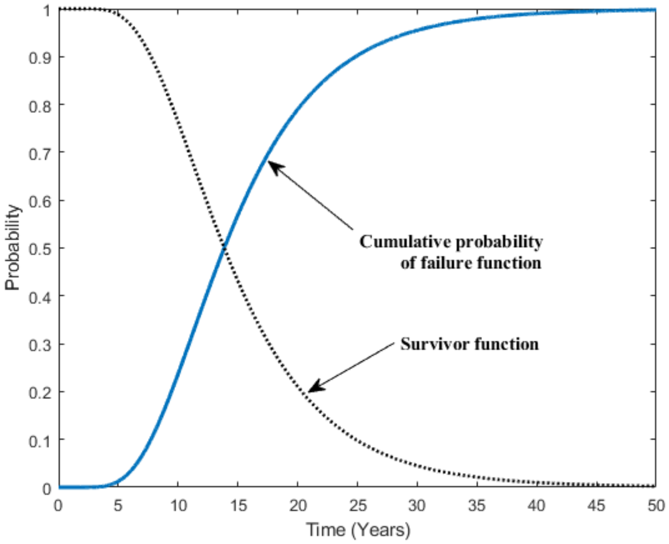


Figure 2.2 Lifetime functions: Cumulative probability of failure and survivor function

Orcesi and Frangopol (2011), presented a framework based on lifetime functions and reliability analysis to find the appropriate inspection time and method to inspect specific bridge girders, and not to inspect the whole bridge at every inspection time. The survivor lifetime function and the cumulative probability of failure were used to predict the performance and deterioration process of a steel bridge. The study found that interior steel girders should be inspected using higher quality NDE methods than exterior girders which can be inspected using only visual inspection. The reason for this conclusion is that usually the condition of the interior girders represents the whole bridge performance more accurately and has a higher impact on the redundancy of the whole bridge, thus special attention should be provided for these components. Also using lifetime reliability functions, Soliman and Frangopol (2013), presented a framework for finding the appropriate inspection time for fatigue sensitive structures based on pre-defined threshold values, regarding the probability of failure. Once a threshold is reached an inspection should be conducted. Bayesian updating was then utilized to update the fatigue model parameters using inspection outcomes and update the following inspection times. The study provided by Soliman and Frangopol (2013) provided a simple approach for inspection scheduling and showed how Bayesian updating using inspection results can affect the inspection schedule, however did not provide a methodology to choose the pre-defined threshold values. Table 2.4 summarizes the key outcomes of the studies analyzed in this category.

Table 2.4. Summary of main conclusions from studies using reliability theory and lifetime functions for inspection planning

Article	**Main conclusions**
Kwon and Frangopol (2011)	Reliability-based methods that combine information from NDE methods and deterioration models can help in scheduling inspection and repair for fatigue sensitive structures, while maintaining an adequate reliability index of the bridge until the end of its service life.
Dong and Frangopol (2015)	Inspections or repairs do not have to be done on the whole structure at one time but can focus on a specific component to reduce inspection cost and improve inspection quality
Straub and Faber (2004)	Data from previous inspections can help in reducing the number of elements inspected in the following inspections which can reduce inspection cost and time and enhance the inspection quality.
Orcesi and Frangopol (2011)	Different bridge elements do not have to be inspected using the same methods or during the same inspection time.
Soliman and Frangopol (2013)	Updating the lifetime functions using inspection results can have significant effect on the timing of subsequent inspections.

Reliability analysis is quite strong in quantifying the uncertainties associated with bridge performance, which helps in improving the accuracy of the inspection planning process (Melchers & Beck, 2018). Reliability based inspection planning frameworks, help in selecting the appropriate inspection times and methods that will guarantee to a high probability that a bridge is maintained before failure. As shown in the analyzed studies, reliability theory can also assist bridge inspection planners to identify the elements in the structure that have the highest effect on the structure's performance, and accordingly focus inspection efforts on these elements, while avoiding unnecessary inspection for the whole structure. Also, reliability frameworks can help bridge owners update the information regarding the capacity and condition of the bridge more accurately, leading to better decisions regarding maintenance activities (Estes & Frangopol, 2003). On the other hand, reliability-based methods require several assumptions regarding the loading, resistance and deterioration modes, which might affect the accuracy of the inspection planning process (Estes & Frangopol, 2003). Also, one of the main limitations of the studies that used reliability-based inspection methods is that they focused on the safety of the structure without considering other limit states that consider also the serviceability of the bridge (Frangopol, Dong, & Sabatino, 2017). Some deterioration mechanisms can have a significant effect on the serviceability of the bridge and the safety of the travelling public but will not be considered in the analyzed reliability-based inspection frameworks since it does not affect the structure safety. For example, concrete spalling from a bridge deck will not have a high impact on the capacity of the structure in the short run but can cause injuries and accidents for the public underneath the bridge and hence immediate attention should be provided.

2.4.2. Risk Based Inspection Planning Frameworks

Risk analysis is based on considering the probability and consequence of a system or element failure in terms of both serviceability and safety. The main difference between risk-based inspection (RBI) methods and reliability-based methods, is that risk-based methods consider the consequences of the failure not just the time of failure such as reliability-based frameworks. To enhance the efficiency of bridge inspection, federal law recently required the FHWA to use risk-based approaches in selecting the inspection frequency (FHWA, 2019; MAP-21, 2012). The first step in a risk-based procedure is to identify the damage modes that can damage the structure and the likelihood of their occurrence. The effects of the deterioration mechanisms acting on a structure are highly uncertain, thus there is always a probability that the structure fails during operation. Then the second step is to assess the consequence of this damage on the safety and serviceability of the bridge (Washer et al., 2016a). The consequence of this component or structure failure depends on its redundancy, level of service and criticality. This section presents the inspection planning frameworks that depend on risk-based procedures in planning inspections and the different approaches that can be used to determine the probability of bridge deterioration and its consequences.

2.1.1.1. Risk Based Inspection Planning Frameworks Based on the Value of Information

Different inspection strategies with different quality and costs will have a different impact on the risk level associated with a structure (Faber, 2002). In RBI the consequence or cost of failure associated with each inspection strategy can be quantified using the value of information (VoI) framework which has been used in the oil industry and offshore structures since the 1970s (Benjamin & Cornell, 1970). The VoI along with Bayesian updating can help in choosing the inspection plan with the least risk (i.e., cost of failure) and highest value of information and utility (Luque & Straub, 2019). The VoI is a powerful tool for quantifying the merit of an inspection technique before implementation and is typically calculated as the difference between the prior cost and pre-posterior cost in terms of money or utility (Straub, 2014). In other words, the VoI is the difference between the expected outcome of a decision with and without the inspection information. If the cost of inspection is lower than the VoI, then the inspection is justified (Memarzadeh & Pozzi, 2016). In many studies to quantify the consequence of failure, the cost function will include the cost of inspection, maintenance and expected cost of failure (Haladuick & Dann, 2018). A valuable inspection strategy will reduce the probability of failure thus reducing the expected cost of failure. Accordingly, inspection scenarios are compared and the scenario that mainly has the minimum cost or risk will be chosen. The VoI can be calculated using deterministic values or probabilistic random variables to consider the uncertainty in the decision process (Quirk, Matos, Murphy, & Pakrashi, 2018). Also, graphical approaches such as Bayesian networks and influence diagrams can be used to quantify the VoI. Overall, the VoI helps in identifying the inspection scenario that can minimize the risk of bridge failure in terms of serviceability or safety.

Liu and Frangopol (2019), presented a risk-based framework for inspection scheduling that will assist decision makers to achieve maximum value of information. Bayesian updating was used to integrate inspection results into the fatigue deterioration model. The results showed that UT will provide higher value of information at earlier inspection times compared to PT due to its higher PoD and therefore UT will be a better choice in the early stages of the structure's service life, whereas the PT should be considered for later inspections. The results concluded by Liu and Frangopol (2019) agreed with the findings of (Agusta et al., 2017; Soliman et al., 2013), that NDE methods with higher PoD provided higher VoI at earlier stages of the structure service life compared to NDE methods with lower quality where the PoD is still low and defects are hard to detect at early stages of the deterioration process. For example, as shown in Agusta et al. (2017) for an offshore structure with a 30-year service life, the optimum inspection time was found to be at year 10 and that inspections before year 4 will yield a value of information (VoI) almost equal to zero due to the small defect size and the low probability of damage detection and limited information provided. However, it was also concluded that little value is gained if the inspection is conducted very late in the structure service time when repairs are essential regardless of the inspection outcomes.

Based on the VoI concept and the work provided in (Straub, 2009, 2014; Straub & Der Kiureghian, 2010); Yang and Frangopol (2018a), presented an inspection/repair planning framework for engineering systems using dynamic Bayesian networks. In this study during the inspection planning phase when there is still no inspection data collected, an evidence-based decision-making process is performed in a pre-posterior framework to predict all inspection outcomes corresponding to different inspection techniques and timing, and the associated repair action for each inspection scenario. Then after exploring all scenarios, the VoI obtained from each inspection scenario was quantified by the difference between the expected life cycle cost without inspection and the life cycle cost with inspections, which is predicted through pre-posterior analysis and discretized Bayesian updating. The life cycle cost included the expected cost of failure, inspection cost and repair cost. The expected cost of failure will drop as the value of inspection improves leading to timely inspections and repair and lowering the probability of failure. The results showed that optimal inspections should be conducted later in the lifetime of the structure and as the number of inspections increases higher quality NDE methods are not required in the later inspections. Further, the analysis indicated that the life cycle cost decreases when budgets for inspection and repair increases preventing structure failure.

To evaluate the value of the information provided from an inspection plan the expected outcomes from different inspection and maintenance scenarios have to be estimated, which can introduce a lot of inaccuracies and uncertainties if these projections are based on a long period in the future such as the whole life cycle of the bridge. Given this concern, Haladuick and Dann (2018), presented a framework that uses the VoI to find an appropriate inspection technique for the next inspection time, considering the accuracy and cost of different inspection methods and without having to consider the whole life cycle of the system. The methodology focuses on estimating the VoI of only the next inspection. Thus, if the VoI is larger than the cost of a higher accuracy inspection then the cost of the inspection is justified. To avoid performing a full life cycle analysis the bounds of the VoI at an alternative inspection time are estimated; if the cost of the inspection lies outside the bounds, the inspection alternative is eliminated from the available options. According to Haladuick and Dann (2018), the higher the inspection accuracy the narrower will be the probability distribution of the detected defect, leading to a lower uncertainty regarding the structure performance and a lower posterior marginal probability of failure, enabling a more informed maintenance decision. The main limitation of the approach presented by Haladuick and Dann (2018) is that it only provides the bounds of the value of the inspection not the expected VoI. This can lead to scenarios where the most cost-effective inspection method is not determined because the costs of several different inspection techniques lie within the bounds, and there is no justification for the more expensive method.

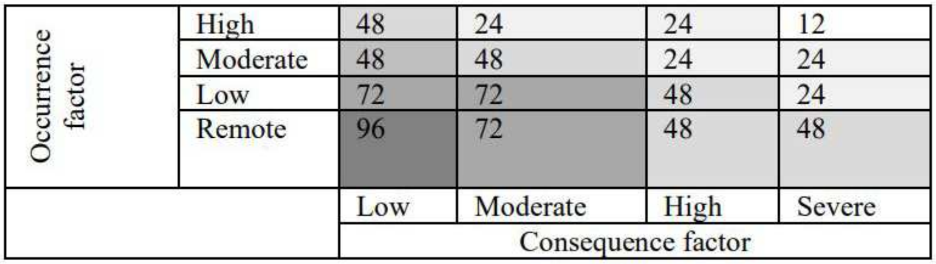
Overall, determining the VoI and estimating different inspection scenarios and outcomes requires significant modeling and computation, which in practice can be hard to apply by bridge inspection planners. Also, estimating the cost of bridge failure can be associated with several errors, and different costs of failure, inspection, and repair can lead to totally different VoI and decisions. Bridges are unlike oil pipes where the concept VoI emerged, bridges have many elements and factors that can affect its redundancy and performance. As such, quantifying and combining the VoI for all these elements simultaneously will be extremely difficult and will make risk-based inspection frameworks that involve estimating the VoI limited to a single bridge element.

2.1.1.2. Risk Based Inspection Planning Frameworks Based on Expert Judgement

In 2010, Parr et al., presented a procedure to establish inspection intervals for steel bridges with fracture critical members (FCMs). The purpose of this study was to provide a rational alternative to the calendar-based approach used to schedule hands on inspections for FCMs. This framework mainly depends on expert judgement, and the bridge is evaluated according to a screening phase consisting of different criteria focusing on the type of fracture details the bridge contains, age of the bridge and the element conditions. Based on the screening phase a score is assigned to the bridge depending on expert judgment and qualitative analysis. The score assigned to the bridge correlates with required inspection interval and risks associated with the bridge component. If the bridge passed all the criteria an inspection interval more than 24 months will be assigned to the bridge. The maximum interval that can be assigned to the bridge is 10 years. If the bridge was evaluated to be in a risk critical condition and did not pass any of the screening criteria, then an inspection interval less than 24 months should be assigned to the bridge. The minimum interval considered in this study was 6 months. In this study the consequence of failure was mainly represented as bridge failure due to fatigue stresses leading to fracture failure. Also, the authors stated that this framework does not eliminate routine bridge inspections, which in this case does not solve the problems or the costs associated with routine inspections.

Accordingly to provide a framework that can be an alternative for scheduling routine inspections, Washer et al. (2014) presented a simple method for risk-based inspection planning, that does not require complex computations and is based on expert judgement and qualitative risk analysis. The framework was presented in different journal articles and NCHRP- 782 report (Washer et al., 2014), and has been promoted by several scholars and FHWA officials as an efficient approach (Ekpiwhre, Tee, Aghagba, & Bishop, 2016; Everett et al., 2008; Hartmann, 2018; Washer, Connor, Nasrollahi, & Rebecca, 2016b; Washer et al., 2016a). This RBI program involves evaluating the likelihood (probability of occurrence) and consequences for a certain type of damage to occur during a certain period of time in terms of safety and serviceability of the bridge. This information is used to rank the bridge according to its inspection interval category. Categories range from 12 months to 96 months based on the bridge's risk characteristics. According to Washer et al. (2014), this framework can be applied on a single bridge or a group of bridges with similar properties and by choosing the appropriate inspection interval, can help in performing timely repairs and reducing unnecessary inspection risks and money.

The evaluation process starts by categorizing the likelihood for a damage to occur in a bridge element into one of four occurrence factors (OFs) ranging from remote to high. The OF is mainly the probability of failure; and failure can be defined as the bridge component is no longer performing its required function or reaching a specific condition stage or rating (i.e., CS3 or CS4). The OFs for the identified damage modes are estimated using a simple scoring scheme that considers the attributes which contribute to the likelihood of the damage occurring in the next 6 years. These attributes have a significant effect on the performance and durability of the structural element, for example concrete cover in concrete structures or average daily traffic. Then the consequences of this potential damage are categorized into one of four consequence factors (CFs) ranging from minor effect to major. According to OFs and CFs a simple risk matrix as shown in Figure 2.3, is used to prioritize inspection needs and assign an inspection interval that ranges from 12 months to 96 months and can be updated based on inspection results and bridge rate of deterioration over time. The proposed process requires a bridge owner to establish a reliability assessment panel (RAP) that consists of experienced engineers that are experts in the field of bridge inspection and repair. The expert panel uses engineering judgement, experience, and typical deterioration patterns to evaluate the likelihood of the damage (i.e., OF) and the consequences of damage (i.e., CF).



Occurrence factor	High	48	24	24	12
	Moderate	48	48	24	24
	Low	72	72	48	24
	Remote	96	72	48	48
		Low	Moderate	High	Severe
		Consequence factor			

Figure 2.3. Risk matrix indicating the inspection interval (in months) based on OF and CF of a bridge adopted from (Washer et al., 2014) and adapted

Also, risk-based approaches are the base for scheduling extended inspection cycles for specific bridges. Originally, the NBIS required bridge owners to consider eight criteria before establishing an extended inspection interval (more than 24 months but not to exceed the 48 months) for certain bridges. These criteria are: 1) structure type, 2) structure age, 3) load rating, 4) structure ratings 5) volume of traffic carried, 6) ADTT, 7) major maintenance actions that were performed in the past 2 years, and 8) the frequency of overload that is anticipated on the structure (FHWA, 2012b). In 2018, a memorandum was issued by the FHWA following the MAP-21 (FHWA, 2018), to allow using the risk-based approach presented in Washer et al. (2014) in scheduling inspections for certain bridges that can be inspected on an extended interval. Additionally, the memorandum indicated that the risk-based process can help in scheduling inspections for bridges that need to be inspected at less than 24 months. However, the inspection intervals cannot exceed 48 months and in any case the risk assessment criteria and the resulting intervals must be approved by the FHWA. The assessment process should consider the bridge material properties, applied loads, structure capacity and condition. Also, the damage modes that need to be considered in the assessment process are: 1) section loss, fatigue stresses and fracture for steel members, 2) corrosion and cracking for reinforced concrete sections, 3) seismic loads, vehicle impact and overloads for the superstructure and 4) seismic, scour and settlement for substructure (FHWA, 2018). Overall, the RBI framework presented in Washer et al. (2014) is simple and can be applied in practice while helping bridge owners consider more than one bridge component when scheduling inspections. However, DOTs will need enough time and resources to assemble the expert panel and collect the required data. Also, the decision process might be, affected by the subjectivity and judgement of the expert panel especially if mathematical methods were not used when determining the probability of bridge deterioration (OF).

The OF or the probability of failure can be determined using more robust approaches such as statistical methods or reliability-based methods that can help reduce the subjectivity and variability of expert judgement. Thus, Nasrollahi and Washer (2015), presented a paper that discusses a statistical approach to determine bridge inspection intervals using archived NBI rating data collected from 20 years of routine bridge inspections. The purpose of this analysis was to determine the probability of a bridge staying in a certain condition or deteriorating to a lower condition using data analysis. In this paper, time to failure was defined as the time for a bridge component to drop in rating. The mean time and standard deviation for a bridge component to remain in a certain condition were calculated, and it was found that bridge superstructures tend to stay longer in a good condition, and as the rating drops the time in the rating decreases. Therefore, when a bridge is still in a good condition, inspections can be postponed saving resources without affecting the bridge's performance, however in later stages of the bridge service life more frequent inspections should be conducted to reduce the risk of failure. Also, according to the analyzed data the authors found that for several bridges in the NBI database, the inspection intervals can be extended to 72 months and that using the 24-month interval policy as recommended by the NBIS might be unnecessary, over conservative and a waste of resources. The quality of the data collected can highly affect the accuracy of the data analysis process and the decision regarding the bridge inspection. Therefore, the authors recommended the use of this framework in conjunction with expert judgement and risk analysis methods, where the probability and consequence of failure are considered in the decision process. The studies presented by (Nasrollahi & Washer, 2015; Parr et al., 2010; Washer et al., 2014), focused on providing bridge inspection planners with a method to select inspection time, but did not clearly specify how to select the inspection technique. Table 2.5 summarizes findings of the studies included in the risk-based category.

Table 2.5. Summary of main conclusions of studies that discussed inspection planning using risk analysis

Article	Main conclusions

Liu and Frangopol (2019)	High quality inspections will be a better choice in the early stages of the structure's service life, whereas lower quality should be considered for later inspections.
Agusta et al. (2017)	Little value is gained if the inspection is conducted very late in the structure service time when repairs are essential regardless of the inspection outcomes.
Yang and Frangopol (2018a)	Optimal inspections should be conducted later in the lifetime of the structure and as the number of inspections increases higher quality NDE methods are not required in the later inspections. The analysis indicated that the life cycle cost decreases when budgets for inspection and repair increase.
Haladuick and Dann (2018)	The higher the inspection accuracy the lower the uncertainty regarding the structure performance, enabling a more informed maintenance decision.
Parr et al. (2010)	For fracture critical bridges, inspections can be short as 6 months and can be extended to 10 years depending on the bridge condition.
Washer et al. (2014)	The RBI proposed is simple and can help in deciding on the inspection interval for different bridges and can be applied on a group of bridges simultaneously, which can help in minimizing delayed or unnecessary inspections and repairs.
Nasrollahi and Washer (2015)	Bridge superstructures tend to stay longer in a good condition, and as the rating drops the time in the rating decreases. For several bridges in the NBI, using the 24-month interval policy as recommended by the NBIS might be unnecessary, over conservative and a waste of resources

In short, when selecting inspection time and method, risk-based approaches can help bridge inspection planners consider both safety and serviceability of the structure, while considering not only the time of failure like in reliability-based methods but also the consequence of failure. As shown risk-based approaches can be conducted using computational approaches or qualitative methods and expert judgement. Expert-based approaches such as the one presented by Washer et al. (2014) can help bridge owners consider more than one bridge component or damage mode during the inspection planning process. On the other hand, computation methods can be significantly complex, and methods based on expert judgement can be subjective. Also, these methods consider only the performance and failure of the structure, whereas other objectives need to be considered when choosing inspection time and methods such as minimizing the delay of maintenance or maximizing the probability of detection.

2.4.3. Inspection Planning Frameworks Based on Optimization Methods

In inspection planning, different objectives in both single and multi-objective optimization problems have been considered such as minimizing the expected damage detection delay, minimizing the probability of failure, maximizing the extended service life, and minimizing the expected total life-cycle cost (Kim & Frangopol, 2017, 2018; Kim, Ge, et al., 2019). This section discusses inspection frameworks that focused on finding the optimum inspection time and/or method that will satisfy either a single objective or multiple objectives using optimization algorithms and pareto front solutions.

As mentioned earlier the PoD has been used by several scholars to describe the quality of an NDE method, one of the first frameworks that used the PoD in inspection planning was presented by Chung et al. (2006). In this study, the objective was to find the optimum inspection interval for a specific NDE method that will maximize its PoD and minimize the total inspection cost, which considered the cost of inspection and failure. Fixed interval inspection schedules were considered in this study. By mapping the propagation of the fatigue crack size with the PoD of a specific NDE method using Monte Carlo simulation, the probability of detecting a certain crack size was estimated at each inspection time. Three NDE techniques were compared: Ultrasonic Testing (UT), Liquid Penetrant Testing (PT), Magnetic Particle Testing (MT), and the framework was applied on two butt welds in the bottom flange of a newly built steel box girder. The optimum inspection interval was obtained for all three NDE methods. The results showed a tendency for longer inspection intervals to be associated with lower costs of inspections but higher expected costs of failure, while NDE methods with shorter intervals tended to have higher inspection costs but lower costs of failure. This was explained by the authors that higher inspection costs were due to the increased number of inspections, while the lower failure cost was due to the smaller likelihood of failing to detect cracks before fracture. Although the UT had the highest single inspection cost, it was found to be the most optimum choice among all three NDE methods with a three-year inspection interval. This was due to the high detectability of the UT and less frequent inspections. This study proposed a novel approach in inspection planning, but still focused on using a fixed inspection interval, which is one of the main limitations of current inspection programs.

To move away from the limitations of a fixed inspection interval, a probabilistic approach for optimum inspection planning, considering uncertainties associated with corrosion propagation for reinforced concrete decks was presented by Kim and Frangopol (2011b). The objective of this inspection program was to minimize the time from damage initiation until the damage has been detected by inspection (i.e., damage detection delay). It was concluded that an increase in the number of inspections or improving the inspection quality will reduce the expected damage detection delay. However, increasing the number of inspections or inspection quality will increase the total inspection cost. Therefore to consider both contradicting objectives, the same approach was applied on structures with fatigue sensitive details in (Kim & Frangopol, 2011a, 2011c), and the cost of inspection was considered in formulating the multi objective optimization problem and optimum inspection timings were obtained. In Kim and Frangopol (2011c) the total cost included the cost of inspection only, while in Kim and Frangopol (2011a) total cost included the cost of inspection and failure. Findings revealed that inspections with higher quality should be conducted earlier to minimize the expected damage detection delay and that higher inspection qualities and quantities will increase the inspection cost if the cost of failure was not considered. But when the failure cost is incorporated higher quality inspection methods will be more cost effective and the failure cost will affect the inspection schedule. Also, when two or more inspections were to be conducted during the service life of the analyzed structure, the inspection plans allowing different inspection qualities to be considered will require less cost than the inspection plans based on a single type of inspection for a similar damage detection delay. Further, to reduce the damage detection delay and to develop a more robust inspection strategy, Kim and Frangopol (2012) recommended combining structural health monitoring techniques with NDE methods in a framework to find the optimum inspection and monitoring times. This strategy will increase the PoD of detection and will assure that inspections are optimally conducted when there is better chance for detecting flaws. However the framework will require a significant increase in funds, that might not be attainable by a bridge agency's budget (Kim & Frangopol, 2012).

To consider the effect of minimizing damage detection delay on the repair process of a concrete bridge, Kim, Frangopol and Zhu (2011) extended the optimization process presented in (Kim & Frangopol, 2011a, 2011b, 2011c), and applied it on a RC deck under pitting corrosion, while considering maintenance in the inspection management process. The study found that the behavior of the bridge managers and their attitudes towards maintenance has a major effect on the inspection intervals and that increasing the inspection quality will extend the service life of the bridge but will also increase the total inspection cost which included the cost of inspection and repair. Also, after analyzing the pareto front solution it was noticed that as the PoD of an NDE method increases the probability of unnecessary or early repairs decreases because bridge owners consider that the bridge inspection method is more accurate and provides a good representation of the bridge condition, thus being more cautious and conducting an expensive maintenance action (e.g., replacing the concrete cover and the top reinforcement) early in the service life of the bridge to avoid failure will be a waste of resources. However, this study considered only a single repair type, thus Kim et al. (2013), demonstrated a more generalized probabilistic framework for inspection and maintenance planning while considering multiple types of maintenance actions and different structures. The framework was applied to an RC bridge, where two maintenance actions were compared, a preserving activity such as corrosion protection using a sealer and a more intrusive action such as deck replacement with a much higher cost. Pareto optimum solutions were obtained providing the optimum time and method of inspection and the corresponding time and type of maintenance. The results showed that conducting high quality inspections combined with early preserving maintenance can be cost effective and will extend the service life of the bridge, however if the inspection quality was low, then replacing the bridge deck will be more preferred during a later stage in the bridge's service life.

The previously discussed frameworks focused on providing an inspection plan for a single structural component or element which does not reflect practice where different elements must be considered simultaneously during the planning process. Accordingly, Soliman, Frangopol and Kim (2013) provided an inspection planning approach for a steel bridge with multiple fatigue sensitive details. An optimization problem was formulated to find the inspection schedule and NDE method that will minimize the inspection cost and maximize the probability of damage detection before fatigue failure. The pareto optimal solutions provided different inspection plans for the decision maker to choose from, based on the available budget and target probability of damage detection before failure. It was noted by the authors that the optimizer chooses the low-quality inspections to be performed later since they will have a higher probability of detection when cracks will be larger and easier to detect.

Moving forward with their work and to investigate the effect of collected inspection data on the inspection planning process Soliman and Frangopol (2014) presented a framework where inspection outcomes were integrated to update a fatigue crack growth deterioration model using Bayesian updating and Metropolis-Hasting algorithm. Various inspection outcomes were explored to decide on the appropriate inspection and repair plan. The updated model parameters were used to update the fatigue damage profiles and to determine the inspection times and the probability of failure, which was the probability of failing to detect a crack before it reaches its critical crack size (Soliman & Frangopol, 2014). The pareto front solutions showed that as the width of a measured fatigue crack increases the time span between inspections should decrease to avoid structure failure. Also performing inspections and repairs early in the service life will reduce the maintenance delay, however increases the life cycle cost, which agreed with the findings of the study conducted by Soliman et al. (2016), where structural health monitoring (SHM) was incorporated in the planning process.

To facilitate the optimization process and to consider more than two objectives at the same time Kim and Frangopol (2017), presented an efficient multi-objective probabilistic optimization framework to determine the optimum inspection time and method. Four objectives were considered in this study, minimizing the expected damage detection delay, minimizing the probability of failure, maximizing the extended service life, and minimizing the expected total life-cycle cost. An objective reduction algorithm was used to find the redundant objectives while considering a reinforced concrete bridge deck. The results showed that omitting the life cycle cost and probability of failure from the quad objective set will not affect the pareto front solutions and concluded that a decision maker can only focus on the expected damage detection delay and the service life to obtain the optimum inspection time and reduce computational time. The same conclusion was obtained in Kim and Frangopol (2018), where the objectives were weighted, but then a multi-attribute decision making process was used to choose between the pareto solutions.

This time in Kim and Frangopol (2018) the process was applied on a steel bridge with fatigue detail and six objective functions were considered; maximizing the probability of fatigue crack damage detection, minimizing the expected fatigue crack damage detection delay, minimizing the expected repair delay, minimizing the damage detection time-based probability of failure, maximizing the expected extended service life and minimizing the expected life cycle cost. The optimum inspection times provided by the optimizer did not change even when different weights were assigned to the considered objectives. However, the results were affected by the chosen multi-attribute decision making method. Then Kim et al. (2019), explored how Bayesian updating and different inspection outcomes can affect the multi-attribute decision process proposed in (Kim & Frangopol, 2017, 2018). In this study the planning process was used to find both the optimum inspection and repair time that will minimize expected damage-detection delay and expected total inspection cost and a comparison between different multi-attribute decision making methods was conducted. Unlike the findings in (Kim & Frangopol, 2018), Kim et al. (2019) found that incorporating Bayesian updating in the decision process will reduce the effect of multi-attribute decision making method on the obtained optimum inspection times, and the maintenance times will be highly dependent on the inspection outcomes. Table 2.6 summarizes the outcomes and of the optimization-based studies described in this section.

Table 2.6. Summary of main conclusions of studies that discussed inspection planning using optimization-based approaches

Article	**Main conclusions**
Chung et al. (2006)	The results showed a tendency for longer inspection intervals to be associated with lower costs of inspections but higher expected costs of failure. NDE methods with shorter intervals tend to have higher inspection costs but lower costs of failure.
Kim and Frangopol (2011b)	An increase in the number of inspections or improving the inspection quality will reduce the expected damage detection delay.
Kim and Frangopol (2011c)	Inspections with higher quality should be conducted earlier to minimize the expected damage detection delay. Higher inspection quality and frequency will increase the inspection cost if the cost of failure is not considered.
Kim and Frangopol (2011a)	When two or more inspections were to be conducted during the service life of the analyzed structure, the inspection plans based on different inspection qualities will require less cost than the inspection plans based on the same type of inspection for a similar damage detection delay.
Kim and Frangopol (2012)	SHM can help improve the inspection management strategy and increase the PoD of the NDE method. However, this will increase the cost of inspections significantly.

