A State-of-the-Art Review of Bridge Inspection Planning: Current Situation and Future Needs

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Abstract: Inspections are important to ensuring adequate safety and performance of a bridge throughout its service life. Bridge inspections are highly connected with maintenance decisions and can help in managing maintenance activities while maintaining a reliable bridge network. Routine inspections are the most common type of highway bridge inspections in the United States. The National Bridge Inspection Standards (NBIS) requires that, for almost all bridges, a routine inspection should be conducted at least every 24 months. However, limitations of current bridge inspection practices impact the quality of information provided about bridge conditions and the subsequent decisions made based on that information. Much research in the field of bridge inspection planning has been conducted to assist bridge inspectors in the inspection planning process and improving routine inspections. Accordingly, the goal of this study is to provide an overview on current bridge inspection practices in the United States and conduct a systematic literature review on innovations in the field bridge inspections planning while investigating research gaps and future needs. This paper provides a background on the history of bridge inspection in the United States, 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 paper is a thorough analysis of research proposing and investigating different methodologies for inspection planning and scheduling. Studies were analyzed and categorized into three main types of inspection planning approaches, based on: reliability, risk-analysis, and optimization approaches. The study revealed gaps and limitations in the current proposed techniques for inspection planning. The findings of this review will help in characterizing the current state of bridge inspection programs and future research needs to enhance inspection programs and reduce the gap between inspection practice and research. **DOI:** 10.1061/(ASCE)BE.1943-5592.0001812.

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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 were considered structurally deficient, and many bridges required 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 United States were designed for a lifespan of 50 years, and currently 42% of the bridges in the United States are at least 50 years old (ASCE 2021). Thus, maintenance activities must be economically conducted and prioritized depending on the bridge condition (Abdelkhalek and 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 to monitor the damage modes that affect their bridge stock throughout their service life and capture early stages of deterioration. Catching damage early allows preservation and prompt maintenance actions to be performed, improving the bridge management process and reducing the overall bridge life-cycle cost (Soliman et al. 2013). In the United States, 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 are 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 United States, in 2008, a team of bridge inspection professionals was formed to study bridge inspections in European countries, specifically the aspects related to quality assurance, and provide bridge owners and the Federal Highway

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Administration (FHWA) with ideas that can help refine bridge inspection programs in the United States. 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 judgment (Everett et al. 2008). In addition, 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 to 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 United States, 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 on maintenance decision making.

Background

Brief History of Bridge Inspection in the United States

During the 1950s and the early 1960s, as the United States 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 over the Ohio River between Ohio and West Virginia in 1967 that killed 46 people (Lee et al. 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 and 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 et al. 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 in Connecticut and the Schoharie Creek Bridge in New York State 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 and Ingraffea 1991). Also in 1988, the FHWA issued an important revision for the *Recording and Coding Guide* that helped in shaping the NBIS in the next decade and provided bridge inspectors with information on how to conduct more uniform and consistent inspections (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 and 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 that every state DOT develop a bridge management system (BMS) specific for every state bridge inventory (Tarighat and 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 et al. 1998). During the same decade, another software named "BRIDGIT" was developed by the National Cooperative Highway Research Program (NCHRP) and was used as a guide for decision-making processes for local bridge inspection agencies (Khan 2000).

In 1995, the FHWA updated the revised *Recording and Coding Guide* to provide state agencies with continued definite guidelines to comply with the NBIS and the National Bridge Inventory (NBI) database (FHWA 1995; Ryan et al. 2012). This guide required reporting the condition of the bridge's main components: the bridge deck, superstructure, and substructure. The condition was reported on a scale from 0–9, 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 and 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 not only addressed 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 to unify the inspection reports uploaded on the NBI database which currently contains bridge inspection data for more than 600,000 bridges in the United States (Hasan and Elwakil 2020).