Kim, Frangopol, and Zhu (2011)	The behavior of the bridge managers and their attitudes towards maintenance has a major effect on the inspection intervals . As the PoD of an NDE method increases the probability of unnecessary or early repairs decreases.
Kim et al. (2013)	Conducting high quality inspections combined with early preserving maintenance can be cost effective and will extend the service life of the bridge, however if the inspection quality is low, then replacing the bridge deck later in the service life of the bridge will be more preferred.
Soliman, Frangopol and Kim (2013)	The optimizer chooses the low-quality inspections to be performed later since they will have a higher probability of detection and cracks will be larger and easier to detect.
Soliman and Frangopol (2014)	The pareto front solutions showed that as the width of measured fatigue crack increases the time span between inspections should decrease to avoid structure failure. Performing inspections and repairs early in the service life will reduce the maintenance delay.
Kim and Frangopol (2017)	The results showed that omitting the life cycle cost and probability of failure from the quad objective set will not affect the pareto front solutions and concluded that a decision maker can focus on the expected damage detection delay and the service life to obtain the optimum inspection time and reduce computational time.
Kim and Frangopol (2018)	The optimum inspection times provided by the optimizer did not change even when different weights were assigned to the considered objective. However, the results were affected by the chosen multi-attribute decision making method.
Kim et al. (2019)	Incorporating Bayesian updating in the optimization process will reduce the effect of multi-attribute decision making method on the obtained optimum inspection times, and the maintenance times will be highly dependent on the inspection outcomes.

Based on the optimization studies reviewed, inspection strategies based on optimization methods can be very robust and can comprehensively consider the limit states or objectives that were considered by reliability-based frameworks and/or risk-based inspection frameworks. Other considerations, such as the cost and quality of inspection (i.e., PoD) can be included in the management process to decide on optimum inspection time and method at the same time. Also, as shown in the above discussion, due to computational enhancements several objectives can be considered during the planning process. However, optimization approaches like the other discussed approaches (reliability and risk-based approaches) can be highly affected by the uncertainties associated with the random variables used in the deterioration model. Different input values with different statistical descriptors can impact and change the pareto front solutions significantly, affecting the decision regarding the inspection time and method. Inaccurate parameters can mislead the bridge owners and result in delayed or unnecessary inspections and repair activities. Also, the optimization approaches can only be applied to structures under a single time dependent deterioration mechanism. Considering more than one deterioration process at the same time will require complex optimization algorithms that will have a significant computational cost.

The PoD functions have been used in several optimization studies, however establishing the PoD for an NDE method is based on experimental tests which in many cases do not represent the onsite conditions and can be expensive since it has to be repeated several times for the same material for each NDE method. Using Bayesian updating to incorporate assumed inspection results in the optimization process can be highly efficient to schedule inspection times throughout the whole life cycle of the structure. However, it can be hard to apply in practice where several inspection and maintenance scenarios are to be assumed and considered, unlike risk based and reliability-based approaches where incorporating new information in the decision process is relatively easier and will not require complex computations.

2.5. Conclusions and Future Research Directions in Inspection Planning Frameworks

The deteriorating bridge networks in the U.S. require immediate attention and budget for repair and renewal. Maintenance actions can help in improving the performance of a bridge, but maintenance decisions depend on the data collected during inspections, therefore valuable and timely inspections are an important component of enhancing bridge network condition. This paper reviewed current bridge inspection practices in the U.S. and their identified limitations. The review has also highlighted a range of new technologies that have been proposed to improve bridge inspections and devoted significant attention to analyzing inspection planning frameworks proposed in the literature to identify strengths and limitations.

Determining the inspection time and technique is a difficult problem with several uncertainties and contradicting objectives, therefore studies have recently tried to propose different approaches for inspection planning that can mitigate these challenges and assist bridge owners and inspectors. However, despite the extensive research effort in the field of bridge inspection planning, to the authors knowledge, almost none of these methods have been successfully or consistently adopted by the FHWA or state DOTs. The lack of implementation likely is a product of many factors including organizational cultures and a general resistance to change, but the proposed frameworks should also be evaluated regarding their suitability for practical implementation. Moreover, applying a new inspection planning approach or implementing a new policy in inspection practices has to be approved by the FHWA, which can also be a change barrier.

Identifying the limitations or barriers that may be preventing the implementation of new inspection planning approaches suggests useful pathways for future research. The following list summarizes some of the limitations of bridge inspection planning frameworks identified through this review, giving particular attention to the needs of practical implementation:

1- A bridge is a system with different subsystems, elements and components that determine the whole system behavior and could be affected by different deterioration modes (i.e., corrosion or fatigue) at the same time. Most of the bridge inspection planning approaches analyzed herein (especially the reliability-based and the optimization-based frameworks) focus on a single element or similar details and consider only one deterioration mechanism in the decision-making process. However, in reality the bridge will be exposed to several factors that will affect its performance and a bridge inspector will usually inspect the whole bridge at the same time. Therefore, researchers should develop inspection planning frameworks that can consider more than one bridge component and different deterioration mechanisms at the same time when scheduling inspections or selecting an inspection method.

2- One of the main limitations of most of the proposed frameworks is that they require complex computational skills and training, which might not be available in many bridge inspectors working in the field as opposed to academia. Accordingly, the proposed studies should try to present simple approaches or tools that make the computations more time efficient and can be rationally implemented by inspectors.

3- With new inspection planning would come new inspection training requirements. Therefore, to encourage the implementation of new inspection planning frameworks, researchers should also explain the required skills and training that bridge inspectors will need to learn to apply these new frameworks and ideas.

4- Most of the analyzed studies focus on corrosion and fatigue deterioration only, very limited research has considered other deterioration mechanisms such as freeze-thaw cycles, deterioration of prestressed cables and temperature effects. For a more comprehensive inspection planning processes other deterioration modes have to be analyzed and deterioration models that capture these mechanisms have to be developed.

5- Life cycle cost analysis can help bridge owners plan for the future of their bridge stock and determine the required budgets. In fact, considering the whole life cycle cost of a bridge management has been recommended and considered by several studies and the FHWA. However, life cycle planning can be time consuming and require several information and assumptions. Thus, in several cases bridge managers will need an approach to quickly plan for the next inspection only, which has been provided by a limited number of studies.
6- Most of the analyzed frameworks have applied their methodologies on newly constructed structures, without considering that the majority of bridges are existing bridges that have been operating for several years. Therefore, clear guidelines have to be provided by researchers on how to adjust the proposed frameworks to be applied on existing bridges.
7- Unmanned inspection methods have been the focus of many researchers in the field of nondestructive inspections. However limited research has focused on providing a systematic approach on how the information provided from unmanned inspection methods such as robots and drones can be incorporated in the inspection planning process and when choosing the next inspection time and method.

Further, from the reviewed literature and announcements by several research funding sources it can be stated that the future research trends in the field of bridge inspections will focus on but will not be limited to :

1- How to improve the quality and speed of NDE methods using virtual reality, photogrammetry, and unmanned inspection methods.
2- Using machine learning techniques and artificial intelligence in improving the accuracy of the data collected during nondestructive bridge inspections and the PoD.

3- Providing systematic approaches that can incorporate the information from both deterioration models and NDE methods to help bridge inspectors decide on the inspection intervals and method for not only a single bridge but for a whole network of bridges with different deterioration mechanisms and associated risks.
4- Incorporating life cycle cost analysis in bridge inspection planning, not just in maintenance planning.
5- The use of lean concepts in bridge inspections and how to reduce the cost of inspections while increasing their efficiency.
6- Improving the Long-Term Bridge Performance database and developing more advanced prediction models.
7- Providing inspection methods for bridges that have been constructed using accelerated construction methods or have been exposed to natural hazards.
8- Improving the quality of bridge inspectors, through new training programs, while generally improving the bridge inspection standards.

Finally, bridge inspections are one of the main aspects in the bridge management process and have a close connection with maintenance activities and the overall performance of a structure. Therefore, researchers and bridge owners have to work together in developing inspection planning frameworks that reduce the limitations of current inspection programs, are easy to apply in practice and can be adjusted to most of the bridge systems included in the nation’s stock. This can help lighten the burden on the budget required for repairing the current bridges, by improving repair activities, and avoiding delayed or unnecessary maintenance actions.

CHAPTER 3: A COMPREHENSIVE UNCERTAINTY-BASED FRAMEWORK FOR INSPECTION PLANNING OF HIGHWAY BRIDGES

3.1. Introduction and Purpose

In the United States (U.S.), bridge inspections are conducted based on the National Bridge Inspection Standards (NBIS), which were developed by the Federal Highway Administration (FHWA) after the collapse of the Silver Bridge in 1967 (Dorafshan & Maguire, 2018). The NBIS requires that, for almost all bridges, a routine inspection should be conducted every two years using visual inspection, and for structurally deficient bridges, annual inspections should be conducted (FHWA, 2012b). However, this uniform calendar-based approach was established based on expert judgement 50 years ago without any quantitative justification (Washer et al., 2016a) and several limitations have been reported in the literature (ASCE/SEI-AASHTO-Ad-hoc, 2009).

The uniform calendar-based approach does not consider the inspection requirements of a bridge based on its age and deterioration process, which can result in the same inspection interval and procedure for a new or aging bridge (Washer et al., 2014). Further, visual inspections are highly subjective, arduous, and depend mainly on the inspector's experience (Lin et al., 2019). Visual inspections, if not accompanied by a chain drag test, are limited to surface defects and can only locate subsurface deteriorations (i.e., rebar corrosion, delamination, and voids) that have reached a significant extent and have emerged to the surface of the bridge element (Phares et al., 2004). Given the limited information that can be collected from visual inspection, if the inspector suspects a problem with the bridge during routine inspections, Departments of Transportation (DOTs) will conduct a more in-depth inspection using more advanced inspection techniques (Hearn, 2007). Repeating inspections with more sophisticated techniques can consume a lot of time and money. Moreover, bridge inspection methods commonly remain constant throughout the life span of the bridge despite the fact that bridge deterioration processes can change over time, which is another major limitation to current inspection practices (Agrawal & Alampalli, 2010).

On the other hand, the technologies available for bridge inspection and condition evaluation have changed significantly over the past 50 years. For example, nondestructive evaluation (NDE) is an effective enhancement to overcome the limitations of visual inspection. NDE techniques can help predict the bridge performance and establish the internal condition of a structure, such as the likelihood of corrosion in a concrete element, locating subsurface cracks, and detecting fatigue cracks and welding discontinuities in steel members (Gucunski et al., 2013). However, NDE methods are accompanied by inaccuracies or limitations and cost, meaning they should be strategically deployed (Hesse et al., 2015).

In addition to adopting new methods for inspection, several studies have been developed to help predict the deterioration process of bridges. Deterioration prediction models are commonly used to capture the condition of the bridge and schedule bridge maintenance accordingly (Morcous et al., 2010). However, deterioration models can also help in selecting the inspection time and adjusting the inspection techniques depending on the predicted bridge condition (Kim et al., 2013). Parameters used in the prediction model can be highly variable depending on the uncertainty in the properties of the bridge; therefore, probabilistic approaches should be considered during the decision process (Biondini & Frangopol, 2016). Given the limitations of current inspection practice and recent innovations in bridge design and technology, the FHWA is currently encouraging DOTs to improve the efficiency of bridge inspections and move away from the fixed calendar-based inspection interval to a more rational approach that depends on the risks associated with the bridge condition and in-service environment (FHWA, 2019).

The objective of this study is to provide a systematic approach for integrating information from bridge condition prediction models, NDE inspection data, and expert judgement to enhance the understanding of bridge condition, allowing for a more efficient use of inspection resources and better decision making about maintenance activities. As a result, this study developed a new uncertainty-based inspection planning framework that enables bridge inspection planners to determine the inspection time and technique based on the bridge condition. The novel premise of this study is that bridge inspections are conducted to provide knowledge about the bridge's current condition and therefore an inspection should only be conducted when the level of uncertainty about the bridge condition is higher than a certain threshold.

This study contributes to the body of knowledge in bridge management research by providing a novel and rational alternative for bridge inspection planning to the currently utilized uniform calendar-based approach (FHWA, 2012b). This study helps in improving the bridge management process by providing a framework for managing different data sources and using those for inspection and maintenance planning. From a practice standpoint, adopting the proposed framework will result in utilizing inspection resources more efficiently and improving bridge safety and serviceability because the presented methodology can help bridge owners (1) avoid unnecessary or delayed inspections and repair actions, (2) combine both routine and in-depth inspections with a single valuable inspection that utilizes the capabilities of NDE methods, and (3) consider more than one deterioration process or bridge component during the inspection planning process.

In the framework, the inspection time is determined by quantifying the uncertainties associated with the prediction model and the probability of an element transitioning to a certain phase of deterioration during the life cycle of the bridge. Selecting the inspection technique depends on the stage in the bridge element's service life and how effectively the technique can reduce the uncertainty about the bridge condition. After an inspection is conducted, the new inspection data are used to update the deterioration model using Bayesian updating, and the updated deterioration model is used to inform a more accurate prediction of the next inspection and repair time.

Bridge decks play a significant role in representing the serviceability and safety of a bridge since they are part of the primary load path for the whole system (Washer et al., 2014). Therefore, from a scoping perspective, the focus of this study will be on reinforced concrete (RC) decks that are exposed to chloride-induced corrosion. RC decks are considered the most expensive bridge components, requiring regular maintenance and rehabilitation; therefore, accurate evaluation and inspection planning are significant

(Gucunski, Pailes, et al., 2017). However, it should be noted that the framework presented in this paper is flexible and can be applied to different bridge components with different materials and structural systems.

3.2. Inspection Planning: Literature Review

Due to the importance of inspections and their connection to the safety of the structure and maintenance decisions, in the last few decades, research in the field of inspection planning has been performed extensively, using different approaches such as optimization-based methods, reliability theory, and risk analysis using the value of information (VoI) and expert judgement. This section analyzes the research effort that has been conducted in the field of bridge inspection planning and the frameworks that have been proposed.

3.2.1. Optimization-Based Methods

In inspection planning, different objectives in both single- and multi-objective optimization problems have been considered such as minimizing the expected damage detection delay, minimizing the probability of failure, maximizing the extended service life, and minimizing the expected total life cycle cost (Kim & Frangopol, 2018). Deterioration models are used in the optimization process to capture the deterioration mechanism (Paris & Erdogan, 1963; Vu & Stewart, 2000) and the probability of detection (PoD) is used to quantify the quality of different inspection methods (Chung et al., 2006).

An optimization process was presented by Kim and Frangopol (2011b) to find the optimum inspection times and method for inspecting a concrete bridge exposed to corrosion. The study concluded that an increase in the number of inspections or improving the inspection quality will reduce the expected damage detection delay but will increase the inspection cost. In a bi-objective optimization process, Kim and Frangopol (2011a) found that for fatigue-sensitive structures, if minimizing the cost of a structure failure was an objective in the optimization process, the cost of high-quality inspections will be justified, and if more than two inspections are to be conducted, using NDE methods with a higher quality in the early stages of the bridge service life followed by lower-quality methods later in the service life is the most cost-effective.

Kim et al. (2013) extended the optimization process presented in (Kim & Frangopol, 2011b) to find the effect of minimizing the damage detection delay on the repair activities of RC bridges. Kim et al. (2013) found that conducting high-quality inspections combined with early preserving maintenance can be cost-effective and will extend the service life of the bridge. The discussed frameworks focused on providing an inspection plan for a single structure component; therefore, Soliman et al. (2013) provided an inspection planning approach for a steel bridge with multiple fatigue-sensitive details. It was noted by the authors that the optimizer chooses the low-quality inspections to be performed later since they will have a higher PoD and cracks will be larger and easier to detect. Their findings agreed with Soliman and Frangopol (2014), where a Bayesian updating process and inspection outcomes were incorporated in the planning framework to choose the appropriate inspection and repair time. Other optimization planning frameworks with more than two objectives were presented by Kim, Ge, et al. (2019), where redundant objectives were identified and omitted to enhance the optimization process.

Drawbacks of optimization-based approaches have been noted in several studies such as the following: considering more than one time-dependent deterioration mode is very complex (Kim & Frangopol, 2011b); the processes can be very sensitive to the deterioration model inputs (Kim et al., 2013); and incorporating inspection results in the decision process to update the inspection schedule will require an expensive computational effort (Yang & Frangopol, 2018a). Further, the PoD functions that have been used in several inspection planning studies (Chung et al., 2006) can be difficult and expensive to determine for an NDE method since NDE methods are based on experimental tests which do not represent the onsite conditions and have to be repeated several times for the same material for each NDE method.

3.2.2. Reliability-Based Methods

Reliability concepts have been proposed in many studies as an approach for maintenance planning, where maintenance should be considered when the structure reaches a defined limit state. However, some studies propose inspection planning frameworks using reliability theory and lifetime functions, in order to avoid a structure failure and delayed maintenance (Okasha & Frangopol, 2010). Kwon and Frangopol (2011) proposed a combined approach that integrates a fatigue reliability model (FRM), crack growth model curves (CGM), and a PoD model to predict fatigue crack growth propagation with time and to schedule inspections and repair actions. Using a similar reliability approach, Dong and Frangopol (2015) suggested that inspections or repairs do not have to be performed on the whole structure at one time but can focus on a specific component to reduce the inspection cost and improve the inspection quality, which supports the ideas presented by (Straub & Faber, 2004).

Before Dong and Frangopol (2015), Orcesi and Frangopol (2011) incorporated lifetime functions in the reliability analysis process and found that inspection schedules and methods do not have to be the same for the whole structure. This means that for highly critical bridge elements, inspection techniques can be improved compared to less important or more redundant elements. Further, Soliman and Frangopol (2013) used lifetime reliability functions to schedule inspection times, based on pre-defined threshold values. This time, Bayesian updating was utilized to update the fatigue model parameters using inspection outcomes and update inspection times. One of the main limitations of the studied reliability-based inspection frameworks is that they focus on the safety of the structure and time of failure without considering its serviceability or consequences of a failure (Frangopol et al., 2017). Moreover, in some cases, the capacity and the applied loads on the structure have to be predicted which can lead to inaccuracies in the decision process (Estes & Frangopol, 2003).

3.2.3. Risk-Based Methods

There is always a probability that the structure fails during operation and the consequence of this component or structure failure depends on its redundancy and criticality. Risk-based inspection (RBI) is based on quantifying the risk associated with an element or system failure by considering the probability and consequence of a failure in terms of both serviceability and safety. The consequence of a structure failure can be quantified using mathematical concepts such as the value of information (VoI) or expert judgments. Liu and Frangopol (2019) presented a risk-based framework for inspection scheduling that will assist decision makers achieve the maximum value of information using Bayesian theory. Their results agreed with the findings of Agusta et al. (2017) that NDE methods with a higher PoD provided a higher value of information at earlier stages of the structure service life and reduced the risk of failure.

Based on the Bayesian analysis and algorithms presented by (Luque & Straub, 2019; Straub, 2014), Yang and Frangopol (2018a) presented a pre-posterior analysis with assumed inspection scenarios to choose the inspection time and method that will minimize the posterior life cycle cost and provide the highest VoI. The analysis indicated that the life cycle cost decreases when budgets for inspection and repair increase. However, to calculate the VoI, long-term projections of the expected outcomes from different inspection and maintenance scenarios have to be conducted, which can cause several inaccuracies and uncertainties if these projections are made for a long time in the future. Thus, without having to consider the whole life cycle of the system, Haladuick and Dann (2018) presented a framework that uses the VoI to help inspection planners in selecting the inspection technique for only the next inspection time.

Most of the risk-based inspection frameworks discussed in this section required expensive computational efforts and did not incorporate the experience or judgment of bridge engineers, unlike the work presented by Washer et al. (2014), which was a simple method for inspection planning based on a rational and qualitative risk analysis. The planning program involves evaluating the likelihood and consequences for a certain damage to occur using an expert panel of experienced engineers in the field of bridge engineering. Based on the bridge's risk characteristics, an inspection interval was assigned to the bridge using a risk matrix. Although this framework is simple and can be easily applied in practice, it can be subjective and affected by the judgement of the expert panel, which is relatively a similar limitation to other approaches that were based on expert judgement such as the one presented by Parr et al. (2010). Using a more quantitative approach and statistical data analysis, Nasrollahi and Washer (2015) presented a study where bridge inspection intervals were decided using archived NBI rating data collected during routine bridge inspections. The purpose of this analysis was to determine the length of time a bridge will stay in a certain condition before deteriorating to a lower condition and performing inspections during this time span.

3.2.4. Research Gaps

In a previous paper presented by Atadero et al. (2019), uncertainty-based inspection was introduced but did not consider lifetime functions, different types of deterioration at the same time, or pre-posterior analysis for choosing the next inspection method, and such as other studies, a guide for choosing uncertainty thresholds was not provided. Research in the field of bridge inspection planning and scheduling has covered a wide range of ideas and approaches, but to the authors' knowledge, uncertainty quantification methods in the inspection planning process have not been used or analyzed using a detailed application in the same way that is presented herein. Further, none of the presented frameworks have yet been applied in practice, and until now, bridge owners continue to rely on the two-year routine inspection program, followed by in-depth inspection if required. The lack of adoption could be due to the complexity of the proposed inspection planning approaches, the skills required for applying the methodologies, the desire to eliminate engineering judgment which is found in some of the inspection planning frameworks, and/or focusing only on the life cycle of the structure which, in some cases, can be unnecessary and full of uncertainty as one moves longer into the lifetime of the structure. Moreover, considering more than one deterioration process in the inspection planning phase is important but can be difficult to implement in most of the presented studies (Jia & Gardoni, 2018).

Given these limitations and research gaps, this study proposes a computationally simple and easily implementable (i.e., practical) methodology for bridge inspection planning that can help address some of the research gaps and be applied in practice. The uncertainty-based inspection methodology is flexible and can be adapted to consider different bridge components and deterioration mechanisms. To minimize subjectivity and complexity, the framework integrates simple quantitative methods and engineering judgment simultaneously in the planning process.

3.3. Decision Framework for Uncertainty-Based Inspection Planning

It is important that bridge owners know the condition of their bridge stock and how the condition will deteriorate with time to be able to effectively plan for inspections and repair actions. However, determining the inspection time and technique is a non-trivial problem with several uncertainties and contradicting objectives (Liu & Frangopol, 2019). Uncertainty in the bridge condition arises from various aspects, such as environmental conditions surrounding the bridge and from the properties of the bridge itself, and typically increases over time. Limitations of tools used to analyze bridge performance such as the accuracy of inspection techniques and the variability of parameters used in a prediction model also contribute to uncertainty in establishing the bridge condition. Thus, bridge owners must be aware of the different sources of uncertainty and try to reduce that uncertainty to a limit where appropriate actions and decisions can still be taken.

The uncertainty-based inspection framework is based on two main concepts: (1) bridge inspections should be performed when the degree of uncertainty regarding the bridge condition reaches a defined threshold and (2) inspection methods are determined based on how well a technique can reduce the uncertainty regarding the bridge condition and improve the prediction of the deterioration model. Figure 3.1 provides a summary of the proposed framework and the tasks required to determine the inspection time and methods. The following sections will explain the framework in detail.

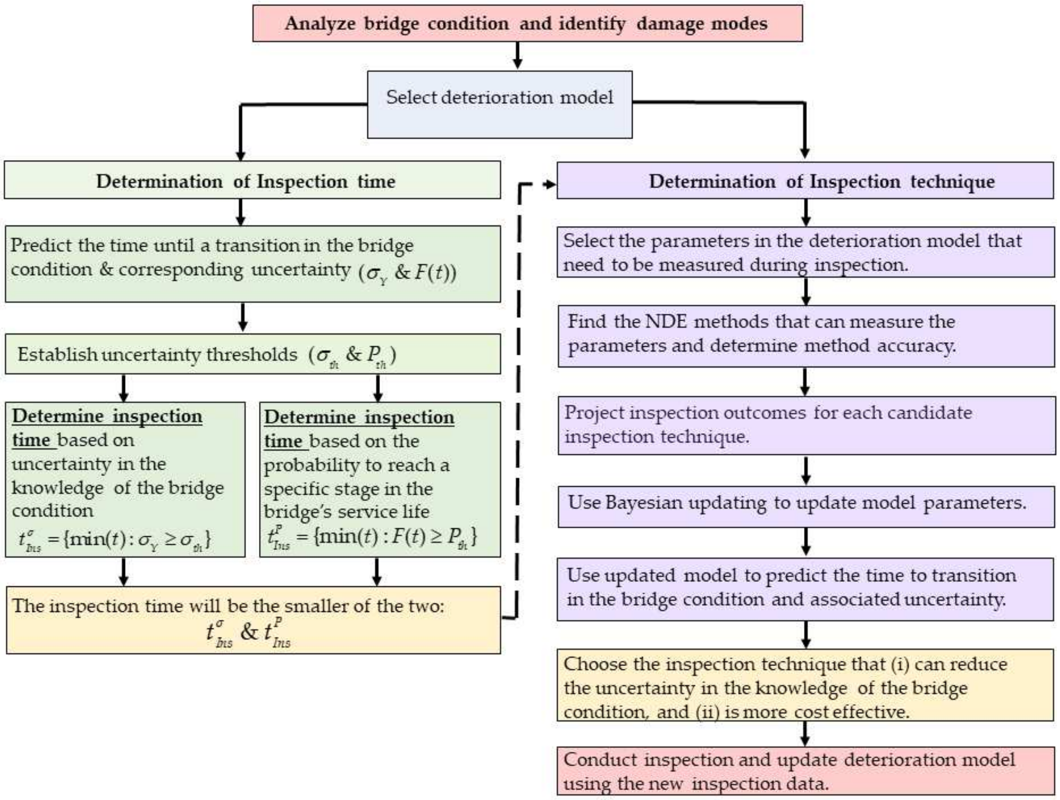


Figure 3.1. Uncertainty-based inspection framework

3.3.1. Indicator of Bridge Condition

In current bridge inspections, the condition of the bridge is evaluated using mainly the NBI rating system (FHWA, 1995) or the AASHTO element level system (AASHTO, 2013). In the NBI rating system, the condition of the bridge components (i.e., concrete deck or piers) is reported on a scale from 0 to 9, in which 0 and 9 describe a failing and a new component, respectively (FHWA, 1995). In the AASHTO element level system, the performance of bridge elements is rated using mainly four condition states (CS): good (CS1), fair (CS2), poor (CS3), and severe (CS4) (AASHTO, 2013). The quality and accuracy of the information and rating provided in the bridge inspection report depend mostly on the experience and training of the bridge inspector which, in some cases, might be inaccurate and subjective (Lin et al., 2019). Further, in the current bridge rating systems, the language used to describe the component condition is qualitative and might be understood differently by different bridge inspectors, leading to several uncertainties and inconsistencies (Lin et al., 2019).

Accordingly, this paper will demonstrate a different approach where the condition of the bridge is represented in terms of the time to transition (TTT) which is the predicted time for the bridge element or component to reach a certain phase or condition in its service life. The TTT is a quantitative measurement estimated based on the information provided from both prediction models and collected inspection data, which can help in minimizing subjectivity and ambiguity among bridge inspectors and improve the quality of the recorded inspection data. Moreover, the core value of a bridge inspection is to support bridge owners in their management decisions. Most bridge management systems (BMSs) are used to project the time for a bridge element condition to transition from one stage to another, in order to decide on an appropriate maintenance time. Similarly, the TTT provides a flexible indicator of the bridge condition, which can represent the time from the beginning of the bridge service life until reaching a certain condition, or the time between different stages in the bridge service life. For example, the TTT could be the time from opening the bridge until corrosion initiation or crack propagation, or it could be the time from corrosion initiation until corrosion cracks propagate on the surface. The TTT can be adjusted to fit different bridge systems, deterioration mechanisms, and materials, such as the time for corrosion propagation in concrete decks and the time for fatigue cracks to reach a certain size limit in steel details.

Further, different bridge elements can spend a long period of time in the initial stages of deterioration, where the deterioration rate is slow. During this time, the bridge element condition is changing, but bridge inspectors are not able to document any sign of deterioration. For instance, chlorides in concrete decks might spend a long period accumulating in the concrete substrate without showing any signs of deterioration for bridge inspectors to report, as well as not providing any chance for bridge owners to perform preventive maintenance. Considering these initial phases of deterioration using the TTT concept and the presented framework will help bridge owners make timely and accurate inspection and maintenance decisions, as the TTT can also be set as the time when a maintenance activity should be conducted. In addition to identifying the appropriate maintenance time, the TTT will help a bridge inspection planner track the different stages of the bridge service life so they can decide on prediction models and NDE methods that are appropriate to capture and measure the deterioration process during a defined phase in the bridge life cycle.

Overall, evaluating and reporting the TTT for a bridge component is an essential step in the proposed framework; however, the TTT does not replace the NBI or AASHTO rating system (AASHTO, 2013; FHWA, 1995). In fact, it can be used along with the other rating systems to enhance the data gathered during inspections and the quality of the inspection reports.

3.3.2. Choosing Inspection Time

To choose the next inspection time using the uncertainty-based inspection framework, a bridge inspection planner should select a prediction model able to capture the deterioration mechanism and predict the TTT and then quantify the uncertainty in the model prediction and compare the model uncertainty with the uncertainty thresholds to select the next inspection time.

3.3.2.1. Properties of Deterioration Model and Corresponding Uncertainty

The framework starts by analyzing the structure properties, in-service environment, and inspection and maintenance records, if available, to establish the deterioration mechanisms that are most likely to affect the bridge performance. Based on the identified deterioration mechanisms, appropriate prediction models that can describe and predict the uncertainty in the time-dependent deterioration process are adopted. For example, in this paper, three mechanistic deterioration models, as detailed in Appendix (A), will be utilized to predict (1) the corrosion initiation time, (2) the time for corrosion cracks to reach a certain size, and (3) the time needed for corrosion to reach a certain depth in the steel reinforcement. Moreover, the proposed framework seeks to select the inspection method based on the ability of the method to reduce uncertainty. Therefore, it is important to choose a model that has parameters that can be refined and updated using inspection measurements (i.e., NDE inspection data), which will reduce the level of uncertainty associated with the prediction model.

To consider uncertainty in a deterioration model prediction, a probabilistic approach should be used. One can assume that $Y(t)$ is a random variable representing the bridge condition at time t or the TTT and $y(t)$ represents the corresponding realization. A suitable deterioration model can be used to predict $Y(t)$ at any future time t including the model uncertainties. Therefore, a general form for the deterioration model can be expressed as (Atadero et al., 2019)

$$y(t \mid \theta) = M_d\left(t;\theta\right) \tag{1}$$

where $M_d\left(t;\theta\right)$ is the deterioration model and θ is the uncertain model parameters (e.g., material properties, environmental exposure, use of deicing salt, loading conditions) with a probability distribution function (PDF) $f(\theta)$ for each random variable representing the prior information a bridge inspector has about the parameters. By propagating the uncertainty in the model parameters θ using an appropriate computational method (e.g., Monte Carlo simulation or importance sampling), we can establish the associated uncertainty in the prediction of $Y(t)$. The time to reach a certain bridge condition (i.e., TTT) can be probabilistically represented using a PDF or can be characterized using a mean μ_{TTT} and standard deviation σ_{TTT}. It should be noted that the framework is general and, depending on the problem, any deterioration model (i.e., stochastic, or mechanistic) that fulfills the aforementioned requirements can be implemented in the planning process.

3.3.2.2. Criteria Used to Choose Next Inspection Time

Based on the results of the prediction model, the bridge inspector can choose the inspection time considering two criteria, (1) the level of uncertainty in the predicted bridge condition before the TTT and (2) the probability to reach the TTT using lifetime functions. In this paper, the inspection time will be denoted by $t_{Ins,N}$, where N is the number of the inspection in a sequence of inspections.

Statistical descriptors such as the standard deviation σ_Y or coefficient of variation COV_Y can be used to quantify the uncertainty in the results of the deterioration model. For the first criterion, we start by predicting the time for the bridge to reach a series of specific conditions before the TTT and quantifying the uncertainty in the prediction results using the aforementioned statistical descriptors. Then, to determine the inspection time based on the first criterion, let σ_{th} denote the threshold (i.e., upper bound) for σ_Y. The corresponding inspection time can be selected as the first expected time that σ_Y equals or exceeds σ_{th}, i.e., $t_{Ins}^{\sigma} = \{\min(t) : \sigma_Y \geq \sigma_{th}\}$. To explain further, let us consider that the TTT will be the time to reach a crack size of 10 mm. Then, to propagate the uncertainty with regard to the bridge condition, we will calculate the expected or average time ($E[t]$) to reach different crack sizes before reaching 10 mm (TTT), for example, 2, 3, and 5 mm and the corresponding σ_Y at each crack size which will be expressed as a unit of time (years, months, etc.). Then, at the time σ_Y exceeds σ_{th}, an inspection has to be considered.

For the second criterion, lifetime functions will be used to calculate the probability of a bridge reaching a defined stage in its service life. Several lifetime reliability functions have been successfully used as performance indicators in the field of asset management (Okasha & Frangopol, 2010). One of the main lifetime functions is the cumulative probability of failure which will be used in this paper as the cumulative probability of transition, in order to choose the inspection time. The cumulative probability of transition $F(t)$ is defined as the probability that the TTT to the Kth stage of the service life of a bridge component is less than or equal to the time t and is expressed in Equation (2), where $f(.)$ is the PDF of the TTT:

$$F(t) = P(TTT \leq t) = \int_0^t f(x)\ dx \tag{2}$$

To select the inspection time based on the second criterion, let P_{th} denote the threshold (i.e., upper bound) for $F(t)$; then, the corresponding inspection time can be selected as the first time that $F(t)$ exceeds P_{th}, i.e., $t_{Ins}^{P} = \{\min(t) : F(t) \geq P_{th}\}$. Finally, the bridge inspector should choose the smaller t_{Ins}^{σ} or t_{Ins}^{P} as the next inspection time.

Another issue that needs to be considered when scheduling the next inspection time is the fact that bridges may be subjected to several modes of deterioration simultaneously. These deterioration mechanisms can be related; for example, in the case of cracks on the surface of a concrete deck and loss of the cross-sectional area in the steel reinforcement, both phenomena are due to corrosion. Conversely, the deterioration processes can be unrelated such as corrosion of the concrete deck and fatigue of steel details and can still be considered using this framework. If two deterioration mechanisms g_1 and g_2 affect the bridge performance, a bridge inspection should be considered whenever the cumulative probability of transition of each deterioration process, $F(t)_{g_1}$ or $F(t)_{g_2}$, reaches P_{th} or the standard deviation, σ_{Y,g_1} or σ_{Y,g_2}, exceeds its threshold. Accordingly, a bridge inspector will have four inspection times to choose from; therefore, based on a more conservative and crude decision, the $t_{Ins,N}$ should be the minimum of all four inspection times.

3.3.2.3. Determining the Uncertainty Thresholds Using an Expert-Based Assessment Process

The selected uncertainty thresholds P_{th} and σ_{th} will control the inspection time and, ultimately, the number of inspections conducted over a bridge's service life. Smaller threshold values will lead to more inspections, and higher threshold values will lead to fewer inspections. The selection of the threshold values depends on the bridge owner's attitude towards uncertainty and the risk associated with bridge component failure. This section will present an expert-based assessment process that can guide bridge inspectors to establish the uncertainty thresholds (P_{th} and σ_{th}) using engineering judgement and information about the bridge. This process helps bridge inspection planners consider the current rating of the bridge (AASHTO, 2013; FHWA, 1995) and the risks associated with the bridge condition when planning inspections. The following paragraphs will explain the steps required to choose the uncertainty thresholds.

Step 1: Identify damage modes: The assessment process starts by identifying the damage modes that have the highest impact on the bridge component and the inspection time, and this can be conducted based on the experience of the bridge owners with similar bridge components and in-service environments. In this paper, the damage mode considered will be corrosion of reinforced concrete decks. Other damage modes such as fatigue cracking can be considered depending on the bridge condition.

Step 2: Identify performance factors and consequence factors: To consider the risks associated with the bridge condition, bridge inspection planners need to identify the "performance factors" and "consequence factors". The performance factors represent the bridge design and construction characteristics that have an impact on the rate of the damage accumulation. The consequence factors represent the outcomes if the bridge component failed.

The seven performance factors that were considered in this study are: (1) the deck drainage system and ponding, (2) year of construction and/or replacement maintenance, (3) protective layer over concrete surface, (4) bridge skewness, (5) average daily truck traffic (ADTT), (6) subjectivity to overspray of deicing salt or water, and (7) type of reinforcement. More information about the selected performance factors and how they contribute in the corrosion damage mode can be found in (Parr et al., 2010; Washer et al., 2014). There are other factors that can impact the corrosion rate that were not considered in the performance factors because they are already considered through the deterioration models described in Appendix (A). A bridge inspection planner should not include a factor that was already considered in the deterioration models or in the bridge rating process (AASHTO, 2013; FHWA, 1995) to avoid overestimating the impact of a single factor on the decision process by considering it multiple times.

When choosing the uncertainty threshold, the severity of outcomes associated with bridge component failure should be analyzed. Herein, four consequence factors were considered: (1) damage to the top of the bridge, (2) features under the bridge, (3) effect of the damage on the structural capacity, and (4) the availability of alternative routes. The study will focus on the consequence of bridge deck failure due to corrosion while considering the four consequence factors. A total of eleven factors were considered in this paper (seven performance factors and four consequence factors)

Step 3: Assign initial score based on current bridge condition: To consider the current bridge condition and previous inspection results, an initial score is assigned to the bridge based on the NBI (FHWA, 1995) or AASHTO element level rating (AASHTO, 2013) of the bridge component. This score is calculated using the total number of performance and consequence factors (P&C factors), as shown in Table

3.1, incorporating the NBI (FHWA, 1995) or AASHTO (AASHTO, 2013) rating of the bridge helps bridge owners in applying the uncertainty-based inspection framework to existing bridges with archived inspection records or new bridges.

Table 3.1. Initial score assigned for bridge component based on the rating system and number of performance and consequence (P&C) factors.

NBI condition rating (FHWA, 1995)	AASHTO rating system (AASHTO, 2013)	Score assigned
7 or more	CS1	Number of factors × 10
6	CS2	(Number of factors − 3) × 10
5 or less	CS3 or CS4	Considered a low category

A bridge with a rating of 7 or higher will be assigned the maximum initial score, which in this study will be 110 (the eleven P&C factors multiplied by 10), and for a bridge with an NBI rating of 6, an initial score of 80 will be assigned. A bridge with an NBI rating less than or equal to 5 will be directly considered in the low category without continuing the assessment process. The rationality of this calculation procedure will be explained further in Steps 4 and 5.

Step 4: Determine P&C factors' point deductions based on bridge condition: As shown in Table 3.2, each of the P&C factors is classified into two or three levels that can help describe the condition of the bridge, and each level is assigned a specific number of points that will be deducted accordingly from the initial score.

Table 3.2. The levels corresponding to each P&C factor, and associated points (Parr et al., 2010; Washer et al., 2014)

Performance factors	Levels corresponding to each factor	Points deducted
Deck Drainage system and ponding	Water is allowed to sit on the surface and no drainage system	-10
	Minor ponding, but drainage system is not maintained	-5
	No problems noted	0
Year of Construction or replacement maintenance	More than 40 years old	-10
	From 40 to 15 years old	-5
	Less than 15 years old	0
Protective layer over concrete surface	No or poor sealer	-10
	Sealer with Limited effectiveness	-5
	Well maintained sealer	0
Bridge Skewness	Skew more than 30°	-10
	From 20°-30°	-5
	Less than 20°	0
	High (ADTT > 1000)	-10

Average daily truck traffic (ADTT)	Moderate (1000>ADTT> 100)	-5
	Minor (100 > ADTT > 15)	0
Subjectivity to Over spray	Severe over spray	-10
	Moderate over spray	-5
	No over spray	0
Reinforcement type	Not epoxy coated	-10
	Epoxy coated	0
Consequence Factors	**Levels corresponding to each factor**	**Points deducted**
Damage to the top of the bridge	The bridge carries a high volume of traffic. Damage to the top of the bridge can cause major traffic delays and accidents.	-10
	The bridge carries a moderate volume of traffic. Damage to the top of the bridge can cause moderate delays due to lane closures.	-5
	The bridge carries a low volume of traffic. Damage to the top of the bridge will not affect the serviceability of the bridge.	0
Features under the bridge	Bridge crosses over a highway or a high-volume roadway such that any spalling will cause major traffic delay, injures or accidents.	-10
	Bridge crosses over a moderate volume roadway, a lightly travelled waterway, or a multi-path railroad. Spalling can cause moderate road delay or minor accidents.	-5
	Bridge crosses over a non-navigable water or unused land.	0
Structural Capacity	The structural capacity is highly affected by the deterioration of this bridge component, and damage can lead to bridge failure.	-10
	The structural capacity will decrease and load posting, or bridge closure might be required.	-5
	The structural capacity will be adequate without any effect on serviceability or performance of the bridge.	0
Alternative routes	There are no alternative routes. So, any bridge closure will be a major blockage on the bridge network.	-10
	There are some alternative routes, but still delays will happen	-5
	There are many alternative routes the public can use	0

In this study, the maximum number of points that can be deducted due to a single factor is 10 and the lowest is 0. Therefore, in Step 3, when we were calculating the initial maximum score, we multiplied the number of factors by 10, so that when we start deducting points in Step 5, we are starting at the highest possible score a bridge can achieve based on its current rating or condition. It should be noted that with a few adjustments, bridge owners can change the weight of each factor depending on its importance and can divide the factor into different levels.

Step 5: Deduct points from initial score: As the condition of the bridge worsens and the outcome of failure becomes more severe, more points are deducted from the initial score. For example, if a bridge did not have a drainage system and corrosion cracks on top of the bridge would cause major traffic delays, then according to the information in Table 3.2, 20 points will be deducted from the initial score assigned in

Step 3. There should be a limit to the number of factors where a bridge can score a −10 or the number of points a bridge can lose before dropping to a lower category. Thus, when assigning the initial score (in Step 3) for a bridge with rating 6, a "3" was subtracted from the number of factors (see Table 3.1). This can help guarantee that a bridge losing more than 30 points (since the 3 is multiplied by 10) or, for example, scoring a −10 in more than three factors will not be considered in the high category. Bridge owners can assign other limits, such as changing the 3 to 4 or directly considering a bridge in the medium category if the bridge scored −10 in more than four factors.

Step 6: Rank the bridge from high to low and choose uncertainty thresholds: To select uncertainty thresholds for inspection planning, the scale shown in Figure 3.2 will be used. Based on the points deducted from the initial score and the calculated final score, the bridge will be ranked in one of the three categories (low/medium/high), and accordingly, the values of the uncertainty threshold P_{th} and σ_{th} will be selected. Simply, if the bridge rank is low, then low threshold values $(\sigma_{th}^{low}\ \&\ P_{th}^{low})$ should be selected.

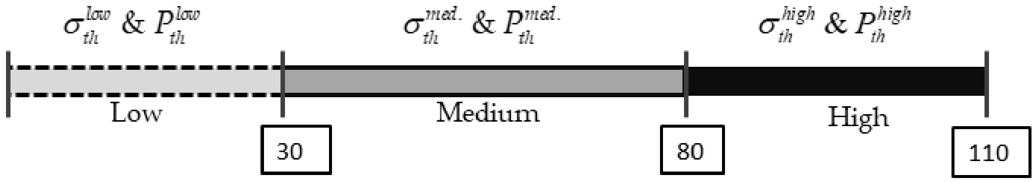


Figure 3.2. Scale for choosing the uncertainty threshold (the figure is not drawn to scale)

There are some recommendations a bridge inspection planner should consider when using the expert-based assessment procedure or the scale shown in Figure 3.2:

1. If the score lands on a cutoff point (e.g., 80), the lower category controls.
2. The upper bound of the high category should not exceed the maximum initial score which is equal to the maximum number of points that can be deducted.

3. The upper bound of the medium category should equal the initial score assigned to a bridge with an NBI rating of 6. It is risky to choose a high threshold for a bridge that was rated to be in a moderate condition (NBI rating of 6 or CS2), since high thresholds will lead to fewer inspections and a longer time interval between inspections.

4. Bridge inspection planners can divide the scale in Figure 3.2 into more than three categories (i.e., low/medium/high) in order to cover a wider range of uncertainty thresholds and bridge conditions.

5. An expert panel should be established to calibrate and decide on the values of the thresholds P_{th} and σ_{th}. The panel should consist of employees with different responsibilities in the agency's bridge management department. Further explanation on how to establish starting threshold values (e.g., $P_{th}^{low} = 15\%$ and $\sigma_{th}^{low} = 2.30\,years$) is shown in the example application.

Finally, once the values of σ_Y and $F(t)$ exceed or equal the chosen σ_{th} and P_{th}, an inspection should be considered

3.3.3. Choosing Inspection Method

While the inspection time is selected to prevent uncertainty in the bridge condition from exceeding an acceptable value, the inspection method is selected such that the information provided by the inspection can be used to most effectively reduce the uncertainty in the condition of the bridge element when the inspection is conducted. Selection of the inspection method is complicated by many factors influencing the effectiveness. One factor affecting the utility of different inspection techniques is the stage of the bridge's service life; depending on the state of deterioration, some techniques may be useless. Accuracy of the inspection technique is another important factor; the level of uncertainty in the bridge condition can only be reduced if the inspection results are trustworthy. However, improving the quality of the inspection technique might lead to higher inspection costs; therefore, inspection techniques must be strategically decided upon. Nondestructive evaluation (NDE) techniques are a valuable tool for bridge inspection as they can provide data to quantitatively assess the physical parameters that represent different damage mechanisms (e.g., cover thickness, chloride content, corrosion rate, and crack width) (Gucunski et al., 2013). These values can be used to evaluate the bridge condition directly or to develop and improve predictions of deterioration models.

To select a suitable NDE method, a bridge inspector should start by identifying the parameters in the deterioration model that can be efficiently measured and for which updated values improve the model prediction. These parameters can be identified by conducting a sensitivity analysis and finding the parameters that have the highest impact on the deterioration model prediction (Li, Wang, & Jia, 2020). Once parameters to measure have been identified, there are a variety of resources to help find relevant NDE methods and information about the methods (FHWA, 2015; Gucunski et al., 2013). However, all NDE methods are accompanied with uncertainties in measurements and difficulties in implementation onsite (Hesse, Atadero, & Ozbek, 2017). Therefore, quantifying the accuracy of the inspection technique and incorporating the uncertainty of different inspection techniques in the selection process is a primary step in the framework, as described in the following sections.

3.3.3.1. Accuracy of Inspection Methods and Data Obtained during Inspections

The accuracy of an inspection technique can be expressed as the relation between the measured defect and the actual defect size (Zheng & Ellingwood, 1998). The detected structure defect is usually subject to inaccuracies and noise during inspection. Herein, the accuracy of an NDE method will be mathematically formulated using the following linear regression analysis, Equation (3) (Zheng & Ellingwood, 1998):

$$Y(t_{Ins}) = \psi_1 + \psi_2 a_M(t_{Ins}) + e \tag{3}$$

where $Y(t_{Ins})$ is the actual defect size at the inspection time t_{Ins}, $a_M(t_{Ins})$ is the measured defect during inspection, ψ_1 and ψ_2 are regression parameters that need to be calibrated according to the inspection technique (i.e., NDE method), and e is the measurement error described as a Gaussian random variable with a zero mean and a standard deviation σ_e that varies according to the accuracy of the inspection and the geometry of the analyzed element (Zheng & Ellingwood, 1998). Overall, Equation (3) can provide a probabilistic representation of the actual defect $Y(t_{Ins})$, which will follow a Gaussian distribution with a mean $\psi_1 + \psi_2 a_M(t_{Ins})$ and a standard deviation σ_e (i.e., $Y(t_{Ins}) \sim N(\psi_1 + \psi_2 a_M(t_{Ins}), \sigma_e)$) (Atadero et al., 2019). The higher the accuracy of an NDE, the lower σ_e will be, which will provide measurements closer to the actual deterioration process, providing a higher reduction in the uncertainty and enhancing the model prediction (Haladuick & Dann, 2018).

3.3.3.2. Incorporating Inspection Results Using Bayesian Updating

To reduce the uncertainty in the deterioration model prediction, Bayesian updating can be used to update the prediction model parameters θ by combining the new inspection data with the prior or existing information (Atadero et al., 2019). The posterior or updated distributions for the probabilistic model parameters θ can be estimated using Equation (4) (Enright & Frangopol, 1999a):

$$P(\theta \mid a_M(t_{Ins})) = \frac{L\left(a_M(t_{Ins}) \mid \theta\right) P(\theta)}{\int L\left(a_M(t_{Ins}) \mid \theta\right) P(\theta) d\theta} \qquad (4)$$

where $P(\theta \mid a_M(t_{Ins}))$ is the posterior distribution of a model parameter θ, $a_M(t_{Ins})$ is the measured defect during inspection, $L\left(a_M(t_{Ins}) \mid \theta\right)$ is the likelihood function of measuring $a_M(t_{Ins})$ for a given θ, and $P(\theta)$ is the prior distribution of θ. Further, if $a_{DM}(t_{Ins})$ is the prediction of the deterioration model using θ, then based on the inspection accuracy represented in Equation (3), the likelihood function can be formulated as Equation (5) (Atadero et al., 2019)

$$L\left(a_M(t_{Ins}) \mid \theta\right) = \prod_{i=1}^{n_{Ins}} \left\{ \phi \left[\frac{a_{DM}(t_{Ins}) - \psi_1 - \psi_2 . a_M(t_{Ins})}{\sigma_e} \right] \right\} \qquad (5)$$

If a number of measurements or inspections n_{Ins} are conducted using the same technique, the likelihood function can be updated as the product of the PDF for each inspection measurement, assuming independence between the measurements.

When the framework is applied for the first time before the TTT for a given bridge, it is very important to note that until this stage of the proposed framework, an NDE inspection has not been performed at t_{Ins} and the actual inspection results $a_M(t_{Ins})$ have not yet been obtained. Thus, to use Bayesian updating in selecting the suitable inspection method at t_{Ins}, a pre-posterior analysis can be conducted, by (1) assuming different values of $a_M(t_{Ins})$ and different inspection scenarios (i.e., NDE methods); (2) establishing the posterior values for each different inspection outcome; and (3) updating the information regarding the condition of the bridge and TTT, according to each assumed or available inspection scenario. The standard deviation σ_{TTT} and COV_{TTT} will be used to quantify uncertainty in the estimated TTT and the reduction achieved by the NDE candidates.

Based on the results of the pre-posterior analysis, the candidate NDE methods or NDE consultants will be compared, and if the inspection cost is not a constraint, then the candidate that can reduce the uncertainty regarding the TTT the most will be selected. In practice, the inspection cost will always be a burden, and in some scenarios, the most accurate inspection method will not be cost-effective compared to other inspection techniques, especially in the short run. However, the bridge inspection planner may find that an expensive inspection method might be worthwhile if the whole bridge life cycle is considered, since a more accurate technique will lead to fewer inspections as will be demonstrated in the application example. If multiple inspection methods satisfy the required criteria, the bridge inspector can choose the appropriate inspection method after considering the cost of the inspection and the availability of the inspection technique.

Finally, after performing the actual inspection, the inspection results will be used to update the model parameters using Bayesian updating, and the posterior values will be used in the next planning cycle to choose the following inspection time and technique.

3.4. Example Application of the Framework

In this example, the uncertainty-based inspection framework will be applied on an existing bridge in Colorado. The example will be divided in two main parts. In the first part, the bridge is assumed to be relatively new, with just two years of operating history. To demonstrate the capabilities of the framework, only one deterioration process will be considered in this part. Then, in the second part of the example, it will be assumed that the bridge has been operating for more than 15 years and corrosion is active, and two deterioration mechanisms will be considered in choosing the inspection time: pitting corrosion depth and crack growth.

3.4.1. Description of Bridge

E-17-HS is a four-span bridge in Colorado, and according to the information provided by (Akgül & Frangopol, 2005; Kim & Frangopol, 2011b; Marsh & Frangopol, 2008), the bridge is a two-lane bridge crossing over interstate highway 25 at 160th Avenue. Figure 3.3 shows a schematic drawing of the deck cross-section. The thickness of the concrete slab is 18 cm and the concrete cover over the top slab reinforcement is 30 mm. The deck is supported by four RC beams in the end spans and steel girders in the intermediate spans. The concrete deck in the end spans is 11.3 m long and 10.40 m wide. The spacing between the RC girders is 2.65 m and the depth and width of the RC girders are almost 66 and 40 cm, respectively. This example focuses on corrosion of the top slab reinforcement, where maximum negative moments will occur due to transverse loads on the bridge deck.

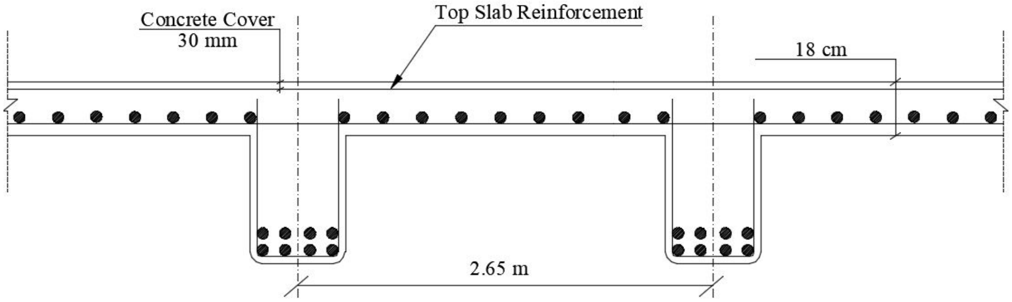


Figure 3.3. Schematic drawing for the cross-section of the reinforced concrete (RC) deck

3.4.2. Part 1: Applying the Proposed Framework on a New Bridge

Applying the proposed framework to a new bridge begins in year two of the bridge service life. At this time, a visual inspection has been conducted to make sure everything is operating well and according to design. The time to transition (TTT) in Part 1 considers only the first corrosion deterioration stage in the RC deck service life and will be expressed as the time when corrosion initiates in the top reinforcement. Corrosion is assumed to initiate when the chloride concentration at the rebar level reaches 0.04 g/mm^3 (Kim & Frangopol, 2011b). The TTT can be considered by a bridge inspection planner as the appropriate time to apply a preserving maintenance (e.g., adding a sealant to the concrete surface) to delay corrosion propagation and help avoid a late and costly maintenance action (e.g., removing the whole top cover of the concrete surface). To clearly demonstrate how the framework can be implemented, the planning process will be represented as a series of tasks the bridge inspection planner is expected to follow.

3.4.2.1. Task 1: Year 2, Selecting Suitable Deterioration Model

Deterioration models for corrosion meeting the requirements of Section 3.2.1 have been selected for Parts 1 and 2 of this example and are detailed in Appendix (A). The prediction model shown in Equation (A1) was selected for Part 1 of the example to predict the TTT (corrosion initiation time) and to propagate uncertainty in the deterioration process. This mechanistic model can be updated by measuring some of its parameters onsite using well-established NDE methods as discussed subsequently. In addition to selecting a model, appropriate model parameters must be established. The values of the parameters can be obtained from previous inspections, archived data for similar bridges, or from the available literature. The values and probabilistic descriptions of the parameters in Equation (A1) used for this example are summarized in Table 3.3.

Table 3.3. Values and probabilistic descriptors of parameters used in Equation (A1)

Variable	**Notation (units)**	**Mean**	**COV**	**Distribution**	**References**
Cover	x (mm)	30	0.2	Lognormal	(Marsh & Frangopol, 2008)
Surface chloride content	C_0 (g/mm^3)	0.15	0.1	Lognormal	(Kim & Frangopol, 2011b)

Diffusion coefficient	D_c (mm^2/year)	26.68	0.1	Lognormal	(Akgül & Frangopol, 2005)
Critical chloride content	C_{th} (g/mm^3)	0.04	0.14	Lognormal	(Kim & Frangopol, 2011b; Kim et al., 2011)

3.4.2.2. Task 2: Year 2, Predicting the TTT and Developing the Two Criteria for Choosing Next Inspection Time

As mentioned earlier in Section 3.2.2., there are two criteria used in the framework to select the next inspection time. The first criterion is based on the uncertainty level in the predicted bridge condition before the TTT and the second is based on the probability of transitioning to another stage in the bridge service life.

For the first criterion, the deterioration model in Equation (A1) and Monte Carlo simulation (sample size 100,000) were used to predict the corrosion initiation time (i.e., TTT, when chlorides reach $0.040\ g/mm^3$ at the rebar level). Then, to propagate uncertainty in the condition of the bridge before the TTT, the expected time $E(t)$ required to reach a specified chloride concentration C_{ch} at the rebar level and the corresponding standard deviation σ_Y were estimated. PDFs for the corrosion initiation time and time to reach a certain C_{ch}, ranging from $0.010\ g/mm^3$ to $0.040\ g/mm^3$ with an increment of $0.005\ g/mm^3$, are shown in Figure 3.4. The PDFs in Figure 3.4 show that as the target chloride concentration and thus the length of simulation increase, there is a greater spread in the distribution, indicating less certainty in the prediction model results.

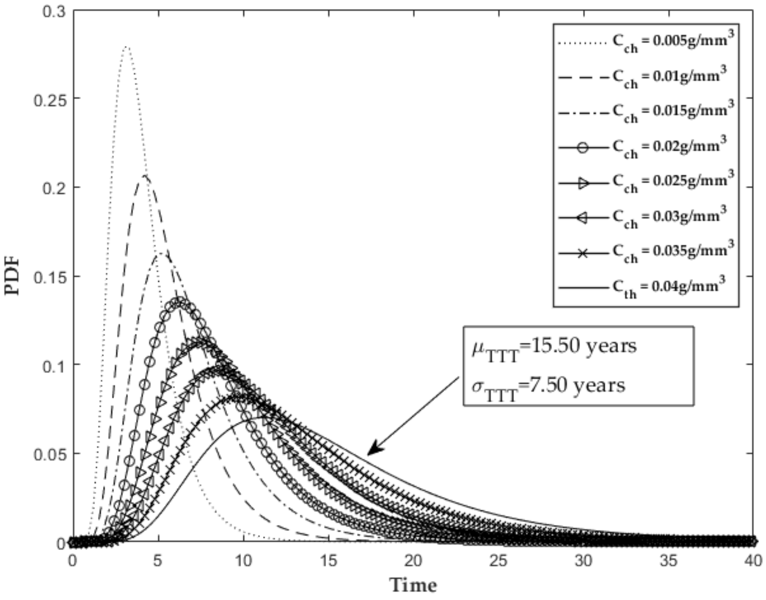


Figure 3.4. Probability distribution functions (PDFs) for corrosion initiation time and time to reach a certain C_{ch} at the rebar level

From Figure 3.4, it can be seen that the expected corrosion initiation time μ_{TTT} (expected TTT) and the corresponding standard deviation σ_{TTT} are 15.50 and 7.50 years, respectively. Table 3.4 shows the $E(t)$ to reach a specified chloride concentration at the rebar level and the corresponding σ_Y. For example, at a mean time of 9.50 years, the C_{ch} at the rebar level is anticipated to equal 0.025 g/mm^3 and the σ_Y is expected to reach 4.50 years.

Table 3.4. Expected time to reach specified chloride concentration at the rebar level and corresponding standard deviation

C_{ch} (g/mm^3)	**$E[t]$** (years)	**σ_Y** (years)
0.005	4.00	2.00
0.010	5.50	2.50
0.015	6.50	3.50
0.020	8.00	4.00
0.025	9.50	4.50
0.030	11.00	5.00
0.035	13.00	6.00
0.040 = C_{th}	15.50 = μ_{TTT}	7.50 = σ_{TTT}

For the second criterion, to calculate the probability of corrosion initiation (i.e., reaching the TTT) at different time periods, the cumulative probability of transition $F(t)$ (i.e., lifetime function) was obtained from the conducted Monte Carlo simulation as shown in Figure 3.5. For example, according to the $F(t)$, there is almost a 22% chance that the TTT for the concrete deck will be at year 10 (i.e., 22% probability that corrosion will initiate at year 10).

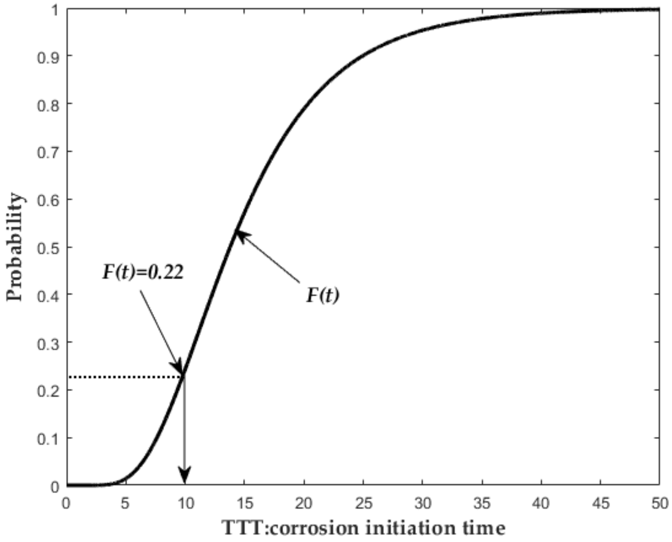


Figure 3.5. Cumulative probability of transition

According to the obtained cumulative probability of transition $F(t)$ and the calculated σ_Y, the first bridge inspection $t_{Ins,1}$ should be considered whenever σ_Y or $F(t)$ exceed their corresponding uncertainty thresholds, σ_{th} and P_{th}, respectively.

3.4.2.3. Task 3: Year 2, Determining the Uncertainty Thresholds

To determine the uncertainty thresholds, the expert-based assessment process (described in Section 3.3.2.3.) will be conducted in this section. As discussed earlier, the damage considered here is corrosion of reinforced concrete decks, and the total number of performance and consequence factors (P&C factors) considered is eleven (See Table 3.2). The bridge in this part of the example is considered new with an NBI condition rating above 7. Therefore, based on the scoring system described in Table 3.1, the initial maximum score of the E-17-HS bridge deck is 110.

Table 3.5 shows the points that will be deducted from the initial maximum score based on the information available on the bridge E-17-HS in (Akgül & Frangopol, 2005; Kim & Frangopol, 2011b; Marsh & Frangopol, 2008), the levels and description of each performance and consequence factor provided in Table 3.2, and rational assumptions.

Table 3.5. Points that will be deducted from initial score based on the P&C factors.