After the collapse of the I-35W bridge over the Mississippi River in Minneapolis, Minnesota, 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 United States (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 and Newton 2014). The AASHTO MBEI included some significant

Table 1. Timeline of bridge inspection in the United States

Year	Main events
1967	Collapse of the Silver Bridge killing 46 people
1968	National Bridge Inspection Program was 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 an important revision 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 updated the revised *Recording and Coding Guide*, to provide state agencies with continued definite guidelines to comply with the NBIS and the NBI database
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 (FHWA 2012c) 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

improvements and provided different elements and element units than the CoRe guide (AASHTO 2013). Also, the MBEI discussed the different distress paths associated with bridge condition state. The multiple distress approach provided bridge owners with the opportunity to consider different damage modes during the condition assessment process (Farrar and Newton 2014).

In 2019, a second edition of the MBEI (AASHTO 2019) was released as a result of the NCHRP (12-104) study (Washer et al. 2019) and is currently used by most DOTs. The NCHRP study was conducted to improve the quality of element-level data collected during routine bridge inspections. One of the primary outcomes of the NCHRP (12-104) was providing visual guides that show the inspector what the damage looks like for each bridge condition state (Washer et al. 2019). The visual guides were incorporated in the MBEI second edition and the manual content was reorganized by element materials rather than structural elements, which helped in reducing the size of the manual (AASHTO 2019).

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 (FHWA 2012c). Among other aspects, MAP-21 required that after October 1, 2014, element-level data must be collected during any inspections on the National Highway System (NHS) (Campbell et al. 2016). Currently, the FHWA plans on updating the NBIS through the *Notice of Proposed Rule Making* (NPRM) (FHWA 2019). 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, establishing a uniform procedure for reporting and monitoring critical findings during inspections, and allowing a risk-based approach for scheduling inspections based on the NCHRP-782 study (which will be discussed later in the paper) (FHWA 2019). Table 1 provides a timeline of bridge inspection history in the United States.

Table 2. US bridge inspection types

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
Underwater	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

Source: Data from Hearn (2007).

Current Bridge Inspection Practices

There are different types of bridge inspections in the United States: 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 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, such as chain drag or hammer sounding, can also be used during routine inspections to detect subsurface defects, such as delamination in 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).

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; 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 expressed approval from the FHWA, routine inspection 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, following an element numbering system and a checklist (AASHTO 2019). All inspected elements are rated and documented using standard inspection reports (FHWA 1995), which are uploaded to the state BMS and NBI database, to be accessible for other bridge inspectors (Farrar and 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 (FHWA 2012c) and consists of 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, superstructure, 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 0–9 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 manage 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 load path components, such as the deck, superstructure, and substructure, and the elements that form these major components. The NBEs should be consistent among state agencies to standardize the national rating system (Farrar and Newton 2014). The BMEs are secondary elements, such as coatings 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 and Newton 2014).

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 or when interacting with traffic. 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). In addition, equipment and access vehicles used during visual inspection, such as ladders, man-lifts, and scaffolding, are expensive and 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 and 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 et al. 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 that covers all aspects of bridge inspection and enables inspectors to evaluate bridge conditions. 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 5 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 are collected during routine bridge inspections. Visual inspection and element-level evaluation are subjective and mainly depend on the inspector's experience (Bu et al. 2014; Lin et al. 2019). 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 et al. 2019a; Morcous et al. 2010). 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 skewed, 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. In addition, only half of the inspectors took photos of the deteriorated locations. There was also a significant variability in the time inspectors predicted as 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).