Performance Factors	**E-17-HS condition**	**Points deducted**
Deck Drainage system and ponding	The deck does not have a drainage system	-10
Year of Construction or replacement maintenance	Bridge is assumed new and has been operating for two years only	0
Protective layer over concrete surface	The deck has an asphalt overlay but with limited effectiveness	-5
Bridge Skewness	The bridge is not skew.	0
Average daily truck traffic (ADTT)	This bridge only has an average of 5 heavy trucks per day	0
Subjectivity to Over spray	The bridge crosses over a roadway exposed to deicing salts and has a clearance of 5m which makes it subject to moderate overspray	-5
Reinforcement type	Uncoated carbon steel bars	-10
Consequence Factors	**E-17-HS condition**	**Points deducted**
Damage to the top of the bridge	Bridge E-17-HS has a moderate average daily traffic ranging from 600 to 1000 vehicles per day and any damage to the top of the bridge or closing the bridge for long durations of maintenance can cause moderate delays	-5
Features under the bridge	The bridge crosses over a highway (Interstate-25) and any spalling of concrete due to corrosion could cause major traffic delays and may cause accidents or injuries	-10
Structural Capacity	The initiation of corrosion will have almost no effect on the capacity of the steel rebars, structural safety, or serviceability since cracking has not yet started and the area of the steel rebars have not been affected due to corrosion	0
Alternative Routes	There are two main alternative routes that the public can use if the bridge was closed, to avoid public delays as much as possible	0

According to the points assigned in Table 3.5, the total number of points that will be deducted from the score of 110 is 45 points, resulting in a final score equal to 65. According to the scale shown in Figure 3.2, the concrete deck will be considered in the medium category and medium uncertainty thresholds should be used. This shows that although the bridge had a rating above 7 and is new, it still was not considered in the high category due to the factors that can affect its performance and the risks of the failure outcomes.

If the uncertainty-based inspection framework had been used in the past, the agency could use or perhaps update existing threshold values. In this case, since it is assumed that this is the first time implementing the uncertainty-based inspection framework, the agency will need to establish threshold values to assign to each inspection category. Threshold values used for this example to represent low, medium, and high uncertainty thresholds will be those shown in Table 3.6. It should be noted that these values are not fixed and can be changed. Moreover, the number of categories can be increased as discussed earlier, but here, only three categories are used for simplicity (low/medium/high). The threshold values shown in Table 3.6 are only for demonstration purposes, and when choosing the values, the aim was to: (1) show that the two criteria can yield different inspection times, (2) avoid having a threshold in a lower category yielding an inspection time after any threshold in the better category, for example, if P_{th} was 25% in the low category, it would have required an inspection (i.e., around year 10.5) after the inspection time required by the $\sigma_{th} = 0.5\sigma_{TTT}$ (i.e., at year 8) in the medium category, and (3) avoid performing inspections after the expected TTT, for example, the σ_{th} was considered as a fraction from the $\sigma_{TTT} = 7.5 years$, and this will help assure that when σ_Y exceeds σ_{th} (i.e., an inspection should be considered), its value will still be less than σ_{TTT} and inspections will be conducted before the TTT. Based on these concepts and others, agencies can calibrate their inspection thresholds to provide inspection intervals that satisfy expert judgement and guarantee the safety of the bridge, and once the thresholds are set, they can be used on many bridges.

Table 3.6. Values of uncertainty thresholds to be embedded from Figure 3.2's scale.

Uncertainty thresholds	σ_{th}	P_{th}
Low	$0.3\sigma_{TTT} = 2.30 years$	15%
Medium	$0.5\sigma_{TTT} = 3.75 years$	30%
High	$0.7\sigma_{TTT} = 5.25 years$	40%

In short, a bridge inspection should be considered when σ_Y and $F(t)$ exceed or equal 3.75 years or 30%, respectively. According to the first uncertainty threshold σ_{th} and the values of σ_Y at different times in Table 3.4, the first NDE bridge inspection $t^{\sigma}_{Ins,1}$ should be considered at year 8 (i.e., 6 years from year 2), when the σ_Y will equal 4 years, exceeding the 3.75 years threshold (i.e., $\sigma_Y > \sigma_{th}$). Based on the second criterion or threshold P_{th} and the obtained cumulative probability of transition in Figure 3.5, the value of $F(t)$ will exceed 30% at almost year 11 (i.e., $t^{P}_{Ins,1}$ = 11 years). Thus, based on the proposed procedure, the first NDE inspection $t_{Ins,1}$ will be conducted at year 8 (i.e., $t_{Ins,1}$ is the minimum of both $t^{\sigma}_{Ins,1}$ and $t^{P}_{Ins,1}$).

3.4.2.4. Task 4: Choosing NDE Inspection Method for Inspection at Year 8

The deterioration model in Equation (A1) can be updated by measuring the surface chloride content C_0 and/or the concrete cover using NDE methods such as the chloride ion penetration test (CIP) or a cover meter (CM), respectively (NCHRP, 2006) (the most informative approach would be to measure the chloride concentration at the rebar level, but this would involve a destructive core test). Equation (3) will be used to analyze the effect of the NDE accuracy on reducing the uncertainty in the predicted TTT, where a_M represents the measured surface chloride concentration or concrete cover, and $Y(t_{Ins})$ is the real value of the parameters at the time of inspection which is represented as a Gaussian random variable. Agencies may conduct their own nondestructive tests, and in this example, it is assumed that five NDE consultants have offered their services, as shown in Table 3.7, to the bridge agency. The bridge inspection planner is required to select one of these consultants to conduct the inspection using the proposed framework. All five consultants will use a CIP test with different accuracies and only consultant 5 will also use a CM during the inspection at year 8 to make sure the cover is adequate. The concrete cover was added to the inspection options to analyze its effect on the model prediction and to see the effect of measuring more than one parameter on the uncertainty level.

Table 3.7. Accuracy details of NDE methods proposed by of the five different consultants

Consultants & NDE methods used	**Description of inspection quality**	$Y(8yrs) \sim N(\psi_1 + \psi_2 a_M(8yrs), \sigma_e)$		
		ψ_1	ψ_2	σ_e
Consultant 1 :CIP	Unbiased, with accuracy $\pm 10\%$ out of the measured C_0	0	1	$0.1a_M$

Consultant 2 :CIP		Unbiased, with accuracy $\pm 25\%$ out of the measured C_0	0	1	$0.25a_M$
Consultant 3 :CIP		Biased (real value will be higher than measurement), with accuracy $\pm 10\%$ out of the measured C_0	0	1.2	$0.1a_M$
Consultant 4 :CIP		Biased (real value will be lower than measurement), with accuracy $\pm 10\%$ out of the measured C_0	0	0.8	$0.1a_M$
Consultant 5:	CIP	Unbiased, with accuracy $\pm 25\%$ out of the measured C_0	0	1	$0.25a_M$
	CM	Unbiased, with accuracy $\pm 15\%$ out of the measured concrete cover.	0	1	$0.15a_M^{Cover}$

Table 3.7 shows the difference in the accuracy of the consultants and which consultants are expected to have biased results and require calibration. For example, for consultant 1, it is assumed that the inspection will be unbiased and have an accuracy of ±10% (i.e., $\sigma_e = 0.1a_M$) out of the measured C_0, compared to the NDE inspections conducted by consultants 3 and 4, where biased results are expected (i.e., calibrated using the regression line slope ψ_2). Information about the accuracies of the CIP test and the cover meter can be found in (Atadero et al., 2019; Hesse et al., 2017).

Since only a visual inspection has been completed at this point, to choose the appropriate consultant and to conduct a pre-posterior analysis, it is assumed that the measured concrete cover will be 30 mm, the same as the prior (i.e., $a_M^{Cover} = 30\ mm$), while the measured C_0 will be 0.3 g/mm^3 (i.e., $a_M = 0.3\ g/mm^3$), which is double the prior assumed value used to begin predictions (see Table 3.3). This higher C_0 value was rationally assumed because at year 8, the bridge would have been exposed to several deicing cycles and traffic splashes from the highway under the bridge, increasing the C_0 while not having an efficient drainage system. As the C_0 increases, the corrosion rate increases and the TTT decreases, meaning there may be less time for preventative maintenance. Further, this will be the first inspection based on the deterioration model before model accuracy in representing the real bridge condition has been verified. Assuming the condition will be worse than expected is a conservative approach. These assumed values could also be obtained either from prediction models that predict the future values of this specific parameter or from inspection reports of bridges that have similar properties. Using the parameters for ψ_1, ψ_2, and σ_e, the probabilistic values of Y were established as shown in Table 3.8, based on the accuracy of each consultant and the assumed inspection results. These values will be used as the likelihood function in the Bayesian updating process.

Table 3.8. Likelihood functions obtained based on assumed inspection values and consultants' accuracy

Consultants		$\boldsymbol{Y(t_{Insp}) \sim N(\ \psi_1 + \psi_2 a_M(t_{Insp})\ , \sigma_e\ )}$.
Consultant 1:CIP		$Y(8yrs) \sim N(\ 0.3g/mm^3, 0.03g/mm^3)$.
Consultant 2:CIP		$Y(8yrs) \sim N(\ 0.3g/mm^3, 0.075g/mm^3\ )$.
Consultant 3:CIP		$Y(8yrs) \sim N(\ 0.36g/mm^3, 0.03g/mm^3)$.
Consultant 4:CIP		$Y(8yrs) \sim N(\ 0.24g/mm^3, 0.03g/mm^3)$.
Consultant 5:	CIP	$Y(8yrs) \sim N(\ 0.3g/mm^3, 0.075g/mm^3\ )$.
	CM	$Y(8yrs) \sim N(\ 30mm, 4.5mm\ )$.

Table 3.9 summarizes the results of the pre-posterior analysis and the calculated posterior values (i.e., the mean μ_P and standard deviation σ_P) for the C_0 and concrete cover associated with the accuracy of each NDE consultant. The posterior values were used as the new inputs for the deterioration model Equation (A1) to obtain the expected TTT and reduction in the uncertainty level (i.e., σ_{TTT} and COV_{TTT}) associated with each consultant.

Table 3.9. Pre-posterior analysis for choosing inspection method and corresponding expected time to transition (TTT)

Consultants		**Posterior values of measured parameters**		$\boldsymbol{\mu_{TTT}}$ **(years)**	$\boldsymbol{\sigma_{TTT}}$ **(years)**	$\boldsymbol{COV_{TTT}}$
		$\boldsymbol{\mu_P}$	$\boldsymbol{\sigma_P}$			
Consultant 1 (Unbiased-accuracy 10%)		$0.181g/mm^3$	$0.0134g/mm^3$	12.50	5.00	40%
Consultant 2 (Unbiased-accuracy 25%)		$0.156g/mm^3$	$0.0147g/mm^3$	14.50	6.50	45%
Consultant 3 (Biased-accuracy 10%)		$0.192g/mm^3$	$0.0134g/mm^3$	11.50	5.00	43%
Consultant 4 (Biased-accuracy 10%)		$0.168g/mm^3$	$0.0134g/mm^3$	13.50	6.00	44%
Consultant 5 (Unbiased-accuracy 25%)	C_0 :	$0.156g/mm^3$	$0.0147g/mm^3$	14.00	4.50	32%
	Cover:	$30mm$	$3.6mm$			

In the prior prediction of the TTT, σ_{TTT} was 7.50 years and the COV_{TTT} was around 48%; both values express the uncertainty in the first prediction. Based on the accuracy of the NDE consultants and the assumed inspection measurements a_M, it can be seen that updating the deterioration model using an NDE inspection can reduce the uncertainty in the model prediction. However, the reduction in some of the cases was smaller compared to other consultants and prior predictions. For example, due to the low accuracy of consultant 2 (i.e., $\pm 25\%$), the reduction in the σ_{TTT} was only 1 year and there was a 3% reduction in COV_{TTT} (compared to the prior), whereas when consultant 1 was considered (accuracy $\pm 10\%$), the reduction in the σ_{TTT} was 2.50 years and the COV_{TTT} decreased by 8%.

The maximum reduction in uncertainty will be achieved by hiring consultant 5, where the σ_{TTT} and the COV_{TTT} compared with the prior will be reduced by 3 years and 16%, respectively. Although the accuracy of the CIP method conducted by consultant 5 was lower than consultant 1, which had the highest CIP accuracy, the reduction in the uncertainty was greater. This shows the importance of updating the concrete cover and how sensitive the model prediction is to the cover parameter, which agrees with the findings of (Morcous et al., 2010). It should be noted that if the accuracy of the CIP test of consultant 5 was similar to consultant 1, the predicted TTT will have a μ_{TTT} and σ_{TTT} of 12 and 3.50 years, with a COV_{TTT} of 29%, which means even more improvement in the uncertainty reduction (i.e., COV_{TTT} reduced by 19% compared to the prior). Moreover, as shown in Table 3.9, a low accuracy inspection (i.e., consultant 2) or a biased inspection such as with consultants 3 and 4 can misguide a bridge inspector and lead to inaccurate decisions regarding the TTT and appropriate time of repair. Thus, bridge inspection planners should give attention to the quality and accuracy of the NDE method. However, as the quality of the inspection increases, the cost of inspection will increase.

In some cases, enhancing the quality of the inspection by using a more accurate NDE or combining more than one NDE method can enhance the value of the inspection and reduce uncertainty regarding the TTT and repair time, which, as a result, can help in avoiding unnecessary repairs or expensive delayed repair activities, outweighing the increase in the inspection cost. Based on the information provided by (Enright & Frangopol, 1999b), conducting an NDE inspection with a CIP test on a similar bridge to the E-17-HS will cost USD 8400. This inspection cost includes the cost of personnel, the maintenance of traffic, the snooper, laboratory analysis, and the CIP test. Hence, adding a cover meter (i.e., difference between consultant 1 and 5) to the inspection process can increase the cost of the inspection by a range of USD 500–USD 1500 (Hesse et al., 2017; Taylor et al., 2016). In practice, a bridge inspection planner should consider both the reduction in uncertainty and the cost of inspection when choosing the inspection method, and this reduction in uncertainty regarding the TTT will either help in improving the maintenance decision process or it will not. Finally, based on the above analysis, it is assumed that consultant 5 will be hired by the agency to conduct the inspection at year 8.

3.4.2.5. Task 5: Year 8, Incorporating Inspection Data in the Planning Process to Predict the Updated TTT and Choose the Following Inspection Time

To show how the collected inspection data impact the inspection planning process, four different inspection scenarios are assumed as the outcomes of the first NDE inspection conducted at year 8. The analyses for each scenario are shown in Table 3.10, indicating how the inspection outcome can change the decision regarding the next inspection time and TTT. In scenario 1, it was assumed that the average values of the measured C_0 and cover are similar to the prior values illustrated in Table 3.3 (i.e., $C_0 = 0.15 g / mm^3$ and $\text{cover} = 30 mm$); however, the standard deviations were different due to the accuracy of the NDE test conducted by consultant 5 (see Table 3.7). In scenario 2, it was assumed that the surface chloride concentration will be higher (i.e., $C_0 = 0.4 g / mm^3$) than the prior and the concrete cover ($Cover = 28 mm$) will be lower, leading to a faster rate of corrosion and a shorter TTT. On the other hand, in the third scenario, a slower corrosion rate was assumed with a lower surface chloride concentration ($C_0 = 0.13 g / mm^3$) than the prior and a larger concrete cover ($Cover = 32 mm$). In the last scenario, it was assumed that the concrete cover test failed, and no data were collected, but the measured surface chloride concentration was similar to the prior.

Table 3.10. Statistical descriptors of the bridge condition and TTT based on the assumed inspection scenarios and posterior values.

Inspection scenario	**Value of measured parameters. (Likelihood)**	**Posterior value of measured parameters.**	C_{ch} **(g/mm^3)**	$E[t]$ **(years)**	σ_Y **(years)**
Scenario (1): (Same C_0 and higher cover)	$C_0 \sim (0.15 g/mm^3, 0.0375 g/mm^3)$ $Cover \sim (30mm, 4.5mm)$	$C_0 \sim (0.15 g/mm^3, 0.014 g/mm^3)$ $Cover \sim (30mm, 3.6mm)$	0.025	9.50	3.00
			0.030	11.00	3.50
			0.035	12.50	4.00
			0.040 = (C_{th})	14.50= μ_{TTT}	5.00= σ_{TTT}
Scenario (2): (Higher C_0 and smaller cover)	$C_0 \sim (0.40 g/mm^3, 0.1 g/mm^3)$ $Cover \sim (28mm, 4.2mm)$	$C_0 \sim (0.160 g/mm^3, 0.0148 g/mm^3)$ $Cover \sim (28.7mm, 3.45mm)$	0.025	8.50	2.50
			0.030	9.50	3.50
			0.035	11.00	4.00
			0.040 = (C_{th})	12.50= μ_{TTT}	4.50= σ_{TTT}
Scenario (3): (Smaller C_0 and higher cover)	$C_0 \sim (0.13 g/mm^3, 0.013 g/mm^3)$ $Cover \sim (32mm, 4.8mm)$	$C_0 \sim (0.1385 g/mm^3, 0.010 g/mm^3)$ $Cover \sim (31.22mm, 3.74mm)$	0.025	11.00	3.50
			0.030	14.00	4.00
			0.035	15.50	4.50
			0.040 = (C_{th})	17.50= μ_{TTT}	6.00= σ_{TTT}
Scenario (4): (Smaller C_0)	$C_0 \sim (0.15 g/mm^3, 0.0375 g/mm^3)$	$C_0 \sim (0.15 g/mm^3, 0.014 g/mm^3)$	0.025	9.50	4.00
			0.030	11.50	5.50
			0.035	13.50	6.00
			0.040 = (C_{th})	15.00= μ_{TTT}	7.00= σ_{TTT}

Bayesian updating was performed considering the new values measured during inspection as the likelihood (Table 3.10, column 2) and the parameter values stated in Table 3.3 as the prior. Then, the new posterior values shown in Table 3.10 (column 3) were obtained and used in the prediction model to find the new TTT and the corresponding inspection time using uncertainty propagation and lifetime functions (see Figure 3.6), similar to Section 3.4.2.2. According to scenario 1, the TTT is expected to be at year 14.50, which is 1 year earlier than the prior prediction (i.e., prior TTT = 15.50 years). When a faster corrosion rate was considered as in scenario 2, the TTT was expected to happen earlier at year 12.50, which is opposite to scenario 3, where the TTT was expected to be delayed by 2 years. Based on the inspection outcome, the TTT predicted, and the associated uncertainty can change significantly, affecting the decision of the bridge inspector regarding the appropriate time and method of intervening or conducting a repair. For example, if maintenance is to be considered at TTT, based on the prior prediction, a preserving maintenance to reduce the corrosion rate could be conducted at year 15.50, but if the inspection outcome was similar to the one in scenario 2, this intervention should be done earlier at year 12.50.

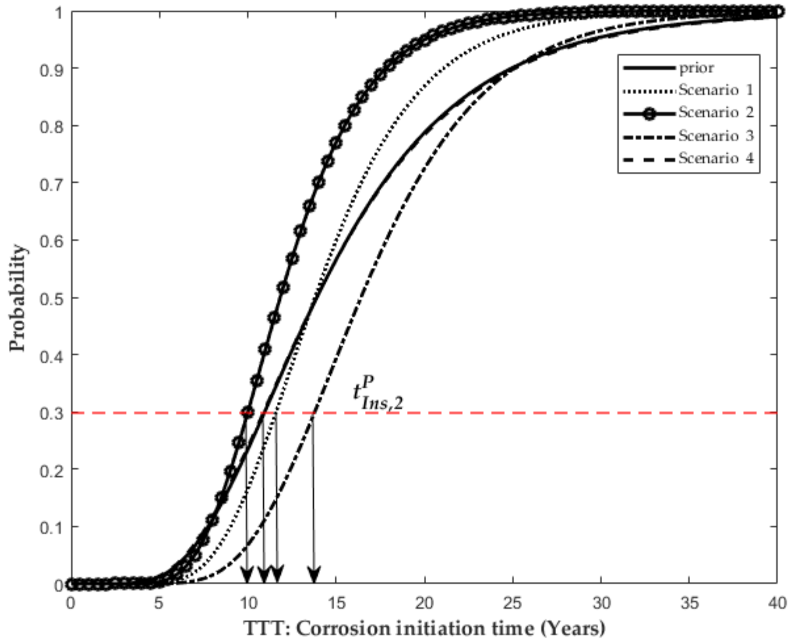


Figure 3.6. Cumulative probability of failure lifetime function based on inspection scenario

Before choosing the next inspection time, $t_{Ins,2}$, a bridge inspection planner should perform the expert-based assessment procedure and decide on the uncertainty thresholds, since the condition and risks surrounding the bridge could have changed. However, if the same uncertainty thresholds were used in this stage (i.e., $\sigma_{th} = 3.75 years\ and\ P_{th} = 30\%$), according to scenario 1, the second NDE inspection $t_{Ins,2}$ is to be considered at year 12.50 or 12.00, where σ_Y and $F(t)$ exceed 3.75 years and 30%, respectively (see Table 3.10 and Figure 3.6). Hence, based on the minimum criteria adapted (i.e., the inspection $t_{Ins,2}$ is the minimum of both $t^{\sigma}_{Ins,2}$ and $t^{P}_{Ins,2}$), the second inspection should be at $t_{Ins,2} = 12.00 yearrs$. With a similar approach considering scenarios 2 and 3, the next inspection $t_{Ins,2}$ should be conducted at years 10.00 ($t^{P}_{Ins,2} = 10 years$) and 14.00 ($t^{\sigma}_{Ins,2} = 14 years$), respectively. This shows the value of the inspection outcome and how it can impact the next inspection time. Bridges where deterioration is happening as predicted, or more slowly, will be able to have longer stretches between inspections, while bridges that are showing faster deterioration will be inspected more frequently.

As mentioned earlier, in some cases, improving the inspection quality or combining more the one NDE method can help in reducing the uncertainty level regarding the TTT and corresponding repair time. In this context, the reason for assuming that scenario 4 happened during inspection is to show that improving the inspection quality, for example, by combining two NDE methods, can also help in reducing the number of inspections and total inspection cost during the life cycle of the bridge. When the cover meter was used as in scenario 1, this reduced the uncertainty, leading to a second inspection at year 12.00, which is almost 4.00 years from the last inspection at year 8 and about 2.5 years from the TTT when a maintenance can be considered. Meanwhile, in scenario 4, failing to measure the cover led to a very small reduction in uncertainty, which, according to the uncertainty thresholds, will require the bridge inspector to conduct an inspection at year 9.50, which is only 1.50 years from the last inspection. Although the inspection conducted with the cover meter will be more expensive, having a small gap between inspections and a small reduction in uncertainty can lead to more inspections, increasing the total inspection cost.

3.4.3. Part 2: Applying the Proposed Framework on an Existing Bridge

This part of the example moves forward in time and demonstrates how the uncertainty-based inspection framework can be applied on a bridge that has been operating for many years, where corrosion is already active, and the bridge is in the corrosion propagation stage. This part of the example also shows how the framework allows for consideration of more than one deterioration process at the same time. It is assumed that the bridge has been operating for 16 years, and the last visual inspection conducted at year 16 spotted hair cracks and rust stains on the concrete surface, indicating that corrosion is already active in the concrete substrate of the E-17-HS bridge and the bridge has entered the corrosion propagation stage. Thus, the proposed framework will be applied to choose the appropriate inspection time and methods after year 16.

To show how this framework can plan for inspections while considering more than one deterioration process at the same time, in this part of the example and stage of the bridge service life, two primary deterioration mechanisms or limit states will be considered simultaneously, pitting corrosion of the steel reinforcement and cracking of the concrete cover due to corrosion. The average diameter of the transverse reinforcement in the E-17-HS bridge deck is 16 mm (Marsh & Frangopol, 2008), and accordingly, the allowable pitting corrosion depth (PCD) (i.e., limit state 1) is 4 mm (Kim et al., 2013). Previous work also showed that concrete cracks tend to connect, causing longitudinal cracking and spalling at crack widths between 0.3 and 0.5 mm (Molina, Alonso, & Andrade, 1993), whereas concrete cracks larger than 0.8 mm can have a significant impact on the serviceability of a bridge deck (ACI, 1978). As such, a crack width limit of 0.6 mm will be assumed to represent severe cracking (i.e., limit state 2). After reaching either of the limit states, a repair activity should be considered by the agency.

Based on the above discussion, in this part of the example, the TTT will be the expected time to reach a pitting corrosion depth of 4 mm (TTT_{PCD}) or the time to reach a crack width of 0.6 mm (TTT_{Cr}). The mechanistic models in Equation (A2) and Equation (A3) will be used to predict the TTT_{PCD} and TTT_{Cr}, respectively. The random variables that will be used in both equations are defined in Table 3.11.

Table 3.11. Values and probabilistic descriptors of parameters used in Equations (A2) and (A3).

Variable	**Notation (units)**	**Mean**	**COV**	**Distribution**	**References**
Concrete cover	X (mm)	30	0.2	Lognormal	(Marsh & Frangopol, 2008)
Rate of corrosion	r_{corr} (mm/year)	0.065	0.3	Lognormal	(Kim & Frangopol, 2011b)
Corrosion current density	i_{corr} $(\mu A / cm^2)$	1.2	0.3	Lognormal	(Cheung & So, 2015; Val, Stewart, & Melchers, 2000)
Limiting crack width	$w_{\lim}$	0.6 mm	--	--	(ACI, 1978)
Water cement ratio	wc	0.5	0.1	Normal	(Vu & Stewart, 2005)
Ratio between the maximum pit depth to the mean pit depth	V	5	0.1	Normal	(Val & Melchers, 1997)
Corrosion initiation time	T_{CI} (years)	14	0.15	Lognormal	Assumed
Time to reach a hair crack of size 0.05mm	t_{1st} (years)	$T_{CI} + 2yrs$	--	--	(Liu & Weyers, 1998; Liu, 1996)

3.4.3.1. Year 16, Choosing Next Inspection Time Considering Pitting Corrosion and Surface Cracking

Monte Carlo simulation and Equations (A2) and (A3) were used to predict both expected times to transition, $\mu_{\text{TTT}_{PCD}}$ and $\mu_{\text{TTT}_{Cr}}$, and the corresponding $\sigma_{\text{TTT}_{PCD}}$ and $\sigma_{\text{TTT}_{Cr}}$, respectively. Then, to choose the next inspection time based on the first uncertainty criterion (i.e., $\sigma_Y \geq \sigma_{th}$), the expected time to reach a certain pitting depth $(E[t]_{PCD})$ before reaching the maximum pitting corrosion depth (TTT_{PCD}) and corresponding standard deviation ($\sigma_{Y,PCD}$) were predicated, as shown in Table 3.12. Further, the expected time to reach certain crack sizes ($E[t]_{Cr}$) before reaching the maximum allowable crack size and corresponding standard deviation ($\sigma_{Y,Cr}$) were obtained, as shown in Table 3.13.

Table 3.12.The expected time $E[t]_{PCD}$ to reach a certain pitting corrosion depth (PCD) and the corresponding $\sigma_{Y,PCD}$.

PCD (mm)	$\mathbf{E[t]_{PCD}}$ **(years)**	$\sigma_{Y,PCD}$ **(years)**
1.00	18.50	2.00
1.50	20.00	2.50
2.00	21.50	3.00
2.50	23.00	3.50
3.00	25.50	4.00
3.50	26.50	5.00
4.00 (Limit state 1)	28.50 (TTT_{PCD})	6.50 ($\sigma_{\text{TTT}_{PCD}}$)

Table 3.13. The expected time $E[t]_{Cr}$ to reach a certain crack length and the corresponding $\sigma_{Y,Cr}$.

Crack width (mm)	$\mathbf{E[t]_{Cr}}$ **(years)**	$\sigma_{Y,Cr}$ **(years)**
0.30**	22.00	2.50
0.35	23.50	3.00
0.40	24.00	3.50
0.45	25.00	4.00
0.50	25.50	4.50
0.55	27.00	5.50
0.60 (Limit state 2)	28.00(TTT_{Cr})	6.00 ($\sigma_{\text{TTT}_{Cr}}$)

** The propagation started with 0.3 mm because this is the minimum limit of the model (Vu & Stewart, 2005).

Further, the cumulative probability of transition lifetime function for both limit states have been obtained and are illustrated in Figure 3.7, in order to help in choosing the next inspection time based on the second criterion (i.e., $F(t) \geq P_{th}$). As shown in Table 3.12, the expected TTT_{PCD} (i.e., time to reach a 4 mm depth of pitting corrosion in the steel rebar diameter) will be at $\mu_{\mathrm{TTT}_{PCD}}$ = 28.50 years, with a $\sigma_{\mathrm{TTT}_{PCD}}$ = 6.50 years. Meanwhile, as shown in Table 3.13, the expected TTT_{Cr} (i.e., time for surface cracks to reach a maximum width of 0.6 mm) will be at $\mu_{\mathrm{TTT}_{Cr}}$ = 28.00 years, with a $\sigma_{\mathrm{TTT}_{Cr}}$ = 6.00 years. Further, a bridge inspection should be considered once $\sigma_{Y,PCD}$ or $\sigma_{Y,Cr}$ exceed the uncertainty threshold σ_{th}, or when the cumulative probability of transition $F(t)$ for pitting corrosion or crack length exceeds the second criterion threshold P_{th} whichever happens first.

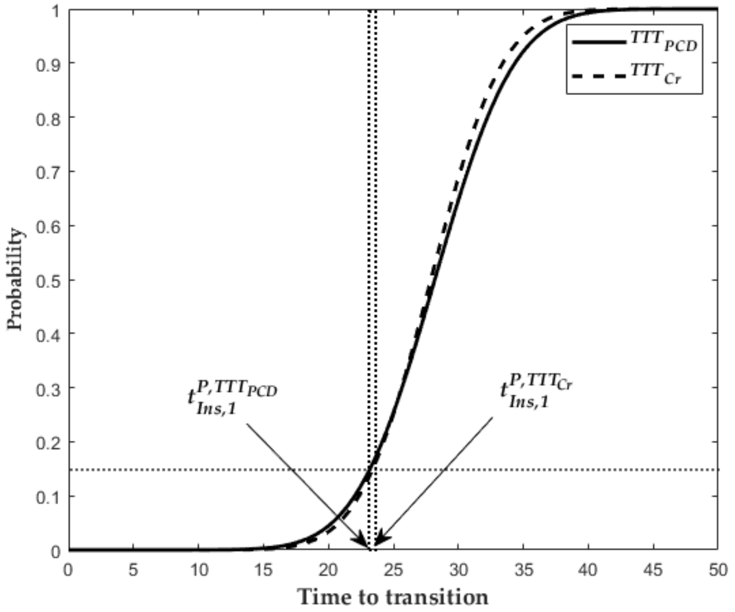


Figure 3.7. Cumulative probability of transition   for time to transition (TTT_{PCD} and TTT_{Cr}).

3.4.3.2. Year 16, Determining the Uncertainty Thresholds

The expert-based assessment process to choose the uncertainty thresholds should be conducted as demonstrated in Section 3.3.2.3. It should be noted that in this example, the decision process for choosing the thresholds for both deterioration mechanisms (pitting corrosion and surface cracking) can be the same since the damage modes considered are both due to corrosion. Alternatively, if a different deterioration mechanism (other than corrosion) or bridge component (other than the bridge deck) was considered such as fatigue cracking for steel elements, then another decision process has to be conducted with factors and considerations relevant to fatigue as a deterioration process.

The bridge in this part of the example has been operating for 16 years now and corrosion is already active with signs of hair cracks and stains. Accordingly, it was assumed that the bridge NBI rating dropped to 6 with an initial maximum score equal to 80 (see Table 3.1). Table 3.14 shows the points that will be deducted from the initial score based on the new conditions of the bridge after 16 years and assuming that ADTT has increased over the years and cracks and pitting corrosion will affect the deck capacity.

Table 3.14. Points that will be deducted based on the P&C factors.

Performance Factors	**E-17-HS condition**	**Points deducted**
Deck Drainage system and ponding	The deck does not have a drainage system	-10
Year of Construction or replacement maintenance	Bridge has been operating for more than 15 years now	-5
Protective layer over concrete surface	The deck has an asphalt overlay but with limited effectiveness	-5
Bridge Skewness	The bridge is not skew.	0
Average daily truck traffic (ADTT)	The ADTT has increased to a moderate level	-5
Subjectivity to Over spray	The bridge crosses over a roadway exposed to deicing salts and has a clearance of 5m which makes it subject to moderate overspray	-5
Reinforcement type	Uncoated carbon steel bars	-10
Consequence Factors	**E-17-HS condition**	**Points deducted**
Damage to the top of the bridge	Bridge E-17-HS has a moderate average daily traffic ranging from 600 to 1000 vehicles per day and any damage to the top of the bridge or closing the bridge for long durations of maintenance can cause moderate delays	-5
Features under the bridge	The bridge crosses over a highway (Interstate-25) and any spalling of concrete due to corrosion could cause major traffic delays and may cause accidents or injuries	-10
Structural Capacity	Pitting corrosion and cracking will affect the capacity of the steel reinforcement and the concrete deck	-5
Alternative Routes	There are two main alternative routes that the public can use if the bridge was closed, to avoid public delays as much as possible	0

According to Table 3.14, 60 points will be deducted from the initial score, leading to a final score equal to 20, putting the bridge in the low category (see Figure 3.2). Table 3.6 will be used to calculate the new threshold values that can be implemented in the scale shown in Figure 3.2. Accordingly, P_{th} will equal 15% and since $\sigma_{TTT_{Cr}} = 6 years$, which is smaller than $\sigma_{\mathrm{TTT_{PCD}}} = 6.5 years$, then σ_{th} will equal $0.3\sigma_{\mathrm{TTT}_{Cr}}$, which is almost 2 years. Based on Tables 3.12 and 3.13 and the uncertainty threshold for the first criterion ($\sigma_{th} = 2 years$), inspection should be considered at years 18.5 and 22 $(t_{Ins,1}^{\sigma,\mathrm{TTT}_{PCD}} = 18.5 yrs,\ t_{Ins,1}^{\sigma,\mathrm{TTT}_{Cr}} = 22 yrs)$. Meanwhile, based on the second criterion and Figure 3.7, inspection should be considered around the years 24 and 24.5 $(t_{Ins,1}^{P,\mathrm{TTT}_{PCD}} = 24 yrs, t_{Ins,1}^{P,\mathrm{TTT}_{Cr}} = 24.5 yrs)$. According to the minimum criteria used in the framework, an inspection should be performed at year 18.5, which is the smallest of all four inspection times and is 2.5 years from the last visual inspection at year 16.

At this stage of the bridge service life, to update both deterioration models (Equations (A2) and (A3)), along with the concrete cover, the corrosion current density i_{corr} or the rate of corrosion r_{corr} ($r_{corr} = i_{corr} \times V \times 0.0115$ (Cheung & So, 2015)) can be evaluated onsite using a linear polarization test (LPR) (Yehia et al., 2007) at the time of inspection. If various consultants offered their services, the bridge inspection planner can choose between them after conducting the pre-posterior analysis considering the accuracy of each consultant. In Part 2 of the example, it is assumed that until now, only visual inspections have been conducted in the service life of the bridge and no records are available regarding the corrosion rate. Thus, for conducting the pre-posterior analysis and to choose the appropriate NDE method or consultant, the inspection outcome (value of the corrosion rate at year 18.5) needs to be estimated. However, unlike the surface chloride concentration in Part 1, the i_{corr} and r_{corr} at year 18.5 can be estimated using the prediction model stated by (Vu & Stewart, 2000), which predicts how the corrosion rate will change with time.

Finally, after choosing the inspection time (year 18.5) and the inspection method, the final step is to conduct the inspection and use the inspection results to update the deterioration models using the Bayesian theorem.

3.5. Discussion

As shown in Part 1 of the example (the case of a new bridge), the proposed framework allowed for conducting only three inspections in an almost 12-year period following construction (i.e., one visual inspection and two NDE inspections). Meanwhile, if the currently used standard bridge inspection program (FHWA, 2012b) was adopted, six visual routine inspections would have been required in those 12 years based on a two-year fixed inspection interval. Furthermore, it is likely that some of these routine inspections would have been followed by in-depth inspections due to the limitations of visual evaluation. Nasrollahi and Washer (2015) found that for bridge superstructures in good condition, the two-year inspection cycle can be short and result in unnecessary inspections, and that scheduling inspections based on the bridge condition can result in reducing the number of inspections as was demonstrated herein. Further, using only expert opinion, Washer et al. (2016b) verified that inspection intervals for bridges with an NBI rating of 7 or higher can be 4 to 6 years. Similarly, after applying the proposed framework and using both expert opinion and quantitative methods in Part 1 of the example, it was found that for a bridge deck in a new condition, the inspection can be conducted at year 8, which would be 6 years after the first routine visual inspection conducted at year 2. In addition to what was presented by Washer et al. (2016b) and Nasrollahi and Washer (2015), we provided an approach to choose the suitable inspection technique that can effectively evaluate the bridge condition.

Maintenance decisions depend mainly on inspection results and quality. In the application of the proposed framework, it was found that conducting a high-quality nondestructive inspection after only 8 years from the bridge construction can reduce the uncertainty regarding the timing of the bridge repair by 16% as well as reducing the number of future inspections. Soliman et al. (2016) also concluded that a limited number of high-quality inspections can prevent damage detection delay and reduce the number of inspections. Kim and Frangopol (2018) found that replacing visual inspections with high-quality NDE early in the bridge deck service life can be cost-effective and help avoid redundant or delayed maintenance actions and bridge failure. However, the quality of the inspection in (Kim & Frangopol, 2018; Soliman et al., 2016) was defined using the probability of detection which, for some NDE techniques, can be difficult or expensive to obtain. Thus, in our method, we defined the quality of inspection by its accuracy and ability to reduce uncertainty regarding the bridge condition.

Kim, Ge, et al. (2019) recommended the use of Bayesian updating to incorporate inspection findings in the inspection planning process and update prediction model parameters. They found that inspection data can lead to better scheduling of future inspections and repairs which can help in allocating resources efficiently and prioritizing bridges that are in more need of maintenance actions than others. After analyzing different inspection scenarios herein, we found that inspection results can have a significant effect on the bridge management process and can lead to rescheduling interventions. We also found that incorporating inspection results can help in reducing the number of inspections as a result of reducing uncertainty regarding the timing of the bridge repair and the need to conduct more inspections.

Considering more than one bridge component or deterioration during the planning process was one of the main purposes of this study. Soliman et al. (2013) considered more than one fatigue-sensitive detail in their inspection planning process. However, a single deterioration model able to predict the fatigue crack propagation was used for all details. Hence, using a new approach in Part 2 of our example (existing bridge case), we included two different deterioration models simultaneously in the inspection planning process. This explains how the proposed framework can help bridge owners consider more than one deterioration process or bridge component during the inspection planning process.

Liu and Frangopol (2019) commented on how the attitude of bridge owners towards risk and bridge maintenance can have an effect on the inspection time and method and can impact the value of inspection information. In our study, expert judgement was used to choose the uncertainty thresholds. Based on the bridge owners' attitude towards risk and the consequence of a bridge failure, inspection schedules were established. Liu and Frangopol (2019) found that bridge managers with a risk-averse attitude preferred conducting inspections earlier in the bridge service life. On this basis, due to the flexibility of the proposed framework, bridge owners with a more risk-averse attitude can choose smaller uncertainty thresholds, leading to more frequent and earlier inspections even if the bridge was new and deterioration was predicted to be in the early stages.

Further, Kim et al. (2013) indicated that including the consequence of a failure in the inspection planning process can affect the inspection schedule and representing the failure outcome using a high failure cost can lead to more inspections. However, their concern was that putting a monetary value on bridge failure can lead to inaccuracies in the decision process. Thus, in the presented uncertainty-based inspection framework, the consequence of a failure is considered using expert judgement. We found that considering the consequence of a failure when choosing the uncertainty thresholds can reduce inspection intervals for a new bridge due to the risks associated with the bridge failure or delayed maintenance. This can increase number of inspections but will help in maintaining a safe and reliable transportation system.

Overall, the framework presented in this paper builds on the work other researchers have provided in the field of bridge inspection planning. The framework presents a new and practical approach for inspection planning that simply ties different approaches together into one comprehensive framework able to enhance the bridge management process.

3.6. Conclusions and Future Research

A new approach for bridge inspection planning was presented in this paper to help bridge owners determine the bridge inspection time and method by incorporating information from deterioration models, NDE inspection data, and expert judgement. The uncertainty-based inspection framework was developed with the objective to enhance the inspection efficiency, reduce uncertainty regarding the bridge maintenance time, and help bridge inspectors choose the inspection method that is appropriate for the stage of the bridge's life. In the proposed framework, inspections are considered as means to reduce the uncertainty regarding the bridge condition and update prediction models that can predict future bridge performance. Two criteria are used to schedule inspections, the standard deviation associated with bridge condition before reaching the time to transition (TTT) and the probability to reach the TTT. The approach was applied on an RC bridge in Colorado exposed to corrosion deterioration. Based on the analysis conducted in this study, the following conclusions can be drawn:

1. One of the main contributions of this study is to help bridge owners avoid delayed or unnecessary inspections. In the example, during a 12-year period, the proposed framework helped in reducing the number of inspections by 50% compared to the traditional uniform calendar-based approach while combining both routine visual inspections and in-depth inspections into a single inspection. Using the proposed uncertainty quantification methods to schedule inspections and conducting inspections only to reduce uncertainty regarding the bridge condition can help in utilizing inspection resources more efficiently.
2. The framework provides a clear guide on how to select the appropriate inspection procedure using Bayesian and regression analysis while considering the bridge deterioration stage, model parameters that need to be updated, and inspection accuracy. As shown in the example, inspection methods are selected based on their ability to reduce the uncertainty regarding the transition in the bridge deck condition and repair time. This can help in improving the value of the data gathered during inspections and hence improve maintenance decisions.
3. The analysis conducted in this study showed that improving the inspection accuracy can not only help in reducing the uncertainty regarding the bridge condition but can also help in reducing the number of inspections. Different inspection scenarios were compared, and it was found that when the concrete cover was not updated and the chloride content was measured by a relatively low accuracy, more inspections were required in the near future to reduce the uncertainty level.
4. Most of the presented inspection planning frameworks in the literature are limited to new bridges or a single deterioration mechanism. In Part 2 of the example, the framework was demonstrated on an existing bridge, and pitting corrosion of the steel reinforcement and concrete cover cracks were both considered simultaneously during the inspection planning process. This shows how the framework can be tailored to different types of bridge deteriorations and components, which is a major advancement compared to other inspection planning frameworks where only a single deterioration mechanism is considered

5. The process used to choose the uncertainty thresholds considers the consequence of the bridge failure and additional factors impacting the bridge performance other than the ones considered in the deterioration models. Due to this contribution, the risks associated with a bridge condition are considered during inspection planning to enhance the safety and serviceability of the bridge.

Finally, the use and potential benefits of the proposed framework still require further analysis and research. The application of the framework needs to be extended and real-time investigations on complex bridges should be conducted. Since the framework is still under development and has not been applied in practice, it is recommended not to use the framework on a new bridge before conducting an initial or routine inspection or on a structurally deficient bridge. Having a variable inspection interval can make it difficult for bridge owners to plan their budget for inspecting the bridges in their inventory. Therefore, this methodology should be developed to help bridge owners in estimating the bridge inspection life cycle cost. Some tasks in the framework require a background in statistics and software coding, which might not be available in some personnel working in government agencies. Thus, before implementing this program, some employees will require specific preparation. Further, including the effects of bridge redundancy and load ratings in the framework can help in improving the planning process even more.

CHAPTER 4: TRANSFERRING RESEARCH INNOVATIONS IN BRIDGE INSPECTION PLANNING TO BRIDGE INSPECTION PRACTICE: A QUALITATIVE STUDY

4.1. Introduction

The viability of our nation's infrastructure depends on continuous innovation and organizational cultures that encourage the application of valuable research ideas and technologies (Hood et al., 2014). In the transportation sector several strategies have been employed to accelerate research transfer into practice yet these approaches did not provide the desired outcomes and a lag between academia and the industry persists (Dekelbab, Hedges, & Sundstrom, 2017; Harder, 2014). In this qualitative study we focus on the field of bridge inspection planning and the reasons behind the gap between researchers and practitioners in the industry. While our study is within the specific context of bridge inspections, we seek to provide insights about how to facilitate research implementation and change in state Departments of Transportation (DOTs) that can be generalized and applied to other aspects of transportation or government organizations.

Bridge inspection planning is a non-trivial process impacted by various uncertainties and contradicting objectives (Morcous et al., 2010). Accurate and timely bridge evaluations can help maintain a safe and reliable bridge network while optimizing the cost of repair activities, reducing the overall expenditure on bridges (Kim et al., 2013). In the United States (U.S.) routine bridge inspections are conducted every 24-months regardless of the bridge condition and using visual inspection which has been reported to be subjective, uncertain, and limited to detecting deteriorations that have emerged on the surface of the structure (Graybeal et al., 2002). The limitations of current inspection practices have been documented in several studies and a variety of improvements have been the focus of several researchers such as changes to inspection intervals (Parr et al., 2010; Soliman et al., 2013; Washer et al., 2016a), implementing Nondestructive evaluation methods (Gucunski et al., 2015) and drones (Hubbard & Hubbard, 2020; Seo et al., 2018), and developing new software and database management systems that can enhance the inspection management process (Abdelkhalek & Zayed, 2020).

However, despite these research efforts and their potential to improve inspection quality and save inspection time and resources (Clarke-Sather et al., 2021), DOTs and the Federal Highway Administration (FHWA) have not yet adopted significant changes and still depend on the conventional inspection methods which cost around $1.3 billion dollars each year (Zulifqar et al., 2014). Therefore, the qualitative study presented herein aims to provide a descriptive and practical analysis of the barriers limiting the transfer of new ideas and technologies into DOTs and the actions that can be conducted to improve research products. After engaging with different DOT bridge staff members, data analysis was conducted using a thematic framework, and research findings were presented accordingly.

4.2. Purpose

The benefits of research results begin after practitioners and organizations use them in practice (Dekelbab et al., 2017). However, there is no ultimate solution or action plan to facilitate the implementation of research in practice as each type of action and implementing agency is unique, it is more of a combination of recommended protocols and frameworks (Harder, 2014). Implementing research requires a team of skilled and experienced people in the field of implementation. The knowledge and expertise for accomplishing the necessary activities associated with implementing a new research product is important for a smooth transition process, whether the expertise lies in the party presenting the research idea or the other party implementing the idea into practice (Hood et al., 2014). In addition, there are several factors that can affect the research transfer process such as the quality of the research products, organizational culture, time constraints, limited resources, and government policies and procedures (Fixsen et al., 2005).

To help the transportation community develop a research implementation infrastructure and facilitate research transfer in DOTs, the objectives of this study are:

1. Analyzing the current situation in bridge inspection practices by engaging with different DOT staff members and investigating their opinion on some of the approaches they use in current inspection

practices such as the 24-months inspection cycle used in routine inspections, NDE methods and visual inspections.

2. Identifying the factors that can help improve research efforts in the field of bridge inspection to provide the transportation community with usable and implementable research products.
3. There is a strong connection between research implementation and organizational change, hence another important objective of this qualitative study is to identify the barriers to adoption of new inspection techniques and planning methods from an organizational culture and change perspective.

Although the study focuses on the field of bridge inspection, the findings of this study are expected to be both specific to changes in bridge inspection practice and have some generalizability to other significant changes to engineering practice at transportation agencies.

4.3. Literature Review

In this literature review we focused on three major topics: bridge inspection, research transfer and organizational change. These topics are very broad; however, to achieve our study objectives we focused on the aspects that are directly related to the framework of our study and can help us develop our data collection methods (described subsequently).

First, we overviewed some of the main features of bridge inspections which is the context of our study. We aimed to understand current inspection standards, especially the aspects related to routine inspection planning, inspection methods and data management. This body of literature identifies the limitations associated with current practices and the main areas of research focus. This background was essential to analyze the current situation in DOTs and develop interview questions to collect required information on current practices. Also reviewing the research efforts in bridge inspection planning helped us identify the research products that were used during our interviews on how to enhance research products in the bridge inspection field.

Strategies to improve research transfer are evident in the literature in different scientific fields (Fixsen et al., 2005). Thus, in the research transfer topic we tried to review the problems researchers, sponsors, and practitioners in different domains face while implementing new research findings. Then we aimed to identify the strategies that can help overcome these challenges and be applied in the transportation sector.

Implementing new research products requires organizational change and development in DOTs' culture (Harder, 2014). In the third section of the literature review we focused on the factors and models that can help facilitate organizational change and avoid resistance (Al-Haddad & Kotnour, 2015). We used this information to accomplish our third study objective and discuss with participants their experience with organizational change and if they agree that the change drivers found in the literature can help facilitate change in DOTs or not. Moreover, participants in this study are not experts in change theory and models so we had to have the required information as investigators to develop a well-structured and informative discussion (Alshenqeeti, 2014). The information on organizational change also allowed us to identify the stakeholders that we need to contact for a rich and diverse perspective.

4.3.1. Bridge Inspection

There are different types of bridge inspections in the U.S.: initial, routine, in-depth, damage, fracture critical, underwater, and special inspection (AASHTO, 2011b). Routine bridge inspection is the most common type of inspection and, based on the requirements of the FHWA and the National Bridge Inspection Standards (NBIS), routine inspection is usually conducted every two years using visual evaluation. The information gathered during inspections help in reporting the bridge condition using the National Bridge Inventory (NBI) rating system (FHWA, 1995) or the AASHTO element level rating system (AASHTO, 2013; Farrar & Newton, 2014). Inspection reports are then incorporated into the state Bridge Management System (BMS) and NBI database (Farrar & Newton, 2014).

However, current bridge inspection programs have been associated with several uncertainties and limitations that have been addressed in previous research (Atadero et al., 2019; Graybeal et al., 2001; Nasrollahi & Washer, 2015; Parr et al., 2010; Phares et al., 2004). During routine inspection, inspectors are exposed to risks of injury due to limited accessibility and mobility in some locations (Hallermann & Morgenthal, 2014). Inspectors' qualifications and training may significantly vary, which can affect the quality of the reported inspection data (Ahamdi, 2017). Further, general and subjective visual inspections are limited to surface defects and associated with a high level of uncertainty (Kim, Gucunski, et al., 2019; Morcous et al., 2010). Another major concern about current bridge inspection programs is that there is no engineering justification for the 24-month inspection cycle specified for routine inspections (Washer et al., 2016a). The calendar-based inspection interval does not consider the condition of the bridge or the in-service environment. In fact, some studies have concluded that this approach is not the most cost-effective method for scheduling bridge inspections and can waste resources and lead to unnecessary or delayed inspections and risks (Atadero et al., 2019; Nasrollahi & Washer, 2015; Soliman & Frangopol, 2014; Washer et al., 2016a).

Due to the limitations of visual inspections, some researchers have focused their effort on developing and accessing nondestructive evaluation (NDE) techniques (Gucunski et al., 2013; Gucunski et al., 2012; Yehia et al., 2007), integrated systems (Gucunski et al., 2015; La, Gucunski, Dana, & Kee, 2017; Lim, La, Shan, & Sheng, 2011; Vaghefi, Ahlborn, Harris, & Brooks, 2015) and automated unmanned inspection methods (Hallermann & Morgenthal, 2014; Hubbard & Hubbard, 2020; Seo et al., 2018; Wells & Lovelace, 2018; Xu & Turkan, 2019). These techniques mainly depend on the bridge construction material and the defect that needs to be analyzed (Alampalli & Jalinoos, 2009; NCHRP, 2006; Ryan et al., 2012; Vaghefi et al., 2012).

In addition, to establish a more systematic approach for inspection scheduling and planning, various frameworks with different approaches such as reliability-based inspection methods, risk-based inspection methods and optimization-based inspection frameworks were proposed (Abdallah, Atadero, & Ozbek, 2021). Reliability based methods help in conducting inspections before failure, while considering the uncertainty in the bridge capacity and applied loads (Dong & Frangopol, 2015; Kwon & Frangopol, 2011; Orcesi & Frangopol, 2011; Soliman & Frangopol, 2013; Straub, 2014; Straub & Faber, 2002). Risk-based inspections consider the probability and consequences of a structure failure, and some of these studies quantify risk using mathematical approaches (Faber, 2002; Haladuick & Dann, 2018; Liu & Frangopol, 2019; Yang & Frangopol, 2018a), while others use expert judgement (Nasrollahi & Washer, 2015; Parr et al., 2010; Washer et al., 2016a). Optimization approaches help in finding the optimum inspection time and method while considering a single objective or multiple objectives and providing a range of pareto front solutions the bridge inspection planner can choose from (Chung et al., 2006; Kim & Frangopol, 2011b, 2017, 2018; Kim et al., 2011; Kim, Ge, et al., 2019; Soliman & Frangopol, 2014; Soliman et al., 2013; Soliman et al., 2016).

In our study we focused on discussing with participants their opinions on the 24-months used to schedule routine inspections and the alternative approaches presented in the literature. We also discussed the problems practitioners face when using new technologies during inspections such as NDE methods. Inspection scheduling frameworks and NDE methods were our main examples of research products that were used to generate a discussion with participants on the problems they find with research products in the bridge inspection field.

4.3.2. Research Transfer

Research transfer or implementation can be defined as a set of actions with defined dimensions designed or initiated to put valuable and applicable research findings and technologies into practice (Fixsen et al., 2005). Accelerating research implementation has been the aim of several organizations however research conducted to define a set of successful approaches or models has been limited (Harder, 2014). The U.S. Department of Defense has found that depending on more than one strategy during research implementation will lead to better results than depending on a single approach (Csoma, 2010). However, research implementation strategies are not cheap and require resources and enough time to provide training and technical expertise, conduct marketing campaigns to explain the merits of the new technology, and compensate for the delay in performance that can happen until all staff members are comfortable with the new technology (Klein & Knight, 2005). In the public sector, Cáñez, Puig, Quintero, and Garfias (2007) claim that one of the main barriers for research implementation is the rigorous and bureaucratic process required to attain the required resources to support innovation implementation, which requires significant effort and time. Accordingly, Grol and Jones (2000), found that in order to accelerate research implementation and allocate the required resources, organizations need to develop a research implementation infrastructure with systematic implementation frameworks and clear policies.

In the US, there are some key organizations promoting research and technology transfer. In the transportation community many studies are conducted by the National Cooperative Highway Research Program (NCHRP) to help disseminate new research findings, enhance the responsiveness of transportation research programs and build a standard practice for research implementation throughout the whole field (Dekelbab et al., 2017). The NCHRP is focusing on providing effective research products, implementation frameworks and enabling implementation cultures in transportation organizations (Harder & Benke, 2005). Several key players have been involved in those studies such as the Transportation Research Board (TRB), American Association of State Highway and Transportation Officials (AASHTO), state DOTs and the FHWA (Dekelbab et al., 2017). Some of the research efforts have been presented in transportation conferences and guides published by the NCHRP (Burke, 1984; Harder, 2014; Harder & Benke, 2005; Hood et al., 2014; Steven et al., 2013). Also, the Strategic Highway Research Program 2 (SHRP 2) has been one of the national examples in commitment to funding and providing expertise for research implementation. The SHRP 2 has allocated a $75 million budget to help support research transfer in the highway sector (Steudle, 2012). On the state level, the state planning and research federal aid has specified 4% of its budget for accelerating research implementation in DOTs as part of the Moving Ahead for Progress in the 21ST century (MAP) (Harder, 2014). Additionally, a few DOTs such as Pennsylvania DOT have developed a state council consisting of diverse local stakeholders responsible on tracking and evaluating new innovations that can help the DOT, while allocating the necessary resources to facilitate the implementation process (Bonini et al., 2011).

The National Implementation Research Network (NIRN) is another example of the effort done in the field of research implementation and the resources that can help facilitate research transfer (Metz, 2015). NIRN focuses on conducting technology transfer and implementation research, provide updated reviews on new frameworks and approaches in the research implementation field and communicate with governments and research domains to help implementing evidence-based practices (Harder, 2014). In 2005 NIRN provided a systematic framework for research implementation that can be applied in different scientific fields (Fixsen et al., 2005). The model consists of the following steps: 1) exploring the problem that needs to be solved and deciding on implementing a research finding to solve this problem, 2) identifying the resources needed for implementation, 3) launching an initial implementation process to identify barriers, 4) fully operating the new technology and making sure that staff members are successful in applying the new process, 5) evaluating the new practices and learning from feedbacks and 6) ensuring that the new practice will be sustainable and survive for a long-term (Fixsen et al., 2005).

Moreover, innovation needs people with strong connections to connect researchers with sponsors and business companies (Kanter, 2006). A study conducted by Mariello (2007), found that many researchers do not like getting involved in marketing or commercialization aspects to promote their research ideas. Thus, researchers in some cases need to be teamed up with business partners able to convince potential clients to adapt the new technology (Mariello, 2007). In this context, the Manufacturing Extension Partnership (MEP) is a program managed by the federal government and the National Institute of Standards and Technology (NIST) that helps researchers in the manufacturing industry commercialize and market their idea in the industry (Schacht, 2011). MEP helps labs seeking to transfer their new ideas connect with the manufacturing industry. The program also provides technical expertise and training for manufacturers willing to apply a new technology to reduce resistance among workers. The objective of this model is to facilitate research implementation in order to create new jobs, increase production and sales and reduce manufacturing costs (Schacht, 2011). Creating a similar approach in the transportation sector or in the bridge inspection field can help in promoting and commercializing relevant innovations in the field such as NDE methods or new bridge management systems. It can also help in involving the public organizations in the research process by providing researchers with test locations and opportunities to demonstrate their research findings (Harder, 2014).

In addition, the federal government is in continuous development of new partnerships with private intermediaries to help implement scientific findings coming out of federal labs into practice (Harder, 2014). This strategy has been used by many government organizations to allocate solutions for some of their problems through universities and individuals' research efforts (Bauer & Flagg, 2010). The primary goal of the private intermediaries is to market new research findings and provide organizations with agile research implementation frameworks. These organizations can help small innovators in obtaining the necessary funding for their research and legalizing research findings to accelerate its implementation (Bauer & Flagg, 2010). A similar model is the Entrepreneur in Residence (EIR) program implemented by the University of California Los Angeles (UCLA) which helps students and faculty members in the university build a business strategy, commercialize their research ideas and reach venture capital firms (Harder, 2014).

Also, to enhance collaboration between practitioners in the field of research implementation the Global Implementation Conference (GIC) is a biannual meeting held for researchers and practitioners from different countries and domains to address and discuss different topics about research implementation and technology transfer (GIC, 2011). The conference focusses on presenting new ideas and successful practices about implementation science and creating practice groups and workshops to educate participants (GIC, 2011). Fitting another conference in the schedule of DOT staff members or researchers in the transportation sector might be challenging. However organizing similar conferences or workshops that focus on research implementation or technology transfer in the transportation sector might result in more innovative cultures in the transportation community and reduce the gaps between researchers and practitioners (Hood et al., 2014).

One of the main barriers of research implementation in the transportation community is depending on a single individual or champions to lead change and not have a systematic implementation process managed by a qualified team of implementation experts (Dekelbab et al., 2017). Currently some organizations such as the Federal Aviation Administration (FAA) and the National Aeronautics and Space Administration (NASA) are using research transition teams responsible on implementing new research ideas and mitigating barriers during the transition process (Coppenbarger et al., 2012). Research transition teams consist of a skilled staff that has sufficient knowledge of science implementation frameworks and credible connections with different academic organizations, government officials, funding resources and sponsors (Levi & Slem, 1995). Using research and development teams helped the FAA and NASA in accelerating innovation implementation in their organization and establishing a sustainable model for research transfer (Johnson & Barmore, 2016).

Mahoney (2009) reported that training organizational staff on implementing new research findings for solving small and specific problems can help reduce the lag between research and practice. This initiative will remove the fear some humans experience before accepting a new idea in practice and accelerate research implementation (Mahoney, 2009). Rogers (2010) found that training alone will not lead to sufficient changes in research implementation but can help reduce resistance to change among the work force and make them feel prepared to the new technology. The Federal Laboratory Consortium for Technology Transfer (FLC) focuses on providing training for different stakeholders in the research transfer process. FLC trains researchers on how to build an implementation plan for their research products, provides government officials and managers of different entities with tools that can help them evaluate research ideas and identify best implementation practices (Bauer & Flagg, 2010). Wandersman et al. (2008) stated that training staff members on different approaches of research implementation can improve organizations' capacity to implement new technologies.

Rogers (2010) in his diffusion theory claims that research implementation in organizations requires leaders able to motivate employees and take necessary decisions. Klein, Conn, and Sorra (2001) stated that research implementation requires an organizational culture with strong managers able to cultivate and reward innovation and provide communication and shared perceptions among all stakeholders. However, managers who control budgets and critical decisions in an industry do not have enough time to read through whole journal articles or research proposals (Barbour, 2007). Therefore, to accelerate research implementation the Department of Agriculture developed the Joint Fire Science Program (JFSP) (Barbour, 2007). This program focuses on collecting data from the literature and publishing systematic reviews and synopses that are concise and accessible to mangers in the industry. Managers can easily use these synopses to analyze new scientific findings and provide critiques and feedback on the research ideas published on the program website (Barbour, 2007). This model was well received in the agriculture industry by practitioners and helped in disseminating scientific results and opening a dialogue between managers and researchers (Barbour, 2007). A similar approach can be an easy leap in the transportation sector.

Producing guides and clear policies for research implementation practices can help in documenting and assessing the implementation process. The National Oceanic and Atmospheric Administration (NOAA) is in continuous updating of its policy on research and development transition, to guide researchers and developers identify the necessary steps to implement a new technology into practice and gain all the required permits (Digiantonio, Newcomb, & Matlock, 2021). The NOAA transition policy requires innovators to clearly define the purpose and outcome of the research implementation, define the data and training that will be required by the users implementing the new practice, estimate the budget that will be required to execute the project from start to end and justify the costs of the new technology and present its benefits (Harder, 2014). Also, the department of Defense (DOD) developed the “Manager’s Guide to Technology Transition in An Evolutionary Acquisition Environment” that demonstrates a clear sequential plan and activities for implementing research (Csoma, 2010). This guide helps monitoring and measuring progress of research implementation projects and ensures that the new technology will be according to environmental and ethical considerations. The DOD guide also provides resources and websites that can help innovators mitigate barriers of research implementation (Csoma, 2010).