A survey was conducted by Washer et al. (2019) during the development of the NCHRP (12-104) guidelines to improve element level inspection. The survey was concluded in December 2015 and included 36 agencies, 34 of which were state DOTs. The study found broad variations in methods used to conduct routine inspections, with a significant variation in the expected time to conduct inspections (ranging from less than 2 h to greater than 8 h), the utilization of access equipment, and traffic control procedures. The study showed that different methods were used for quantity estimation and area measurements. Half of the respondents used visual inspections and represented areas using approximated percentages, while the other half indicated that areas were measured and tallied. Field trials involving different inspectors and bridges were also conducted as part of the NCHRP (12-104) study. The field exercises showed that there was a variability in the damage quantities determined using visual element level inspections and as the quantity of the damage increases the variation increases. The variation was on the order of 50% of the total measured damage (Washer et al. 2019). In addition, a recent study conducted by Campbell et al. (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 do not 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). 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 et al. 2016; Sacks et al. 2018). In addition, the collected inspection data are associated with several uncertainties and inconsistencies since 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 numerous 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 2-year interval was decided based on engineering judgment 50 years ago (Washer et al. 2016a) and does not have any quantitative engineering justification (Parr et al. 2010). Many studies do not consider the fixed interval as the most efficient scheduling strategy for some bridges and sometimes unnecessary and a waste of resources (Atadero et al. 2019; Nasrollahi and Washer 2015; Soliman and 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 and Washer 2015; Parr et al. 2010; Sanders et al. 2018; Soliman and Frangopol 2014). According to a survey conducted by Lin et al. (2019), more than 40% of 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). The short inspection intervals lead to more frequent inspections, causing more traffic disturbance and site visits by inspectors that may present unnecessary risk on the travelling public and 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.

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 provide accurate, cost-effective evaluations of bridge performance (Rens et al. 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 and Jalinoos 2009; Sohanghpurwala 2006; Ryan et al. 2012; Vaghefi et al. 2012). In addition, 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 et al. 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 et al. 2014; Yehia et al. 2007). The FHWA developed an NDE web manual to 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 a description of each method (FHWA 2015). In addition, 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 et al. (2017), and Yehia et al. (2007).

In 2001, when NDE was still on the rise in the field of bridge inspection, a survey Rolander et al. (2001) conducted a study to analyze the usage of NDE methods in bridge inspection by 41 DOTs. The study found that 10 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; for in-depth inspections, the most commonly used techniques are UT, MT, RT, 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 United States 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 et al. 2013; Olson et al. 1995). A study conducted by Lee et al. (2014) found that, as of 2014, out of 30 states, only eight had local bridge inspection manuals that suggested using NDE.

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 the main reason that 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 and 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 et al. 2016). Also, NDE-based inspection can help predict the performance of a bridge more accurately and precisely, thus optimizing bridge management strategies (Gucunski et al. 2012). However, NDE methods are accompanied by inaccuracies or limitations and cost (Hesse et al. 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 and 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 multisensor robot that has an ER, IE, UT, and GPR, with a visualizing screen attached (Gucunski et al. 2017b). The robotic-assisted bridge inspection tool (RABIT) has been designed for detecting rebar corrosion, delamination, and concrete degradation (Gucunski et al. 2017a); however, the accuracy of the data collected still requires further validation.

Unmanned aerial systems (UASs) and drones are being tested for bridge inspection (Hallermann and Morgenthal 2014; Hubbard and Hubbard 2020; Seo et al. 2018; Wells and Lovelace 2018; Xu and Turkan 2019). A survey conducted in 2016 by AASHTO found that 17 DOTs have investigated the use of UASs in managing their transportation system and infrastructure inspections (Dorafshan and 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 and Johnson 2014). Minnesota DOT has been actively 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 and Lovelace 2018).

Perry et al. (2020) proposed a bridge inspection system that helps bridge inspectors to 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.

Bridge Deterioration Modeling 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. Modeling 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 number 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 and 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 and Washer 2015). 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 and 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 and Madanat 2001). Examples of stochastic models are the Markov Chains or Weibull models that can be used to predict the time of transition from one condition state to another (Agrawal et al. 2010; Gamerman and Lopes 2006; Lethanh et al. 2017; Li and Jia 2020; Morcous et al. 2010; Nasrollahi and Washer 2015; Scherer and Glagola 1994; Tao and Wang 2019; Thompson et al. 1998). Typically, 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 a 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 and Gopinath 1995; Enright and Frangopol 1999; Irwin and Paris 1971; Paris and Erdogan 1963; Stewart 2004; Vu and Stewart 2005). Mechanistic models mainly describe specific bridge elements such as the bridge deck, and the

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parameters used in these models can be deterministic or probabilistic representing the factors affecting bridge deterioration (Nickless and 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 et al. 1995; Morcous et al. 2010; Morcous et al. 2002; Nguyen and Dinh 2019; Straub and Der Kiureghian 2010; Tokdemir et al. 2000; Yang and Frangopol 2018).