One of the main reasons for technology transfer failure is deploying a new technology before reaching full maturity and applicability (Straub, 2015). Thus, NASA presented a systematic technology readiness level scale to ensure that a technology is ready for application (Laughlin, Roper, & Howell, 2007). The framework starts by observing if the new technology follows essential mathematical characteristics and formulations. Then the technology concept is formulated by providing a clear description of how the theory behind the technology serves a certain application in practice. The feasibility of the technology also must be studied while developing analytical tools to simulate the new technology. Each component of technology is then tested in a laboratory environment, followed by a test of the whole system in a prototype of the real environment to analyze the choke points in the system. The actual system is then ready for initial deployment to analyze barriers and feedbacks before fully launching the new technology (Laughlin et al., 2007).

Studies by (Brunt, Lerner, & Nichols, 2011; Kay, 2011) noted that incentives and inducement prizes can help speed technology development and accelerate research transfer into practice. Kay (2011) commented that organizations providing inducement prizes can require candidates to present a clear diffusion and implementation plan before accepting their research idea. Currently, the DOT is managing a few research challenge competitions to motivate practical research findings (Harder, 2014), other organizations such as the National Science Foundation (NSF) use some of the funds available as research prizes to stimulate innovation and applicable research ideas (Williams, 2012). Rumpel and Medcof (2006) state that for researchers, incentives do not have to be financial but have to motivate them about their work and the effort they are making.

There are two main components related to research implementation: the effectiveness and applicability of the research product, and an organizational culture that enables innovation (Dekelbab et al., 2017). Several researchers have found that implementing a new research idea will require organizational changes that need to be well managed to reach the desired outcomes (Aslam, Muqadas, Imran, & Saboor, 2018; Heracleous & Barrett, 2001). Therefore, in the next section we present some of the main aspects related to organizational change and cultures that helped us identify the barriers that will face research implementation in the bridge inspection field from an organizational perspective.

4.3.3. Organizational Change

Due to rapid technological advancement, limited resources and growing global competition, change has become a norm for organizations to succeed and align their operations with changing environments (Armenakis & Harris, 2009). Many strategies have been suggested in the literature to manage change, however organizations are different in their structure, daily operations, goals and staff members (Appelbaum, Habashy, Malo, & Shafiq, 2012) and a one-size-fits model will usually lead to failing change (Kotter & Schlesinger, 1979). Therefore, transportation agencies need to be aware of their organizational cultures, weaknesses, and strengths before conducting an organizational change. DOTs need to also identify the scale of the change and the time it will take to implement this change. A large-scale change will be more comprehensive and lead to radical changes in the organization system, culture, and daily processes. Large changes will involve more stakeholder and require more resources than a small organizational change (Al-Haddad & Kotnour, 2015; Boyd, Lewin, & Sager, 2009). A small-scale change will lead to less disturbance in an organization however will result in less significant outcomes (Boga & Ensari, 2009). Also, long-term changes can be challenging and require participation of human resources in the change process to maintain a good work force morale during the long duration of change (Harrison, 2011).

To facilitate change and transformation in an organization, it is important to identify the critical factors that will enable a successful organizational change (Chrusciel & Field, 2006). The literature provides a wide range of factors that are related to successful change process. First of all, awareness of the need for change, and conducting a complete assessment of the current situation is the beginning of any successful change process (Brisson-Banks, 2010). Hence, our first study objective is to analyze the current situation in DOTs and understand what participants think about some of the conventional approaches used in bridge inspections. Bingham and Wise (1996), stated that managers should be able to persuade employees about the urgency of change while demonstrating the benefits behind this change. Further, organizational changes that are not supported by a systematic strategy and aligned with the organization’s main purpose or goal will end up failing and will not be supported by employees and managers (Smith, 2002). Kotter (1995), noted that proper planning is crucial during an organizational change to identify the environment and mind set an organization will need during a smooth transition. To reach the desired change outcomes in the public sector, organizational change goals need to be well-defined with a clear policy, to avoid ambiguity and different interpretation and implementation among public leaders (Fernandez & Rainey, 2006).

Another important facet for any transition is the personnel involved in conducting and leading the change. The content and process of an organizational change needs to be aligned with the people involved and their capabilities and values (Anderson & Anderson, 2002). For example, implementing a new technology in a company without preparing the workers and training them will lead to resistance and low probability of accepting this new change (Yang & Yoo, 2004). Smith (2002), commented that the major reason behind organizational change failure is to initiate a change without having enough resources and trained manpower to sustain this change. Also, implementing a new technology in an understaffed organization with limited time to learn and adapt to the new technology might be difficult due to the responsibilities and tasks required by the staff members (Desouza et al., 2009). Kanter (2006) found that allowing enough time for staff members to adapt to a new technology is important to reduce resistance and to relax the implementation of the new technology.

Moreover, Ulrich and Brockbank (2005) indicated that involving different levels of employees and human resource professionals in planning and executing the change process is prudent for a sustainable and consistent transition. According to Rouda and Kusy (1995), involving all levels of employees in identifying the goals of the change and classifying the required actions can help avoiding resistance from staff members, while uncovering different problems that higher-level managers may not consider, but still have an impact on the transition. Also, a leadership committed to the change and able to lead by example and communicate with different participants, is a key component to drive the transition phase (Fernandez &

Rainey, 2006). Strong leadership will ensure that the required goals are attained and a stable position is reached throughout the whole organization once the organizational change is complete (Burke & Ng, 2006).

Kotnour (2011) found that having a well-defined change management model, that is systematic and suited with organizational change goals, will reduce the resistance to change, uncertainty during change and employee burnout, leading to a smooth transition. Change management methods or models help managers engineer their organizational change process to take into account the overall organizational strategy and objective by establishing a vision and plan able to involve different stakeholders into the change process (Grover, 1999). Several change models have been proposed in the literature and were based on the principles of sociology and strategic change theories (Worren, Ruddle, & Moore, 1999).

One of the first organizational change models was introduced in 1947 by Kurt Lewin. This model was demonstrated in the book entitled *Field Theory in Social Science* (Lewin, 1951). This model consists of three main steps: unfreezing, changing, and refreezing. In the unfreezing step, the present stable environment in an organization is being altered by the newly introduced changes. The changing step involves analyzing the barriers and driving forces that will impact the transition process. Once the organization has reached a new stable state, and workers are accepting the organizational change by working through the new tasks and daily routine, then the refreezing phase should take place. Conducting a celebration where workers feel appreciated for their part in the successful change can help in stabilizing the new state and building a new sense of hope (Ritchie, 2006).

In 1969 Richard Beckhard developed a change model consisting of four main tasks (Beckhard, 1969). The first task focuses on clearly identifying the desired goals and rewards from the organizational change. Then a detailed diagnosis of the current condition has to be conducted with regards to these goals. The third task requires defining the role of each employee and the activities required for this transition to succeed. Finally, a management strategy is established to monitor the progress of the transition and identify any barriers slowing down the process. Dunphy and Stace (1988) argued that a change model should depend on the organization's leadership style. They also provided a change model that focuses on two dimensions: the scale of change and the leadership style.

In the early 90's Judson (1991) presented a change implementation model to avoid resistance to change, the model consisted of five main phases : 1) analyzing the change required, 2) communicating this change, 3) gain acceptance among the staff 4) perform the change to reach desired outcomes 5) consolidate the change. Judson (2011) found that predicting the sources of resistance before it occurs and providing different media of communications and bargains can facilitate the change, avoid resistance, and increase staff readiness to change. Following Judson (1991), Kanter, Jick, and Stein (1992) provided a sequential process for managing change. In this model, leaders had a role in identifying the external and internal sources that can slow down the organizational change in order to face them and present them to the main stakeholders.

One of the most famous organizational change models is the "Leading change" model which was developed by Kotter (1995) and has been under continuous development since then (Kotter, 1995, 2012). This model was one of the key aspects that helped us in developing our interview questions and discussing the necessary steps for a successful organizational change with participants. One of the advantages of this model is that it includes eight comprehensive and clear steps, which makes it relatively easy to understand, implement and control. The eight systematic steps are as following (Kotter, 2012): 1) establish a sense of urgency, 2) assemble a group of people with enough power and influence to lead others thorough the transition, 3) develop a vision and a strategy, 4) communicate the vision, 5) implement serious actions that can help remove obstacles and facilitate change, 6) create short term goals to help track the transition process, 7) consolidate gains and encourage further improvements, and 8) anchor new approaches in the organizational culture while showing the successes that the organizational change was a reason for.

Furthermore, Luecke (2003) believed that strong leadership during change will allow staff members to see change as an opportunity not as a threat to their comfort or careers. The Luecke method depends mainly on participation of all staff members and communication. The method encourages identifying a shared vision among employees and identify the problems and solutions to reach this vision and finally implementing the action plan while monitoring it during the change process. Also, in the early twenty first century, Hamel (2001) presented a change model that aims to provide clear steps for radical and large-scale changes in organizations. The model recommends writing the policies of change and making them clear among employees in the organization. In our interviews we focused on identifying if participants agree with some of these factors that can facilitate change and what other factors, they consider can help drive a successful and smooth transition process

4.4. Methodology

To address our specific research objectives; and given the practical and exploratory nature of our study, we selected a qualitative research method that involves interviews and questionnaires. The aim of this methodology was to help us gain in-depth descriptions and insights from a variety of DOT employees about how to improve current bridge inspection practices and facilitate the implementation of new research findings and technologies in DOTs.

4.4.1. Research Questions

The investigation protocol was developed to address the following research questions:

- Research question 1: What do bridge inspection professionals think about the current bridge inspection practices and how can the quality of inspections be improved?
- Research question 2: What are the actions that can be taken by researchers and DOTs to help improve the effectiveness of research products in the bridge inspection field and promote their utilization?
- Research question 3: What are the factors that should be considered from an organizational change perspective that can help accelerate research implementation in bridge inspection practices?

The research questions are strongly connected with the study objectives. The first research question addresses our first objective which is analyzing the current situation in bridge inspection practices by investigating participants' opinions on some of the aspects related to bridge inspections. In addition, our second objective is to understand how research products can be improved in the bridge inspection field, which links with our second research question. We developed our third research question to identify the factors that can facilitate change in transportation organizations from an organizational perspective, and that is the third objective of this study.

4.4.2. Participants

Staff members in public organizations can perceive innovation and change differently depending on their position and responsibilities (Fernandez & Rainey, 2006; Savage, Nix, Whitehead, & Blair, 1991). Accordingly we aimed for a maximum variation sample of key personnel in the organizational structure of state departments' bridge management divisions (Creswell & Poth, 2016). The goal of the sampling approach was to provide us with different perspectives to fully describe how different managerial levels and staff members could contribute to research implementation and organizational change. The participants represent the organizational members that will be involved in any change in the bridge inspection programs. The participants will either be involved in the planning phase, execution phase or both. In our investigation, we sought responses from three main levels of employees or job positions with the following criteria:

Level-1 (L1): A bridge program manager in the DOT, responsible for approving new inspection techniques, new funding, hiring consultants, research, communicating with the FHWA, and deciding on the training programs for inspectors.

Level-2 (L2): A senior bridge inspector in the DOT, decides on the number of inspectors, type of inspections (in-depth or routine), time and method of inspection, and uploads reports to the state's bridge management system.

Level-3 (L3): An assistant bridge inspector in the DOT, conducts the bridge inspection and prepares the inspection report.

It should be noted that these job descriptions are generic and different states might arrange responsibilities differently. Also, the title of each job position can differ depending on the department of transportation, however responsibilities can be the same. For example, in one DOT the Level-1 manager is named a bridge asset manager, while in another DOT the same position is named as bridge program manager.

Individuals invited to participate in the study were identified from the DOTs' websites and from professional connections of the authors. We then emailed participants asking them to participate in our study and telling them the reason they were chosen and the possible risks and benefits. A consent form was obtained from participants before participating in any part of the study and participants had the option to withdraw from the study at any time without penalties.

4.4.3. Data Collection

To obtain rich answers for our research questions, the investigation protocol consisted of four main data collection methods: "Bridge Inspection Questionnaires", "Journal Articles Interviews", "Organizational Change Interviews" and "Written Interviews". Also, to broaden the range of the viewpoints and to make sure that participants are answering questions related to their responsibilities and managerial level, each data collection method involved different job levels or positions (L1, L2 and L3). Before starting our data collection process, we obtained institutional review board (IRB) approval from Colorado State University.

Bridge Inspection Questionnaires: The value of bridge inspections depends on the time of inspections, inspection method and quality of inspection reports (Emal, 2017). Also, the first step to implement change and innovation in organizations is to analyze the current situation and the changes required (Fixsen et al., 2005; Judson, 1991). Therefore, the Bridge Inspection Questionnaires were developed to gather information about current inspection practices and how DOTs plan and conduct inspections and what participants think can help improve current inspection practices. The questions also focused on understanding how bridge inspection planners use inspection data in their decision process. The questionnaires were self-administered and consisted of six open-ended questions found in Appendix (B). The Bridge Inspection Questionnaires were sent by email to L2 and L3 participants only.

Journal Article Interviews: To generate rich data from interviews, especially the ones discussing broad topics, investigators need to build their discussions on examples or scenarios that make sense to interviewees or are related to their field of expertise (Schultze & Avital, 2011). To do so for this study, the participants received by email three journal articles that discuss three different strategies for bridge inspection planning. These articles represent a small but representative sample of the research that has been done in the field of bridge inspection. With this approach, our goal was to use the inspection planning frameworks proposed in the articles as examples of research products the DOT bridge staff members can relate to, since our participants are mainly experts in the field of bridge inspection. Then in the Journal Articles Interviews our discussions focused on identifying the concerns or questions participants found in these articles, that can be generalized to other research products in the transportation sector.

Each journal article discusses a different inspection planning strategy, has been published in prestigious journals in field of civil engineering and has been cited numerous times. The first article was published by Washer et al. (2016a) and presents a risk based inspection planning framework based on the NCHRP 12-82 study (Washer et al., 2014). The second article discusses an inspection planning framework proposed by Kim and Frangopol (2011b). The framework uses optimization algorithms and decision trees to choose the optimum inspection time and method that will minimize maintenance delay and inspection cost. The third article focuses on using the probability of detection in choosing the appropriate inspection interval for different NDE tools. The study was written by (Chung et al., 2006) and focused on inspection planning for steel bridges. Appendix (C) contains a summary of each article. The articles were sent to the participants along with a brief summary of each article before the interview.

The interviews were 45 minutes and semi-structured to provide the same basic interview structure for all participants but allow participants to add additional information during the interview and allow researchers to ask follow-up questions. Only L1 and L2 staff members were involved in the Journal Articles Interviews. Also, in the Journal Articles Interview we discussed with participants some of the important aspects related current inspection practices such as the 24-months inspection cycle and using NDE methods during inspections, since both of these topics were also discussed in the journal articles sent to participants.

Organizational Change Interviews: According to Oreg, Michel, and By (2013), designing a successful change framework starts by analyzing the views of those who have previously experienced change in their organization. Also, organizational change models such as the ones discussed in the Background section provide systematic frameworks for organizations to follow during change. However, Rosenbaum, More, and Steane (2017) pointed out that these models are not comprehensive and change leaders need to recognize other change drivers or barriers that could be specific to their organizational culture and still have significant impact on the transition process.

Therefore, in the Organizational Change Interviews, we asked participants about their past experience with organizational change and the factors they think can facilitate change and research transfer in bridge inspection divisions. Our questions tried to analyze if the participants agree with the factors mentioned in some of the theoretical change models (Judson, 1991; Kanter, 1983; Kotter, 1995; Luecke, 2003) and if there are other factors DOTs need to be aware of. The Organizational Change Interviews were also semi-structured interviews to understand how different organizational contexts informed the participants responses to the interview questions. This part of the study included all levels of participants, to understand how different staff members in the organizational hierarchy perceive change. We also used this advantage (involving all participants) to ask participants directly about the reasons behind the gap between research and the industry, and the research topics researchers should focus on.

Appendices (D) and (E) contain the questions asked during the Journal Articles Interviews and the Organizational Change Interviews. All interview questions were sent to participants before the interviews. All Journal Articles Interviews and Organizational Change Interviews were conducted in a private setting with participants either using video conference or telephone conference due to COVID-19 pandemic. Some of the interviews were audio recorded after participant's consent, as a basis to develop detailed transcripts. For those interviews that were not recorded, investigators took notes of participants responses.

Written Interviews: Due to the tight schedule of employees working in the DOTs, it became apparent that it was difficult to schedule the phone or video interviews. Accordingly, to increase the response rate we prepared a written format (Written Interviews) of the most critical parts and questions of the Bridge Inspection Questionnaires, Journal Articles Interviews and Organizational Change Interviews that were central to our research objectives. The questions added to the Written Interviews were based on our preliminary analysis and the quality of the responses in the Journal Articles and Organizational Change Interviews. The Written Interviews consisted of mostly open-ended questions and were sent out anonymously using Qualtrics to participants who we believe are L1 and L2 employees in different state DOTs, but we cannot for sure verify if it was only L1 and L2 employees who responded as this was an anonymous process. In the Written Interviews, participants were provided only a brief summary of the first journal article to save their time. The participants were then asked if they will consider applying a similar inspection planning approach in their department and what will be the resources required and obstacles to implement new ideas in inspection programs. The anonymous Written Interviews did not contain any questions that can identify the participants. Appendix (F) shows the questions asked in the Written Interviews.

All the data was stored on password protected computers only accessible by the authors for confidentiality. A total of twenty-six DOT staff members participated in this study consisting of nineteen anonymous participants, three Level 1 managers, two Level 2 and two Level 3 staff members. The response rate to the Written Interviews was significantly higher than other parts of the study. Table 1 summarizes the number of participants involved in each data collection method.

Table 4.1. Data collection methods and participants involved

Method	**Purpose**	**Participants**

Bridge Inspection Questionnaires	Gather information on current inspection practices	Two L2 and Two L3
Journal Article Interviews	Discuss the three journal articles and some aspects related to current practices such as the 24 months inspection cycle and NDE methods	Three L1 and two L2
Organizational Change Interviews	Discuss factors related to organizational change	Three L1, two L2, two L3
Written Interviews	Contains some of the critical questions in other data collection methods	Nineteen anonymous L1 and L2 participants

4.4.4. Data Analysis

Two researchers were present for all interviews. Interview data were transcribed and analyzed along with the participants' written responses using thematic analysis (Braun & Clarke, 2006). Minimum edits were conducted on extracts to enhance readability, without changing the meaning or inference. The analysis started with the researchers familiarizing themselves with the data, then establishing initial codes, themes, and subthemes, reviewing, and organizing themes and subthemes, and finally presenting the results. Participants' responses were initially read by the first author and iteratively coded using inductive coding to identify ideas emerging from the data, together with deductive coding based on literature review to address the research questions. All authors were included in each stage of the analysis process and frequent meetings before and after reaching data saturation were conducted to discuss themes and ideas, resolve converged or diverged interpretation in our respective analysis and to make sure we are answering our research questions. The literature review and data collection methods both helped us answer our research questions as shown in Figure 4.1 and explained in the following sections.

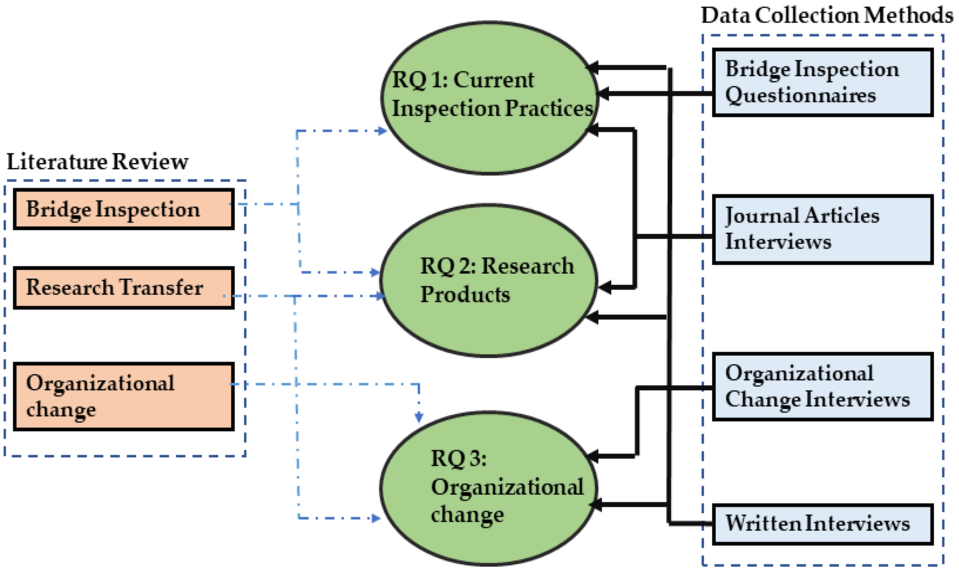


Figure 4.1. The contribution of the literature review and data collection methods in answering the research questions

4.4.4.1. Research Question 1

The Bridge Inspection Questionnaires helped us identify the approaches DOTs currently use to schedule bridge inspections, evaluate bridge performance, and manage inspection data. Also, L2 and L3 participants provided us with some important insights on how to improve current inspections from their perspective. In the literature researchers pointed out several limitations associated with conventional bridge inspection practices. Thus, the Journal Articles Interviews and the Written Interviews helped us analyze if practitioners in the bridge inspection field agree with researchers on these limitations, especially the ones related to the 24-months inspection cycle, visual inspections and NDE methods. The Bridge Inspection Questionnaires, the Journal Articles and Written interviews helped us identify some of the gaps between researchers and practitioners in the bridge inspection field.

4.4.4.2. Research Question 2

The Journal Articles Interviews and the Written Interviews also helped us understand if bridge inspection professionals will be willing to apply different inspection planning frameworks such as the ones provided in the journal articles and what will be the barriers, requirements, and advantages for implementing new frameworks and ideas in current bridge inspection programs. Our discussions helped us identify how researchers and DOTs can work together to improve research products and find applicable and practical solutions for important problems in the field.

4.4.4.3. Research Question 3

The organizational change that we focused on in this study is intended to facilitate the implementation of new inspection planning frameworks and technologies in bridge inspection programs. The Organizational Change Interviews and part of the Written Interviews helped us explore what participants thought are the main reasons for a successful organizational change based on their experiences with DOTs. This helped us identify the potential facilitators and barriers of change that will face new innovations and transitions in DOTs and map them with the evidence found in the organization change literature. Also, this part of the study helped us analyze the differences and commonalities between the participants' perspectives on organizational change, and how can different managerial levels and employees with different authorities and responsibilities embrace or resist change.

4.4.5. Quality Assurance of Findings

Forms of triangulation were conducted on parts of the data involving all three authors to enhance credibility and dependability (Jonsen & Jehn, 2009). For some of the interviews that were not allowed by participants to be recorded, the authors engaged in a member check to reach consensus agreement on the key findings and ensure accuracy of the data collected (Creswell & Miller, 2000). Continuous discussions involving all three authors were conducted to decide on the main study themes and to reach consensus agreement on every theme and relations between themes. This process contributed to the trustworthiness and quality assurance of the findings (Elo et al., 2014).

4.5. Findings

Based on the participants' responses across all four data collection methods five main themes were identified in the data as shown in Figure 4.2, and each theme consists of subthemes.

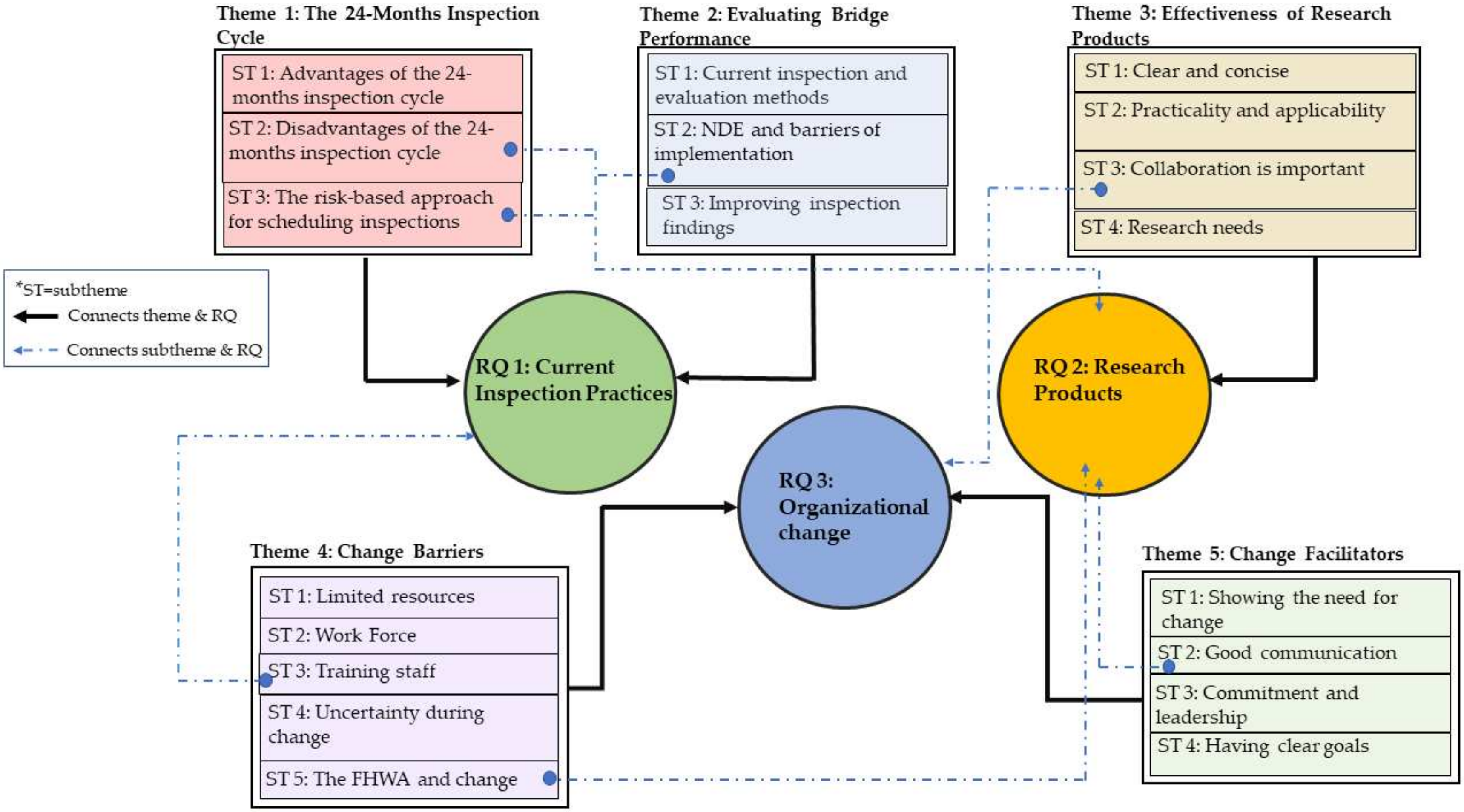


Figure 4.2. Themes and subthemes and their connection to the research questions

The five main themes are as following: 1) the 24-months inspection cycle, 2) evaluating bridge performance, 3) effectiveness of research products, 4) change barriers and 5) change facilitators. In response to the first research question, themes 1 and 2 demonstrate participants opinion on some of the important aspects related to current inspection practice such as the 24-months inspection cycle used to schedule routine inspections and the tools used in evaluating bridge performance. Theme 3 presents what participants suggested can help improve research products, which was our goal in the second research question. While themes 4 and 5 helped us answer our third research question regarding the factors that can help facilitate change and research implementation. As shown in Figure 4.2 the solid arrows represent the connection between the themes and the research questions (RQs), while the dotted arrows represent how some subthemes provide a secondary contribution in answering other research questions.

4.5.1. Theme 1: The 24-Months Inspection Cycle

In our interviews participants confirmed that they follow a fixed interval of 24 months for routine inspections and sometimes this interval can be shortened to 12 months if the bridge is structurally deficient, while in other cases the inspection interval can be extended to 48 months if the structure is in good condition and after approval of the FHWA. The 24-months inspection cycle used to schedule routine bridge inspections has been the focus of many researchers seeking to enhance the efficiency of bridge inspection practices. In our investigation we found that 44% of the participants supported the 24-months inspection cycle, 24% were against it and the remaining 32% stated that it has some advantage and disadvantages.

4.5.1.1. Subtheme 1: Advantages of the 24-months Inspection Cycle

Some participants reported that the uniform 24-months inspection interval helps in planning inspections unlike variable intervals: *"Uniform inspection intervals makes setting up inspection schedules, resources and tracking tools somewhat easier as timelines are uniform"* (Anonymous participant). While other participants commented on how the fixed interval can help them group bridges together to reduce travelling time and cost: "*Variable frequencies can be a bit of a challenge the most difficult thing is getting* *to the bridge, we try to group bridges geographically, so if you have a bridge on a 24-month frequency and one on a 36-month frequency it will not make sense to go out to the middle of nowhere to inspect one bridge"* (L2 employee). Also, participants commented that the fixed interval can help budget inspections especially for states with a large bridge network *"I think it is cost effective for big states, a variable inspection schedule will be hard to budget"* (L1 employee).

From another standpoint participants considered the 24-month cycle as a safe approach for scheduling inspections: *"The fixed interval ensures that bridges are inspected in a generally conservative interval, and that has a proven record of effectiveness"* (Anonymous participant); *"Some Bridges could be moved out from the 24-month cycle, but I would prefer to know sooner than later for issues that need to be addressed on the Bridges"* (Anonymous participant). Several participants commented on how the 24-month cycle helps in tracking bridge deteriorations: *"It helps letting our personnel stay familiar with their group of bridges to understand which ones need more attention or which ones are deteriorating faster, I understand the budgetary advantages of going to longer inspection intervals on good bridges, but for the vast majority of bridges in good to fair condition, 24 months is the right time to stay in touch with the bridge's behavior"* (Anonymous participant).

The simplicity and consistency of the calendar-based approach in scheduling inspections was also mentioned. Some participants found it a clear approach for scheduling inspections that does not require complex analysis: *"It is simple and uniform across the board which makes it easy to remember with no chances to miss due to mixed rules"* (Anonymous participant); *"Provides a clear starting point for each structure in the inventory"* (Anonymous participant).

4.5.1.2. Subtheme 2: Disadvantages of the 24-months Inspection Cycle

On the other hand, some participants thought the fixed inspection cycle is a waste of resources and does not suit every bridge condition: *" A one-size-fits all model for inspections can be an inefficient use of resources, inspection resources should focus on the bridges that need it most and back off from those where* *it has little added value"* (Anonymous participant); *"For bridges with NBI condition rating greater than 6, this could be considered a too frequent requirement and extending frequency will free up resources for other structures"* (Anonymous participant).

Some participants stated that the inspection cycle should be extended especially when the bridge is new and is in good condition, and then it can be adjusted as the bridge performance drops and deterioration rate increases: *"Routine inspections should be performed after the initial inspection at an increased frequency to begin with and if there are no identified issues, I think the frequency should be reduced to at least 4 years or more until it reaches either an actual or predicted deterioration level that may warrant an increased frequency"* (L1 employee); *"New bridges in good condition are being inspected with little benefit because condition changes slowly in the beginning of the life of a bridge"* (Anonymous participant).

Two participants mentioned that the 24-month cycle limits the inspection findings and quality due to weather conditions, because inspections for a bridge will happen in the same weather conditions every time which might limit inspection and the analysis of the bridge performance: "*Performing inspections on a 24-month cycle (in the same calendar month) results in very similar environmental conditions during the inspection. For example, the inspection may occur during the "rainy season" so chain dragging the deck is not commonly performed as part of the routine inspection. Likewise, scour and sediment transport processes can vary by season. A greater variety of conditions may be observed if the inspection cycle was changed to 24 months plus or minus 3 months"* (Anonymous Participant).

4.5.1.3. Subtheme 3: The Risk-Based Approach for Scheduling Inspections

In the participants' responses it was clear that most of them were concerned about the upcoming updates of the NBIS and the risk-based approach for scheduling inspections, which the FHWA is considering as a second option for scheduling inspections (FHWA, 2019). This approach is relatively similar to the framework presented by NCHRP 12-82 study (Washer et al., 2014), which was explained earlier in the Methodology section. An L2 participant stated that the main reason for this transition was the pressure the FHWA has received from the DOTs: *"I think the primary reason is the pressure they have gotten from states, and they are saying ok yes you're convincing us that it isn't always reasonable to use the uniform approach. I think it will happen I am seeing the trend with FWHA going more with risk-based systems with load ratings, and risk-based guidelines; they are going down that road"* (L2 employee).

Participants shared their thoughts on the risk-based approach, 36% said they will apply it once it is allowed, 21% said they will not consider it and 43% indicated that they will wait and see how other state departments will apply it: *"We are not going to deal with trying to figure it out we are just going to do them on a 24-month base and wait for others, we are very conservative here we don't want to be the first ones to do anything because we might mess it up"* (L2 employee).

An L1 manager commented that the reason they will consider applying risk-based inspection timings in their department is that the new approach will help in managing resources and improving inspections quality: *"The number of inspections would be reduced. Therefore, the quality of inspections should improve because our inspectors would have more time to complete them"* (L1 employee); while another L1 manager said that they will not consider applying the approach also for managerial reasons and that most of their bridges will still need to be inspected after 24 months: *"We will not apply it because it will be hard to group ageing bridges togethers and variable inspection intervals will be hard for budgeting. We also looked into similar approaches and it turned out that most of our bridges in our inventory will need to be inspected every 24 months"* (L1 employee)

We asked the participants about the obstacles and resources for specifically applying the risk-based approach, they commented on the risk-based panel that needs to be established to choose the inspection intervals and the effort and time it will require: *"Taking time away from bridge inspectors to sit on a panel is not achievable. The FHWA requirements for inspection frequencies necessitate that the inspectors are inspecting bridges not attending meeting to determine if a bridge can be moved to a different frequency"* (Anonymous participant); *"My concern with it is the expert panel, my concern is time and as with a lot of DOTs I think it will be challenging to be able to assemble the group that has the time to go through the* *structures and figure all of that out. It may be time well spent but sometimes we don't have the luxury of making that decision on our own"*(L2 employee).

Other participants shared their concern regarding the data that will be required to implement a risk-based program: *"We would need a project to review our historical bridge records to determine which elements, which conditions, and which component ages would drive the inspection intervals. Setting the intervals needs to be data-driven and not just based on judgment of the local inspectors and program managers"* (Anonymous participant). Also, some shared their concern regarding the effort and time that will be required to establish the risk-based frequencies: *"Creating this program will cost significant cost and employee time. The research for the basis of the intervals for our specific state elements has not been done and will need to be created from our historical data, and the program RBI intervals will need to be updated regularly"* (Anonymous participant). The FHWA was also mentioned several times by participants they were concerned by its approval on the inspection intervals : *"Once the new intervals are created, they need to be approved by the FHWA and since the FHWA does not give clear guidance on what is an acceptable approach to RBI, it is unclear how long our proposed approach would remain acceptable to the FHWA before they require us to redo a brand new RBI project to reset our intervals using a method that is acceptable to FHWA"* (Anonymous participant).

4.5.2. Theme 2: Evaluating Bridge Performance

The second part of our analysis of current practices focused on understanding how bridge conditions are evaluated, and what do participants think about NDE techniques. Under this theme we also explore what decisions can be made based on the inspection findings and what can be done to improve the value of inspection data.

4.5.2.1. Subtheme 1: Current Inspection and Evaluation Methods

We discussed with participants the techniques they use during inspections, all participants confirmed that visual inspection is the primary method used during routine inspections, while in some routine inspections chain drag can also be used: *"Typically we just use visual inspection techniques during a routine inspection, and we will commonly do deck chaining and sounding with a hammer during our routine inspections"* (L2 employee). For some steel bridges during routine inspections other NDE methods are used such as magnetic particle and dye penetrant test. However, most participants stated that NDE methods are mainly used during in-depth inspections. Also, tools such as snoopers and man-lifts can be used for accessibility.

The value of the information provided from visual inspections has been addressed in the literature in several occasions, along with its reliability and impact on the decisions and management process of the bridge lifecycle performance (Graybeal et al., 2001). Some participants commented that one of the main uses of routine inspections is to check on the safety of the bridges and the critical issues: *"The primary purpose of the routine inspection is to assure that the structures are safe for the traveling public and can remain in-service"* (L3 employee). An L1 manager stated that routine inspections can be used to determine the amount of work or repairs that need to be done on the bridge: *"We use the inspection information to assist with determining what type of work needs to be done on a bridge as well as determining the best time to do the work"* (L1 employee). Other participants stated that routine inspections help in determining if an in-depth inspection will be required or not. Also, in some cases routine inspections and bridge ratings can help in determining if the inspection cycle needs to be reduced or not: "*Routine inspections and coding of the NBI can show the urgency if tighter inspections cycles are needed"* (L3 employee).

As mentioned earlier there are two systems to rate the bridge performance during routine inspections, the NBI rating system (Guide, 1995) and the AASHTO element level system (AASHTO, 2013). Almost all participants commented that they use both systems to report the bridge condition. They use the NBI rating system to rate the main bridge components such as the super-structure and the sub-structure. The NBI rating is based on the element level rating of the elements which form the main bridge components. The inspection data and bridge ratings are managed using a bridge management software, 78% of the participants use AASHTOWare (previously known as PONTIS) (Thompson et al., 1998), while 22%

use other in-house programs. An L1 manager commented: *"We use NBI and Element data to evaluate all of our bridges. We plan to use Element data more and more as it becomes more consistent and reliable. It certainly is the goal. We use AASHTOWare for analysis"* (L1 employee).

4.5.2.2. Subtheme 2: NDE and Barriers of Implementation

NDE has been recommended as a tool to improve the quality of inspections however its use has been hindered in practice. Some participants commented that the main barriers for using NDE more often during inspections are the training required by bridge inspectors, maintenance of traffic, cost of equipment and accessibility required to reach certain bridge locations. An L2 employee mentioned some of these barriers as following: *"Skill and training is a big barrier; we need our inspectors to be certified to do NDE. Access can be a challenge too if inspectors see something during a routine inspection they may have to come back with a left dropper or a snooper to get close enough to do NDE in that areas, it also requires traffic control. I think NDE methods are more appropriate for more in-depth inspections we do visual inspection to identify cracks and we use NDE to confirm on them"* (L2 employee). Also, an L3 employee added that NDE methods can be expensive and time consuming. Some participants mentioned that most of the NDE inspections are done by special consultants hired by the DOT.

4.5.2.3. Subtheme 3: Improving Inspection Findings

Participants commented on the quality of inspection reports and data and how it can be improved. Some of the participants agreed that inspectors training is the most important action that can help in enhancing the value of inspections: *"Most important improvement is training. It helps inspectors understand not only the bridges and how they function, but the reason that they do inspections"* (L2 employee); *"We need to improve the training, knowledge and competence of the inspector"* (L3 employee). Some participants mentioned that having a consistent inspection protocol can help increase the accuracy of inspection findings: *"It is helpful to provide consistent inspection procedures and guidance"* (L2 employee), while one participant suggested that inspection effort and quality should depend on the bridge condition to optimize inspection efforts: *"Bridge inspection is complicated. Uniform application of rules to a complex problem may sound inefficient. I suggest determining what level of inspection effort should be spent depending on the bridge condition. For example, a newer or simple structure may take a cursory inspection of key elements and this could be sufficient to verify if changes to the ratings are necessary. The times saved here should be spent on more complex structures or bridges with poor conditions"* (Anonymous participant).

Further, two participants mentioned that improving inspection equipment and introducing new technologies can help improve the evaluation process of the bridge condition: *"Advancing technologies that provide reliable data suitable for condition assessment is a strong key improvement to improve bridge inspections for the future. Imaging technologies, automated quantification of defects, technologies to gain challenging access are some of the improvements that are needed over present methods"* (Anonymous participant).

4.5.3. Theme 3: Effectiveness of Research Products

One of our goals in this study was to identify the attributes that can help improve the research products in the field of bridge inspections. This theme covers what the participants find are the main factors affecting the quality of the research presented and hindering its implementation such as not providing clear and concise research results, applicability of research only on special bridge cases and how collaboration between DOTs and researchers can help reduce the lag between research and the industry.

4.5.3.1. Subtheme 1: Clear and Concise

Many participants agreed that sometimes research ideas are confusing and hard to understand which makes it difficult to implement. This was clear from their comments on two of the journal articles, which participants found hard to analyze: *"One of the research papers has stuff that I can use and implement it might take some time and have to do some allocation of resources, but I can understand it, its workable, it is like yes this makes sense. While for the other two, at least reading the papers was challenging; it is* *challenging for me to take that and go over here and use it, I feel there is still a gap here"* (L2 employee). An L1 manager commented that one of the reasons that prevent applying new ideas; is that managers cannot permit something in their departments without being able to understand it or explain it to other staff members: *"Very hard to understand this paper because of the statistics, it is hard to follow. I have to learn it in order to be able to explain it and I cannot present something new that I don't understand"* (L1 employee).

Also, it was clear during our investigation that most participants have tight schedules and no time to read the journal articles. In some cases, participants did not want to schedule interviews that will involve reading the journal articles. An L1 manager commented that one of the main obstacles to be updated with research findings is time, he commented: *"A lot of bridge owners and inspection managers do not have time to read through a research paper to evaluate the findings and its applicability to their program"* (L1 employee). Other participants shared their concern regarding the time that will be required to reflect on a new technology or an inspection planning program and understand how to adapt it.

Several participants recommended that researchers should focus on providing clear and practical ideas that can help DOTs solve some of their problems: *"Provide clear, concise, and deployable guidance. Guidance must be practical, understand the demands of the bridge inspector"* (Anonymous participant); *"Provide ideas on emerging and promising technology, but research needs to be directed towards ideas that can be implemented by the DOTs with the limitations they currently have"* (Anonymous participant).

4.5.3.2. Subtheme 2: Practicality and Applicability

During our discussion with an L3 employee he noted out that another problem with research products, is that sometimes research ideas are impractical and cannot be applied on a whole bridge network: *"As far as implementing the stuff you guys come up in the lab well some of these stuffs are awesome but applying it to thousands of bridges statewide seems impractical"* (L3 employee). He added that in order for researchers to be more practical they need to come to the field more often and see what is really happening on site.

An L1 and an L2 participant mentioned that one of the main problems regarding two of the journal articles is that they are only applicable on specific deterioration modes or types of bridges, and cannot be generalized: *"I don't think it would make any sense to apply this idea on the whole network because we are talking about very limited items; because if you are talking about the whole network for instance, we have very few fracture critical elements"* (L2 employee); *"This planning framework works for one deterioration process only; which is an incomplete analysis for a bridge"* (L1 employee)

4.5.3.3. Subtheme 3: Collaboration is Important

Several participants agreed that collaboration between practitioners in the industry and academics can help improve research products and direct research efforts efficiently. Participants found that academics should engage personnel from the industry in their research programs to help them find faster and practical solutions for problems that truly exist in practice not just in theory: *"Continue with your research, one research outcome could be the answer to everything. During the research, engagement with bridge inspectors and program managers performing the work will lead to a more reasonable research outcome. Presentations of research findings to bridge owners could help"* (L1 employee); *"The more we can communicate and work together the better off it is going to be for everybody. The people in academia will not feel that they are doing things for no reason and we are going to feel like, you are going to do things that we understand and need. I think communication is the biggest thing that is going to help"* (L2 employee). Two participants suggested that researchers could conduct workshops or training sessions for bridge inspectors to help them understand new ideas and research findings. They suggested that these sessions can be through workshops, organized conferences or even online: *"Deliver active training/webinars through AASHTO or similar established organizations"* (Anonymous participant).

Also, staff age can influence collaboration and research implementation. A senior inspector mentioned that in some cases old staff members might resist getting involved in new technologies and understanding them, unlike young staff members who might be willing to try new ideas: *"There is gap between old guys like myself and somebody coming out of college. The people coming out of college are more into technology or a lot more willing to accept it. I still want to get out and look at the bridge, there are guys coming out of college that would be ok for forming a circuit camera or centers, or something telling what is going on. Get rid of all us dinosaurs"* (L3 employee).

4.5.3.4. Subtheme 4: Research Needs

Several research ideas were suggested by participants as areas for researchers to focus on. Some participants complimented the research going into drones and how promising they find it: *"Using drones to detect fatigue cracks I think that will be the direction, I think we will see more drones in the future"* (L2 employee). Two participants commented on the data collected from drones and NDE, and that research should focus on improving the quality of the output of this equipment and provide frameworks on how to incorporate it into the bridge management process. An L3 inspector also suggested that academia should focus on helping bridge managers estimate the life cycle of bridges especially new bridges constructed using new materials and technologies. Some participants also talked about finding better methods to link between the element level rating system and the NBI rating system: *"We need a link between element data and condition ratings (NBI components), we also need new technology to more accurately estimate element level data and link it to locations"* (Anonymous participant)

4.5.4. Theme 4: Change Barriers

Many participants agreed that applying a new inspection program or implementing a new technology in the bridge inspection department will require organizational changes and preparations. Participants helped us understand the challenges that a DOT will face during a change and the aspects that can help make the transition successful. This theme presents some of the barriers that participants faced or expect to face during an organizational change.

4.5.4.1. Subtheme 1: Limited Resources

Several participants commented that change can help save resources but at the same time is not cheap and most research ideas such as the ones presented in the journal articles will require funding and resources that are not available to all departments, especially that most DOTs have a very tight budget: *"I think ours and most DOTs, our budget is really limited making big changes difficult for us right now especially if it will cost a lot of money unless it has a big benefit to it"* (L2 employee); *"You can chain drag a deck and reach the same conclusion as thermal modeling or GPR. It is tough to throw that extra money at the new technology until all the federals say you have to use that"* (L3 employee). Some participants commented that one of the barriers they found while reading the journal articles is that some of the frameworks require software and several NDE equipment that are either not available to their department or will require funds to purchase.

4.5.4.2. Subtheme 2: Work Force

A participant noted that applying a new inspection planning program will require person power that might be limited in most DOTs: *"I think probably the biggest challenge we are going to have right now is that we are already challenged with having enough staff. We are very lean staff and whenever there is changes it requires up front time and effort to get those things going and to implement anything, I think that is going to be one of the big things"* (L2 employee). Some DOTs who hire consultants to do inspections thought that a new inspection program will require either revising contracts with consultants or hiring new ones.

Two participants commented that a variable inspection planning program might lead to downsizing or hiring new employees which can be a challenge for the stability of the organization and needs to be considered: *"Adjusting the schedules and cycles based on the condition of the bridges will only in the future* *narrow down the time between inspections and keeping the work force levels consistent to provide the inspections needed will vary from year to year, and hiring employees or downsizing employees is not an easy task"* (Anonymous participant). Another participant suggested developing resource models to help managing the personnel changes: *"Resource models to establish and balance workload would be needed. These models may predict personnel changes. Basic organizational structure will probably be about the same"* (Anonymous participant).

4.5.4.3. Subtheme 3: Training Staff

Three participants stated that training inspectors and staff to adapt to a new technology will be the main challenge during transition: *"The biggest obstacle in implementing a new technology is always having dedicated personnel that can be trained to understand it. There is always less and less personnel in state DOTs performing a very wide range and ever-growing list of duties; so, taking onto technology or processes that do not provide immediate benefit would hurt the program in the short term and may cause those employees to look very poorly to their management"* (Anonymous participant); *"We will need to train our managers and inspectors on the new approach to setting the inspection intervals. They will need to know how their work affects the intervals. We will need to set up protocols to check that intervals are being reset properly and when they should be"* (Anonymous participant).

Some participants commented on the updates that will be required in the bridge management system if a new inspection planning program is to be implemented and the training for staff that will be required to adapt to the new system. They noted that an updated bridge management system or software can help organize inspection schedules and even select inspection intervals based on the bridge condition: *"We will need to update Bridge management systems and the standards that flag upcoming due inspections"* (Anonymous Participant); *"We can customize deterioration models and network policies in bridge management software; and utilize the software in determining inspection intervals based on actual or predicted performance"* (Anonymous Participant).

4.5.4.4. Subtheme 4: Uncertainty During Change

Some participants reflected on their previous experiences with organizational changes in their departments. Most of them mentioned that one of the main challenges they found during the time of change was uncertainty about the new change and how this change will affect them: *"The challenges personnel faced, was to understand what is the job responsibility, what is the hierarchy list, who to contact, and who I have to call for a question if there is a maintenance question, or if there is a critical finding. I think there is a lot of uncertainty throughout the state"* (L3 employee).

4.5.4.5. Subtheme 5: The FHWA and Change

Several participants stated that convincing upper levels of management and the FHWA that a change is required is one of the main challenges to start an organizational change. An L1 employee stated: *"Convincing management and the FHWA that organizational changes were necessary was probably the biggest barrier"* (L1 employee). An L3 inspector talked about how his department wanted to conduct a change in their inspection schedule but were faced by regulations from the FHWA, which made the change expensive to implement: *"We were going to do 48-month inspections for 70% of our in-state bridges. However, the FHWA wanted us to perform an in-depth inspection on every bridge before we put it on there. So, it was cheaper for us to continue doing inspections every two years then doing an in-depth inspection. A lot of what this state organizations do is highly regulated by the Federals"* (L3 employee).

An L1 manager mentioned that one of his concerns about applying a new inspection planning program, is that there will be no help or guide from the FHWA, and the DOT will be left responsible with all the change process: *"My fear is that it could end up being just one more thing that the states will be responsible to develop and implement on their own by a certain date when we have limited resources available and numerous other challenges to overcome"* (L1 employee).

In addition, an L2 employee used one of the journal articles as a reference and commented that before allowing a new inspection planning program the FHWA must be able to evaluate the performance of the DOTs under this new program and must be sure that this program will not affect the safety of the bridge network: *"It will be hard for FHWA to determine if you are inspecting the bridges on time. They already have a set of metric reviews they use to make sure you are doing what is supposed you should be doing. They have to approve and evaluate each of those statistical analysis and figure out if you are calculating the frequency correctly; probably that will be a hard sell to the FHWA"* (L2 employee).

4.5.5. Theme 5: Change Facilitators

This theme demonstrates what participants mentioned as the factors that can facilitate change based on their previous experience with DOTs. Some of these factors such as showing the need for change and staff communication are strongly connected to what is mentioned in the organizational change literature as change facilitators or enablers.

4.5.5.1. Subtheme 1: Showing the Need for Change

Some participants found that in a public organization such as the DOT to promote change and involve staff members in the organization you need to clearly show the benefits and necessity of the change. An L2 employee stated: *"Our bridge engineer is very willing and not afraid of change, but he wants to know that whatever change or idea it is, that it's going to be a benefit to us. We are not doing something because it is just the thing to do. Showing that these are really beneficial changes will make things better, more efficient and help things function better"* (L2 employee). Also seeing improvements along the change process can help keep the momentum and the motivation of the staff as mentioned by some participants.

Some participants during their discussion stated that organizational changes in their division started because there was a need for it. For example, one of the DOTs investigated, initiated a change because the quality of their inspection data was not as required by the FHWA and change was necessary: *"Quality of inspections were deficient. This triggered Plans of Corrective Action (PCA's) from FHWA which helped convince upper management changes were necessary to meet FHWA metrics"* (L1 employee); *"It was really challenging for the reduced staff to stick to a 24-month schedule and because of that we found that* *we were not getting really good inspections we were not meeting timelines. It was not a sustainable model it was not a good model we needed change"* (L2 employee)

4.5.5.2. Subtheme 2: Good Communication

Some participants noted that one of the main reasons that led to a successful change in their department was good communication among staff members. Some participants mentioned that having weekly meetings and being able to reflect on what is happening and what needs to be improved helped during transition: *"Our goal was to have weekly discussions to help us monitor the progress we are doing and share insights and experience, share ideas, issues and try to solve issues so we can still progress forward with our team"* (L3 employee). An L2 manager mentioned that during a successful transition in their department, managers were really keen on interacting with inspectors to help them understand the reasons for the change and be prepared: *"This is one of things that we really tried to do, is to help them understand why they are doing what they are doing. I think if this change makes sense to them, it would help them do a better job"* (L2 employee)

4.5.5.3. Subtheme 3: Commitment and Leadership

Several participants mentioned that for a successful transition to take place staff members throughout the whole organization have to be dedicated to the change. An L1 manager stated that one of the main reasons an organizational change was successful in their organization was the dedicated staff: *"I think what made the transition successful is dedication and persistence of our staff, wanting to realize the changes necessary to make our program a success"* (L1 employee). Other participants commented on the importance of leaders during the change and their ability to make a decision. During our discussion with an L3 inspector he stated that what made the change successful is that someone made the decision: *"At the state level, pressure comes from the top down if you can get the bosses on board that's how it would work. What made the transition happen honestly is that somebody actually made a decision, they wanted to go in that direction, and they went, and it was amazing"* (L3 employee)

4.5.5.4. Subtheme 4: Having Clear Goals

We asked the participants if they thought having short term goals can help manage an organizational change and implement new ideas and technologies. Some of the participants agreed, an L3 inspector commented: *"I think starting out with some short-term goals will give us the groundwork to kind of taking those necessary steps to build that program to what we see fit. I think we would see where we are at, and kind of have some measurables to monitor if we are meeting our monthly goals, are we meeting our expectations to FHWA and are we meeting our expectations to the districts. I think short term goals are a good thing when you are starting a new program to kind of take steps and not just have inapplicable goals"* (L3 employee). Some participants stated that short term goals are important but cannot replace long-term goals especially if you are trying to show the long-term savings or wins behind implementing a new program: *"Short term goals are fine as long as everybody knows what the long-term goal is. If you tell me to change and I don't know why I will be resistant to that" (L3 employee).*

4.6. Discussion

4.6.1. Research Question 1

Much of what was discussed with participants regarding current inspection practices was related to the 24-months inspection cycle and the methods used to conduct inspections. During our analysis of the literature, we found that many researchers were against the 24-months inspection interval (Nasrollahi & Washer, 2015; Soliman et al., 2013; Washer et al., 2016a). For example, Washer et al. (2016a) stated that the uniform inspection cycle does not consider how bridges can be different in age, condition, environment or construction material, and accordingly this fixed approach does not utilize inspection resources efficiently. Also, Nasrollahi and Washer (2015) concluded that the fixed inspection cycle can lead to unnecessary inspections for many bridges in the national bridge inventory.

While some of the participants agreed with what was found in the literature, surprisingly most participants supported the 24-months inspection cycle over a variable inspection cycle. The supporters of the fixed inspection interval stated that it is a simple and clear approach for scheduling inspections, helps in managing resources and preparing inspection budgets especially for large networks, conservative and safe, helps monitoring and keeping up with bridge deterioration, and helps in grouping bridges geographically to save travelling time and cost. From what is available in the literature it is clear that there is a gap in the field of bridge inspection planning between researchers and practitioners. Some researchers in the field of bridge inspection planning do not consider the impact of the bridge location or the travelling cost on the inspection planning process, and how difficult a variable inspection schedule will be in budgeting inspection costs. However, other researchers have considered bridge locations and the bridge's importance in a whole network when developing maintenance management frameworks (Frangopol & Bocchini, 2012; Yang & Frangopol, 2018b; Zhang & Wang, 2017). This provides a small example of the differences between researchers and practitioners in the bridge inspection field.

Although, most of our participants supported the 24-months inspection cycle, an L2 manager mentioned that the FHWA was pressured by DOTs to allow a different alternative for scheduling inspections such as the risk-based approach (Washer et al., 2014), so that DOTs can save some resources spent unnecessarily on bridge inspections, indicating that there is disagreement among practitioners. This variety of opinions was evident in the participants' comments about the risk-based approach which the FWHA is considering to allow as a second alternative for scheduling routine inspections (FHWA, 2019). Some participants found that this approach will help in reducing the number of inspections and save resources, while others were concerned about the time and effort that will be required to set the risk-based inspection panel, update the bridge management system, and collect the data required to set the inspection intervals.

With regards to the methods used during inspections, participants agreed with what was found in the literature and the NBIS (FHWA, 2012b), that visual inspection is the main method used to evaluate the bridge performance during routine inspections, and in some cases a chain drag can be used to detect delamination (Hearn, 2007). Regardless of the limitations and variability of visual inspections proved several times in the literature (Bu et al., 2014; Lin et al., 2019; Pines & Aktan, 2002), participants used visual inspections to rate bridge conditions, decide on whether the inspection cycle need to be reduced or not and even plan for maintenance work.

Due to the limitations of visual inspections many scholars suggested the use of other NDE methods (Alampalli & Jalinoos, 2009; Vaghefi et al., 2012). In our investigation we found that most participants use NDE methods such as Infrared thermography or Magnetic Particle test during in-depth inspections or fracture critical inspections, which agrees with the findings of (Lee & Kalos, 2015). Further, according to a survey conducted by Lee and Kalos (2015), the main barriers hindering the use of NDE methods in state governments is the capital cost needed to purchase the equipment and the difficulty associated with some NDE techniques. Adding to what Lee and Kalos (2015) concluded, in our study participants mentioned that although NDE methods have a potential to improve inspections they require training and certifying inspectors which is a huge burden on bridge inspection divisions. Also, some NDE methods require time to set in the field, traffic control and access equipment such as snoopers.

In connection with our main study objective to improve inspections, we discussed with participants the main aspects that can help improve inspection data. Many participants mentioned that training bridge inspectors and enhancing their abilities can lead to significant improvements in the value of bridge inspections. Lin et al. (2019) found that one of the problems affecting the reliability of the data collected during inspections is the quality of bridge inspectors and lack of training. Also, some participants stated that developing clear policies and protocols for bridge inspections can help reduce ambiguity and differences between DOTs, this agrees with what Phares et al. (2004) found during their study on the reliability of bridge inspections. Also, one participant suggested a relatively interesting idea which is adjusting inspection efforts depending on the condition of the bridge to reduce inspection effort and time.

4.6.2. Research Question 2

Based on our discussion with participants on the different inspection planning approaches and NDE techniques, several participants pointed out that researchers need to provide practical and clear research results that can be readily understood and applied in practice. Also most bridge inspection managers do not have time to read through long journal articles, therefore research products have to be concise and to the point as some participants recommended. Azhar, Ahmad, and Sein (2010), found that some of the main reasons hindering implementation of research findings in the construction industry is that researchers focus on theoretical or conceptual issues that are impractical or inapplicable, and on the other hand practitioners do not accept new research ideas that can require change in their daily procedures or industrial traditions. Bahadori, Raadabadi, Ravangard, and Mahaki (2016) stated that time constraints can make it difficult for practitioners to read and refresh their knowledge with new research or evidence that can be applied in the field. Moreover, participants noted that researchers should not only focus on solving specific problems or providing frameworks and ideas that can only be applied on specific types of bridges or deteriorations. Researchers need to provide solutions that can be generalized on different bridges so that DOTs can weigh its costs and apply it on several assets.

In this context, to provide effective research products participants suggested working together and collaborating as researchers and practitioners to improve research products and direct researchers' effort in the right direction. Researchers in the implementation field found that collaboration between academics and practitioners in the industry can significantly improve research results, and speed research and knowledge transfer into practice (Brannick & Coghlan, 2006; Cheng & Kong, 2009). Also, focusing on problems and research ideas that are important to DOTs such as using drones or improving NDE data can help the implementation process. After studying several case studies in the construction industry Azhar et al. (2010) concluded that using active research techniques can enhance collaboration between researchers and practitioners and help solve some of the important problems which practitioners are facing. Active research is a technique that has been applied in different industries where researchers and practitioners work together to evaluate the current situation and solve immediate practical problems in the industry (Avison, Lau, Myers, & Nielsen, 1999). This approach can be applied in DOTs not just to improve research products and collaboration in the field, but to save time and scarce resources.

In addition, researchers in the bridge inspection field can promote their research findings by providing practitioners with summaries and synopses of key findings to update them and save their time. These synopses can be presented on platforms where bridge inspection planners and researchers connect and exchange ideas, similar to what was presented by the Joint Fire Science Program (JFSP) (Barbour, 2007). Conferences such as the Transportation Research Board (TRB) can also help gather academics and workers in the industry to discuss and address important issues in the industry, and even share successful implementation strategies (Harder, 2014).

To improve research products further and make sure that research findings are applicable, researchers in the bridge inspection field can use ideas like Technology Readiness Scales (Laughlin et al., 2007) or product evaluation criteria developed by NCHRP (Dekelbab et al., 2017). These techniques can help researchers and DOTs make sure that a research product is fully developed, easy to implement by staff members, feasible and can be applied on different cases before deploying it. DOTs can even hire a single staff member or a research and development team responsible on finding innovative solutions and evaluating their applicability.

4.6.3. Research Question 3

Members of the bridge inspection divisions provided valuable information on some of the factors that can potentially contribute towards a successful organizational change in DOTs and facilitate research implementation. Some of these factors are in close correspondence with elements found in well-established organizational change models and implementation theories. First, showing the need for change was mentioned by participants as a necessary step to implement a new technology or planning framework in the bridge inspection divisions. Kotter (1995) indicates that the first step towards a successful change process is to establish a need or urgency to change. Leaders need to explain to staff members the benefits of change to create a sense of readiness among staff members and avoid staff resistance (Armenakis, Harris, & Feild, 2000; Judson, 1991). Similarly, an L2 participant found that explaining to bridge inspectors why they need to apply this new technology or process improves their quality of work. Convincing staff members with the urgency of change requires creating a vision or a list of objectives they can relate to. This can help identify the barriers of change and create a strategy to reach the required outcomes (Kotter, 1995).

Based on several case studies in US local governments Denhardt and Denhardt (1999) found that the need for change does not have to come from top managers or leaders, but can emerge from problems workers are experiencing and mangers might not be aware off. In the bridge inspection divisions, bridge inspectors (Level 3) should take the initiative and present to program managers their problems during inspections and try to figure actions that can help improve the inspection process. Moreover, if researchers have a strong understanding of the DOT needs, researchers can play the role of change leaders and try to persuade state DOTs and the FHWA with a new research idea that can solve their problems or lower their costs. In fact, some DOTs try to encourage researchers in providing them with new research ideas. For example, Colorado DOT (CDOT) has an applied research and innovation program that encourages researchers to present research ideas as problem statements, and if the project gets selected, a funding contract will be provided to the researcher or the university as primary investigators (CDOT, 2021). However, CDOT requires researchers to select or work with one of its staff members as a project/research "champion" who will be responsible on implementing research recommendations (CDOT, 2021) .

Change in DOTs mainly starts with the FHWA as we saw in the risk-based inspection framework. However, participants mentioned that one of the main barriers of change is convincing the FHWA with the importance of this change and its benefits. The organizational change literature related to public organizations contains evidence that change leaders need to justify to external stakeholders the need for change especially if these stakeholders have the ability to provide necessary resources and should authorize the change before it even starts (Abramson & Lawrence, 2001). On the other hand, the FHWA can help stimulate change and promote urgency among DOTs by mandating changes that they see as necessary or showing dissatisfaction towards a DOT's performance that requires immediate change. As shown in the results, one of the DOTs initiated change and developed a centralized inspection team to improve inspection data after being warned by the FHWA. Van de Ven (1993), found that mandating policies or new standards in public organizations can speed change and create a feeling of urgency among staff members.

The role of the FHWA during change and implementing new technologies in bridge inspection programs was an overarching topic mentioned by several participants at different occasions. Gaining support from the FHWA during change can help push the change forward and institutionalize change among DOTs. From our study we recognized that the FWHA can support DOTs during change by: 1) providing guidance, and administrative and technical help during the change process, 2) giving DOTs time to implement change and not quickly over burdening them with regulations and requirements that cannot be reached at early stages of the implementation process, 3) ensure that change goals are clear to remove ambiguity and differences among DOTs, 4) acknowledge that each state has different types of bridges, resources, climates and demographics, and accordingly regulations need to be flexible and allow room for adjusting the new procedures to fit the DOTs capabilities, 5) help DOTs find the required financial resources during change, 6) provide inspectors and DOT staff members with training that can help prepare them for change and reduce variation among bridge inspectors, and 7) develop policies that offer standard and applicable frameworks for research transfer in transportation agencies.

Focusing on staff members and preparing them for the change can also play an important role in achieving a successful transition (Rosenbaum et al., 2017). Participants found that one of the main reasons that led to a successful change in their department was the commitment and quality of the staff members. As a part of creating readiness for change, Armenakis et al. (2000) stated that leaders need to motivate staff members and show them that they have the ability to succeed in this change. Also, communicating with staff members and allowing them to participate is prudent for the transition process (Abramson & Lawrence, 2001; Bunker & Alban, 1997; Judson, 1991; Kanter, 1983). In our investigation, communication among different levels of staff members was mentioned several times as a key component for a successful transition process. Communication can help reduce uncertainty and ambiguity during change (Allen, Jimmieson, Bordia, & Irmer, 2007; Bordia et al., 2004), which was a problem some participants experienced during organizational changes in their departments. Also its essential that leaders present to staff members the short and long-term goals of this change process to create a clear vision of the outcomes of this change, monitor progress and create a sense of direction among staff members (Kotter, 1995).

Participants also mentioned that applying a new inspection planning framework or adapting new tools during inspections such as NDE methods, updating the bridge management system, or automating inspection reports will require skilled staff members trained on the new procedures. Most participants agreed that training is the most important factor to improve inspection quality and facilitate change. Researchers have found that training can provide staff members with the knowledge they need to implement with confidence a new technology and even measure its applicability (Dekelbab et al., 2017). Training can help staff members see change as an opportunity of growth and advancement in their career, especially if they were rewarded with promotions or certificates after attending the training (Bartlett & Kang, 2004).

Managing the work force and having enough skilled workers to conduct the change was mentioned among participants as an important factor that can influence the change process and should be considered before deploying any change. Harder (2014), agreed with our findings and commented that in transportation agencies limited skilled personnel can be a hurdle to transfer research findings into practice. Having an understaffed organization will increase stress and the risk of falling behind during change since staff members will not have enough time to simultaneously work on their primary responsibilities and cope with the new procedures (Desouza et al., 2009). In some cases, transportation agencies can reach out to external expertise and even hire part time workers to carry on with the primary duties of the organization until the in-house staff members adapt with the new change process. Moreover, participants found that one of the main problems to apply a variable inspection planning framework is managing bridge inspectors, since a variable inspection schedule will lead to downsizing or hiring new inspectors, which is not an easy task in public organizations. Therefore, researchers in the field of bridge inspection planning need to provide DOTs with frameworks or models that can help them efficiently manage their resources and predict the number of inspectors they will need to implement a new inspection program.

All of the above factors can help accelerate change, however limited resources or insufficient funding can lead to feeble implementation or change efforts. Indeed, implementing a new research idea can help save resources and time, but change is not cheap and requires ample resources to reach the desired outcomes (Fernandez & Rainey, 2006). Several participants mentioned that one of the main barriers to implementing a new idea is the limited budgets most DOTs currently have. Boyne (2003), found that sufficient funding is one of the important factors to improve public organizations and promote innovation. Funding during change will be required to train and prepare staff, purchase the required equipment, promote and communicate the new idea among practitioners in the field and restructuring the organization (Nadler & Nadler, 1998). Harder (2014), acknowledges that one of the main reasons hindering the rate of innovation adoption in the highway industry is not having a systematic perspective for research implementation that can help in developing sustainable funding sources for research. Most change leaders or innovation promoters in the transportation sector depend on ad-hoc approaches for gaining funds which is an unreliable process and has proven to only provide incremental changes (Dekelbab et al., 2017).

One common factor was found among all the change driving aspects mentioned by participants, which is having a strong leadership able to communicate the need for change, gain support from the FHWA, prepare staff members and motivate them, manage workforce, and find sufficient resources. The literature is full of evidence on the importance of leadership and top management support during change (Abramson & Lawrence, 2001; Armenakis & Harris, 2009; Fernandez & Rainey, 2006; Kotter, 1995; Luecke, 2003; Nadler & Nadler, 1998). Change leaders can be a single individual (Kanter et al., 1992), or a group of staff members able to guide the change process (Kotter, 1995; Yukl, 2008). Change in bridge inspection programs will require leaders able to control change, identify and mitigate barriers and form a coalition among DOT staff members and the FHWA to accelerate the change process from all directions.

Finally, some staff members in the bridge inspection divisions might find these propositions as common sense, however studies have found that managers sometimes ignore or underestimate some of these factors (Fernandez & Rainey, 2006). Also, our focus was mainly on bridge inspections and DOT departments, however one can infer that these factors can help other transportation agencies and government organizations in applying change and implementing new research findings.

4.7. Conclusions and Recommendations

This qualitative study set out to identify the factors that can help improve research products and accelerate change and research transfer in bridge inspection departments. This study used semi-structured interviews, written interviews, and questionnaires for data collection to provide rich and accurate results. Twenty-six staff members from different DOTs, with different managerial levels and responsibilities were involved in this study. A thematic analysis process was used to analyze the data collected; and based on the participants responses we reached the following conclusions and recommendations:

1- Many researchers in the field of bridge inspection planning do not support the 24-months inspection cycle used to schedule routine inspections. However, 44% of the participants in our study supported this fixed-time approach, 24% were against it and the others were in the middle and stated that it has both benefits and drawbacks. The participants who supported the 24-months inspection cycle stated that it is a safe and simple approach that helps in planning and budgeting inspections. It was also suggested that having a variable inspection schedule will require increasing or downsizing bridge inspection crews, which is a hard task in government organizations. On the other hand, participants who were against the fixed approach found that it wastes resources and does not consider the bridge condition or in service environment.

2- For the risk-based approach provided by NCHRP as an alternative for scheduling inspections; 36% of the participants said they will apply it once it is allowed, 21% said they will not consider it and 43% indicated that they will wait and see how other state departments will apply it. Some participants found that this alternative scheduling process will help them reduce the number of inspections and free resources. Others were concerned about the time and effort needed to assemble the expert panel and the data that will be required to establish the inspection intervals.

3- During our investigation of current inspection practices, we found that participants mainly use NDE methods during in-depth inspections and the reasons limiting its use are the training and certifications required by bridge inspectors, cost of equipment, time to assemble on site, and the need for the traffic control and mobility equipment such as snoopers and man lifts.

4- Participants suggested that focusing on training inspectors and developing clear protocols for inspections can help improve the quality of inspections. They also recommended that researchers should focus on enhancing the data collected from NDE methods and drones, developing frameworks to implement these data in the decision-making process, helping practitioners in the inspection field predict the lifecycle of bridges constructed using new materials and technologies and providing new methods that can help link the element level inspection data with the NBI rating system.

5- Participants mentioned that in many cases, research results in the bridge inspection field are not clear and concise and can only be applied on special bridge cases or deteriorations. As a result, some participants recommended collaboration between researchers and practitioners to improve the relevancy and effectiveness of research products to encourage its utilization.

6- Based on our analysis, we recommend using techniques such as action research methods that can enhance collaboration between researchers and practitioners and enhance innovation in the bridge inspection field. Also, researchers and sponsors could develop platforms that publish summaries and systematic reviews of important research results, which DOT managers and decision makers can easily navigate and understand. Hiring a single staff member or forming a team of experts in the DOT, who have the time to review new research findings and evaluate their applicability can also facilitate research transfer.

7- From our discussion with participants, we concluded that the main factors that can help facilitate change in DOT bridge divisions are showing the need for change, gaining support from the FHWA, allocating the required funding and work force, and enhancing the capacity of DOT staff member inspectors through training and effective communication. However, these efforts will not be effective if they were not supported by committed leaders and program managers.

This study provides DOTs and researchers with practical and theoretical solutions to help accelerate change and research transfer. However, it should be noted that participants were not experts in organizational change theories and research implementation, thus the factors recommended in this study are not the only ones that can help facilitate change and other factors can be found in the literature or when including other stakeholders. Future research should focus on including other external stakeholders such as FHWA staff members and consultants working in bridge inspections. This study focused on DOTs in the U.S, however including transportation agencies from other countries will provide a broader picture and can even yield different results. Researchers need to also focus on helping transportation agencies develop a sustainable and reliable source of funding that is dedicated to research and development. Also, during our investigation, it was found that phone or video interviews provided richer answers than written interviews even though the number of participants in the written interviews was higher. This point should be noted by future researchers who will build their studies on interviews.

CHAPTER 5: CONCLUSIONS, RESEARCH CONTRIBUTION, AND FUTURE RESEARCH

This dissertation includes three separate yet related studies with the goal of improving bridge inspection practices and promoting innovation and research transfer in the bridge inspection field. Each study contributes to the main goal of this research project and focuses on essential pieces of bridge inspection planning: 1) conducting a systematic literature review on bridge inspection planning frameworks developed by previous researchers and identifying the barriers preventing the implementation of new inspection planning frameworks, 2) introducing a novel framework for bridge inspection planning that can help bridge inspection planners select inspection time and method based on the uncertainty and risks associated with the bridge condition, and 3) engaging with DOT bridge staff members to identify the factors that can help enhance the effectiveness of research products and facilitate change in transportation organizations. This chapter summarizes the significant findings of the three studies that constitute this dissertation with research contributions and recommendations for future research.

The first study reviewed the history of bridge inspections in the U.S. and current bridge inspection practices and their associated limitations. The review also highlighted a range of new technologies that have been proposed to improve bridge inspections and devoted significant attention to analyzing inspection planning frameworks proposed in the literature to identify strengths and limitations. From this systematic review it was evident that although there have been extensive research efforts in the field of bridge inspection planning, there is lag between research products and implementation in practice. One of the main barriers that may be preventing the implementation of new inspection planning approaches is that the frameworks presented in the literature focus on a single element or similar details and consider only one deterioration mechanism in the decision-making process. However, bridges consist of several elements and can be exposed to different deteriorations at the same time. Also, most of the inspection planning frameworks found in the literature either depend on complex computational efforts which might not be available in many bridge inspectors working in the field, or solely depend on expert judgement which can be inaccurate and subjective.

Based on the findings of the first study, the second paper focused on introducing a novel inspection planning framework that reduces some of the limitations found in other inspection planning approaches and helps bridge owners determine both the bridge inspection time and method by incorporating information from deterioration models, NDE inspection data, and expert judgement. The results of this study showed that the uncertainty-based inspection framework can enhance the inspection efficiency, reduce uncertainty regarding the bridge maintenance time, and help bridge inspectors choose inspection time and the inspection method that is appropriate for the stage of the bridge's life. The study concluded that this framework could help bridge owners avoid delayed or unnecessary inspections and maintenance activities, while considering more than one damage mode or bridge element during the decision process.

Although the second study provides an applicable framework that can help improve inspection practices there remains a need to investigate the factors that can accelerate the implementation of this framework and other research products in the bridge inspection field. Therefore, in the third paper a qualitative study was conducted to investigate the factors that can help improve research products in the bridge inspection field and motivate change in transportation organizations. After engaging with twenty-six bridge staff members and using questionnaires and interviews to collect data, the study found that most participants support the uniform inspection interval over a variable inspection interval, and the main barriers limiting the use of NDE methods are the required inspector's training, time to set equipment in field, maintenance of traffic and cost of equipment. This study concluded that the key to improve research products is that practitioners and researchers need to collaborate together on finding practical solutions for important problems and transferring research recommendations into practice. Furthermore, the results of this study showed that there is gap between practitioners and researchers in the transportation sector and the factors that can help facilitate change in DOTs are showing the need for change, providing necessary resources, gaining support from the FHWA, preparing the work force and support from leaders.

5.1. Research Contributions

With the results and findings of these three studies, this dissertation achieved the following contributions in the bridge inspection field:

- Based on the systematic review and the interviews with DOT bridge staff members, this study revealed that the main two reasons hindering the implementation of new inspection planning frameworks are that the presented approaches consider only a single bridge element or damage mode rather than the whole bridge system, and the approaches presented either depend on complex computation methods or expert judgement, which can be associated with subjectivity and inaccuracies.
- To address some of the limitations associated with bridge inspection planning frameworks presented in the literature, this study provides a novel approach that depends on the uncertainty and the risks associated with the bridge condition and uses both computational methods and expert judgment allowing bridge owners select inspection time and method while considering more than one deterioration process or bridge element.
- This study builds on the connection between maintenance decisions and inspections, and provides a new approach that uses Bayesian analysis and regression models to assist bridge owners in selecting the appropriate inspection method that will reduce the uncertainty regarding maintenance time and time of transition in the bridge performance
- The uncertainty-based inspection planning framework presents a systematic data management process that incorporates different sources of information such as new inspection findings, deterioration model predictions and expert analysis, into one comprehensive decision framework to help bridge owners manage inspection and maintenance resources efficiently.
- Current literature shows that the approaches used to document the bridge performance such as the NBI rating system and the AASHTO element level system still require improvement to avoid ambiguity in inspection reports and provide an accurate representation of the bridge condition. This

was also a problem mentioned by the interviewees working in the bridge inspection field. Thus, this study provided the time to transition (TTT) which is a new concept that can help document the condition of the bridge based on the bridge deterioration stage, predict the bridge service life, and can be updated using new inspection findings and computational methods.

- This study analyzed current inspection practices by engaging with practitioners in the field and highlighting the gap between research efforts and DOTs' requirements. Based on the analysis, this study found that in order to improve research products and facilitate technology transfer, researchers and practitioners need to collaborate and work together in providing practical, applicable, and relevant research recommendations that can be applied to different cases to assess new technology costs and promote its utilization.
- This study identified the factors that can enable organizational change in DOTs, such as showing the need for change and providing necessary resources, most of which are related to information found in the organizational change literature. However, one of the factors that was unique to the transportation sector was the importance of the FHWA in facilitating change. The study showed that most changes in DOTs have to be supported by the FHWA through providing technical and administrative expertise, establishing new polices and criteria, and providing systemic implementation frameworks which DOTs can follow for a smooth transition process.
- Many scholars in the field of bridge inspection planning recommend using variable inspection intervals to save inspection resources. In fact, during our investigation we identified that due to DOTs' recommendations, the FHWA is considering a new alternative for scheduling inspections that is based on risk analysis and will lead to variable inspection intervals. However, during our interviews, most participants supported a fixed inspection interval over a variable interval, because fixed intervals make scheduling inspections and budgeting for inspection costs easier and help in reducing the amount of travel by grouping bridges in the same location together. This shows one of the strong gaps between researchers and practitioners in the inspection planning field, and further shows that practitioners disagree on the approaches used to schedule inspections.

It should be noted that the application and value of this dissertation is not limited to the bridge inspection field. The uncertainty-based inspection framework can be adjusted and applied on other structures that require inspection planning and maintenance. Also, the change drivers and the factors identified that can accelerate research implementation can be generalized and applied easily in other scientific domains.

5.2. Future Research

Along with the recommendations provided in each of the three studies this section highlights some of the main recommendations for future research that stemmed out of the whole research project.

Bridge location is a major issue that needs to be considered during inspection planning since the location of the bridge can have a significant impact on travelling costs, traffic flow and livability of communities. In fact, based on our analysis some DOTs group bridges in the same location during inspection planning to save costs due to inspector travel and traffic control. Accordingly, researchers need to provide inspection planning frameworks that can help bridge owners schedule inspections not only based on the bridge condition but also on its location and its importance to the whole bridge network and community. For example, the uncertainty-based inspection planning framework can be extended by developing the criteria used to choose the uncertainty thresholds (performance and consequence factors) so that the bridge's location and importance to the community is considered during the risk analysis process.

Having a variable inspection interval can help save resources; however, a variable schedule can make it difficult for bridge owners to budget their inspection costs. To address budgeting difficulties, inspection planning frameworks need to be developed to help bridge owners estimate the bridge's inspection life cycle cost if a variable inspection schedule is to be applied. A comprehensive analysis of the direct and indirect costs associated with inspections needs to be conducted and included in the decision process. Another challenge that might face practitioners willing to implement variable inspection programs, is managing their workforce, and adjusting personnel according to their annual inspection needs. Thus, resource models need to be developed that can help bridge managers manage their workforce and estimate the number of inspectors they will need when following a variable inspection schedule.

Applying new research products such as new inspection planning frameworks or NDE tools will require change in transportation organizations and their cultures. In addition, similar to other government organizations, DOTs have very tight budgets; and thus, large changes, or impractical technological advancements can be difficult to apply. Therefore, researchers need to focus on providing systematic change models that are specific to transportation organizations and can be used to implement change and new technologies in the transportation sector. Further, to improve research products and facilitate research transfer, scholars in the field of research implementation need to provide practitioners in the transportation sector with frameworks and criteria to evaluate the readiness and applicability of new research products and whether they will be cost effective.

Researchers in the field of bridge inspections focus on providing new inspection tools, data management methods and planning frameworks to improve the value of inspections. However, this study shows that focusing on improving the capacity of individuals working in bridge inspections and providing them with the necessary training will not only help improve the quality of inspections but will also facilitate innovation in the bridge inspection field. Researchers and practitioners need to work together in developing new training programs that can help enhance the capacity of bridge inspectors and keep inspectors updated with new technologies.

Finally, bridge inspection is a complex process with many uncertainties and contradicting objectives. In addition, bridge systems are always being developed and construction materials and methods are in continuous improvement. Therefore, there will always be a need for improving inspection practices and developing new technologies and procedures that can help save resources and maintain a safe and reliable bridge network.

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APPENDIX (A): CORROSION MECHANISTIC DETERIORATION MODELS

The deterioration of reinforced concrete (RC) structures occurs mainly due to corrosion of the reinforcement, which can be a result of carbonation or chloride ion penetration (NCHRP, 2006). This paper is concerned with corrosion of RC structures due to chloride ion penetration, and this deterioration mechanism consists of two main stages: corrosion initiation and propagation (Enright & Frangopol, 1998; Mori & Ellingwood, 1994). Corrosion of steel reinforcement initiates once the chloride concentration at the rebar level reaches a certain threshold (Tuutti, 1982). The time for corrosion initiation can be predicted using the following deterioration model, Equation(A1) (Crank, 1975; Vu & Stewart, 2005):

$$T_{CI} = \frac{x^2}{4D_c}\left[erf^{-1}\left(\frac{C_0 - C_{th}}{C_0}\right)\right]^{-2} \tag{A1}$$

where T_{CI} is the corrosion initiation time associated with the critical chloride concentration C_{th}, C_0 is the surface chloride content, D_c is the diffusion coefficient, $erf^{-1}(.)$ is the inverse of the error function, and x is the depth from the concrete surface.

Corrosion propagation in an RC structure can cause loss of the reinforcement cross-sectional area, a reduction in the bond strength, and cracks in the concrete cover. The loss of the reinforcement cross-sectional area can be due to uniform corrosion or pitting corrosion. Based on studies conducted by (Gonzalez, Andrade, Alonso, & Feliu, 1995; Stewart, 2004), pitting corrosion has a higher effect on the capacity of RC structures as it leads to a larger reduction in the area of the steel reinforcement. The pitting corrosion depth (PCD) in the steel reinforcement can be estimated as a time-dependent deterioration using Equation (A2) (Val & Melchers, 1997):

$$PCD(t) = r_{corr}V(t - T_{CI}) \tag{A2}$$

where r_{corr} is the rate of corrosion, and V is the ratio between the maximum pit depth to the mean pit depth (values of V range $4 \sim 8$) (Gonzalez et al., 1995). Another deterioration that can happen to concrete decks in the corrosion propagation stage is cracking of the concrete cover, in which hair cracks start appearing on the surface and then grow in length and width, causing excessive cracking to the concrete surface. In this paper, an empirical mechanistic model proposed by (Vu & Stewart, 2005) will be used to estimate the time for cracks to grow from hair cracks (i.e., 0.05 mm) to a severe crack limit (the severe crack limit will be discussed later in the paper), as shown in Equation (A3).

$$T_{SEV} = t_{1st} + 0.0167 i_{corr}^{-1.1} \left[42.9 \left(wc/\mathrm{C} \right)^{-0.54} + \left(\frac{w_{\mathrm{lim}} - 0.3}{0.0062} \right)^{1.5} \right] \qquad \text{(A3)}$$

where T_{SEV} is the time to reach a severe or excessive crack width, t_{1st} is the time to reach a hair crack of size 0.05mm, i_{corr} = corrosion current density, wc = water/cement ratio, C = concrete cover, and w_{lim} = the severe limiting crack width. Note that the model only works for crack limits in a specific range: $(0.3mm \le w_{\mathrm{lim}} \le 1.0mm)$.

APPENDIX (B): BRIDGE INSPECTION QUESTIONNAIRES

1- How do you schedule a routine bridge inspection? Do you follow a fixed interval (e.g., 2 years) or do you use other methods?

2- What techniques do you use for routine bridge inspection? (e.g., visual inspection- Non-destructive testing (NDT) methods)

3- From your experience what actions can be done to improve routine bridge inspections?

4- Based on the data collected during routine inspection, what decisions can be made? (e.g., Repair needs to be done immediately- in-depth inspection is required… etc.)

5- How do you estimate the average cost of a routine bridge inspection? And what are the cost items you consider during your estimation (e.g., Inspectors hourly wage- rent of snooper …etc.) ?

6- What rating system do you follow to evaluate the condition of a bridge? (e.g., NBIS rating system or AASHTO element level ratings) And do you use any software to help in the management process (e.g., AASHTOWare or BRIDGIT)?

APPENDIX (C): SUMMARY OF THE JOURNAL ARTICLES THAT WERE SENT TO PARTICIPANTS

The first article was published by Washer et al. (2016a) and presented an inspection planning framework that was proposed by the National Cooperative Highway Research Board (NCHRP) in the NCHRP Report 782 based on the NCHRP 12-82 study (Washer et al., 2014). The framework is based on risk analysis where the consequences and likelihood for a certain damage mode to affect the safety and serviceability of a bridge is quantified using simple quantitative tools and expert judgement. Based on the condition of the bridge and the consequences of the failure the bridge is ranked and the appropriate inspection interval is decided. To implement this program, a reliability assessment panel is assembled consisting of a group of experts in the field of bridge inspection. These experts are required to decide on the attributes that contribute to the analyzed damage mode and decide on the likelihood and consequences of failure. This study was chosen to be sent to the participants, because it is simple and is based mainly on expert judgment and does not require a great deal of training or sophistication.

The second article discusses an inspection planning framework proposed by Kim and Frangopol (2011b). The framework uses optimization algorithms and decision trees to choose the optimum inspection time and method that will minimize maintenance delay and inspection cost. Prediction models were used to predict the time of corrosion initiation while considering the uncertainty in the deterioration process. The probability of detection was used to describe the quality of the inspection method (NDE method) and compare between the different methods. The method with higher probability of detecting a crack is more preferred than another method with a probability of detection. This framework will require a bridge inspection planner, able to verify the quality of a prediction model, use optimization algorithms and have the required knowledge in probability and statistics. The reason for choosing this study is that it represents a significantly different approach for inspection planning compared to the study proposed by Washer et al. (2016a), and will require high computational tools and skills to apply.

The third article focuses on using the probability of detection in choosing the appropriate inspection interval for different NDE tools. The study was proposed by (Chung et al., 2006) and focused on inspection planning for steel bridges. The objective of the planning framework is to choose the optimum inspection interval that will maximize the probability of detection while reducing the total cost of inspection. The inspection cost included the cost of inspection and bridge failure. Three NDE methods where compared, ultraviolet inspection, liquid penetrant inspection and magnetic particle. The study found that inspection methods with higher quality will allow longer inspection intervals compared to lower quality method. This study requires knowledge of probability and statistics and some computational effort but it is not complex as the framework proposed by Kim and Frangopol (2011b); yet it is also not really simple or depends solely on expert judgment like the study presented by Washer et al. (2016a).

APPENDIX (D): JOURNAL ARTICLES INTERVIEWS

1- Are there any questions regarding the explained inspection program that you would like to ask before we start our questions?

2- How hard do you find this inspection program to understand? Hard-Medium-Easy And why?

3- Does your agency currently have the data and resources needed to implement this program?

4- If you were not constrained by Federal law, will you be interested in implementing this inspection program? And why? Or why not?

5- If the answer is yes, then how long would it take you for this transition? What tools, software and training will be required to implement this program?

6- Will you still need to have different inspection protocols (routine inspection or in-depth inspection) or can this inspection program be conducted on its own?

7- Can this inspection program be applied to a bridge network? And if yes what will be the data required for this implementation process ?

[Note: question 8 and 9 will be asked one time only and not repeated for every article]:

8- How often do you use nondestructive testing (NDT) methods in bridge inspection?
   a) Are there any barriers for implementing NDT and using them in routine inspections?
   b) How do you rank the quality of an NDT method? Do you use the probability of detection (i.e., like the articles discussed earlier.)? or do you only use standard error and accuracy?
   c) Does your bridge inspection manual consider NDT?

9- How likely can the recommended interval between bridge inspection (2 years) be changed or be extended?
   a) Do you think the 2-year inspection interval is efficient and cost effective?
   b) From your experience how can routine bridge inspections be scheduled?

APPENDIX (E): ORGANIZATIONAL CHANGE INTERVIEWS

1- In your department have you witnessed any organizational changes or implementation of new practices?
    a) Why did your department initiate the transition?
    b) How did employees feel about this transition? did they agree to this change?
    c) If the transition was successful, what were some factors that made the change successful?
    d) If it was not successful, what were the barriers?
2- Do you think implementing a new bridge inspection program is necessary in your department?
    a) From an organizational standpoint, what changes will be required to implement a new inspection program?
    b) What will be the desired outcomes from this change?
    c) What is the current organizational hierarchy? And will it be affected by the new inspection program?
    d) Are benefits from this change enough to motivate leaders and employees to get engaged in the change initiatives?
    e) From your experience what other incentives can be provided to professionals to encourage implementations of new technologies and research findings in your organization?
    f) Can setting short term goals help in creating a sense of achievement and guidance for this change?
    g) What would be those short-term goals?
    h) From an organization perspective, what challenges will emerge in order to utilize new inspection programs and implement them in state governments?
    i) Which stakeholders should be involved in planning and executing this transition?
    j) What can academics and researchers do to help bridge managers and inspectors implement new research findings and reduce the gap between academia and the industry?

APPENDIX (F): WRITTEN INTERVIEWS

Q1) Do you think the 24-month inspection cycle currently used to schedule routine inspections for most bridges is efficient?

Yes

No

In some ways Yes, in some ways No.

If yes or in some ways Yes, in some ways No: Q2') What are the main advantages of the 24-month inspection cycle. Please list a few brief ideas.

If no or in some ways Yes, in some ways No: Q3') What are the main drawbacks of the 24-month inspection cycle. Please list a few brief ideas.

Research in the field of bridge inspection planning has been done extensively, and different approaches for scheduling bridge inspections have been proposed. For example, the National Cooperative Highway Research Board (NCHRP) has presented a risk-based approach for determining the bridge inspection interval in the NCHRP Report 782 based on the NCHRP 12-82 study. In this approach, the DOT would need to establish a risk assessment panel consisting of experienced bridge engineers in the field of bridge inspection. The panel would identify the expected damage modes and attributes for the main bridge components and determine the probability and consequence of failure of each bridge component. Based on the risks associated with the bridge component, an inspection interval would be determined as 12, 24, 48, 72, and 96 months and can be changed depending on the DOT requirements. The component with the shortest inspection interval would be the controlling component and its inspection interval would be used for the whole bridge. The Federal Highway Administration (FHWA) has also been considering a similar approach as an alternative for scheduling bridge inspections

Q4) Would your department consider applying new bridge inspection scheduling approaches like the one described above?

Yes, we would, right away.

Maybe, we would wait to see the experiences of other states in applying new approaches before making a decision.

No, we would not.

If yes or maybe: Q5) What additional information and resources would be needed by your department to switch to a new bridge inspection planning approach like the one described above? Please list a few brief ideas.

If yes or no or maybe: Q6) What obstacles do you see in trying to implement a new inspection planning approach like the one described above? Please list a few brief ideas.

Applying a new inspection plan may involve some organizational changes such as changing the department's organizational team structure, hiring new personnel, or altering underlying procedures and technologies used in daily operations.

Q7) Will switching to another inspection planning approach require organizational changes in your department?

Yes

No

Maybe

If Yes or Maybe, please answer questions 8 if not move to question 9

Q8) What organizational changes do you expect might be required? Please list a few brief ideas.

Q9) From your experience what incentives can be provided to professionals to encourage implementation of new technologies and research findings in your organization? Please select all that apply.

(a) Show them the benefits of this change

(b) Provide appropriate training

(c) Get them involved in the planning phase of the change

(d) Other………………………………

Q10) From an organization perspective, what challenges will emerge in order to implement new inspection techniques and planning methods in state governments? Please select all that apply.

(a) Money and other resources

(b) Human resistance to change

(c) Other ……………………………

Q11) What rating system do you follow to evaluate the condition of a bridge?

(a) NBI rating system

(b) AASHTO element level

(c) Both systems

(d) Other……………………

Q12) What software do you use to manage inspection data?

(a) AASHTOWare

(b) BRIDGIT

(c) Other ………………………..

Q13) Approximately how many total bridges are in your state?

Q14) Of these bridges, approximately how many is your state DOT responsible for inspecting and maintaining?

Q15) Do you think that the quality of the information gathered during bridge inspections and resulting inspection reports are sufficient?

Yes

No

If No, Q16): Please list the issues you identify in the quality of the information gathered during bridge inspections and resulting inspection reports. Any suggestions to address those issues?

Q17) What can academics and researchers do to help bridge managers and inspectors implement new research findings and reduce the gap between academia and industry? Please list a few brief ideas.

Q18) Finally, we would like to thank you for your participation and the valuable information you provided. If you have any comments/feedback or any other advice on how to improve bridge inspections you would like to add, please add those comments below.