In 2006, the FHWA launched the Long-Term Bridge Performance (LTBP) program with the goal of collecting high-quality bridge inspection data using detailed forensic analysis, visual inspection, destructive testing, and NDE methods for more than 2,000 bridges in the United States for a period of almost 20 years (Friedland et al. 2007). The goal of this program was to collect information that will help bridge managers to develop 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 et al. 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 continually being enhanced and re-innovated, and deterioration models still cannot capture all the uncertainty in the factors affecting the performance of the bridge.

Methodology for Analyzing Proposed Studies in Inspection Planning and Scheduling

As discussed, current bridge inspections have limitations, such as the physical and process constraints, the impact of inspectors' qualifications on the quality of data collected, inaccuracies of visual inspection, the uncertainty associated with collected inspection data, and the irrationality of the uniform approach used to schedule routine inspections. These limitations impact the quality of information provided and, thus, 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).

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.

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 and 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 December 29, 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 433 papers being excluded. 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. Many 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 modeling, 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 keywords on Google Scholar, such as risk-based inspection (RBI), 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 had been referenced by more than one study were considered. As a result, nine journal articles, three conference articles, two reports, and two book chapters were added to the full-text screening process. Finally, based on the full-text screening, 26 articles (23 journal articles, one report, and two conference articles) were synthesized, categorized, and reported in this study. Fig. 1 summarizes the search protocol.

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) RBI methods based on expert judgment 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 the inspection time and methods while minimizing or maximizing a set of objectives and did not consider a reliability index or lifetime functions were in Category 3.

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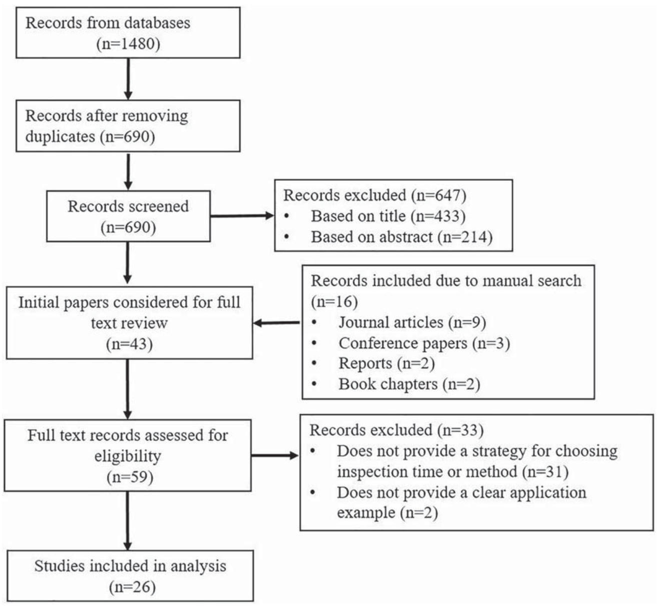

Fig. 1. Flowchart for search protocol.

Findings

The literature review indicated that in the past few decades has seen extensive research in the field of bridge inspection scheduling and planning, and different scholars have proposed a variety of approaches. Table 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.

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 and 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).

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 and 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 and 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 need not 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 (the reciprocal of the cumulative probability of failure) (Okasha and Frangopol 2010). The cumulative probability of failure, as shown in Fig. 2, represents the probability that a structure component is failing at a certain time, and the survivor function represents the likelihood that the structure will not fail before a certain time.

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 for 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 predefined threshold values regarding the probability of failure. Once a

Table 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 predefined 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 et al. (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 (2018)	Find the appropriate inspection strategy that will have the highest VoI using dynamic Bayesian networks and preposterior 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 et al. (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 et al. (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 et al. (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; multiattribute decision-making techniques were used to choose between the Pareto front solution	A steel bridge with fatigue-sensitive detail
	Kim et al. (2019a)	Explore how Bayesian updating and inspection outcomes can enhance the multiattribute decision process presented in Kim and 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

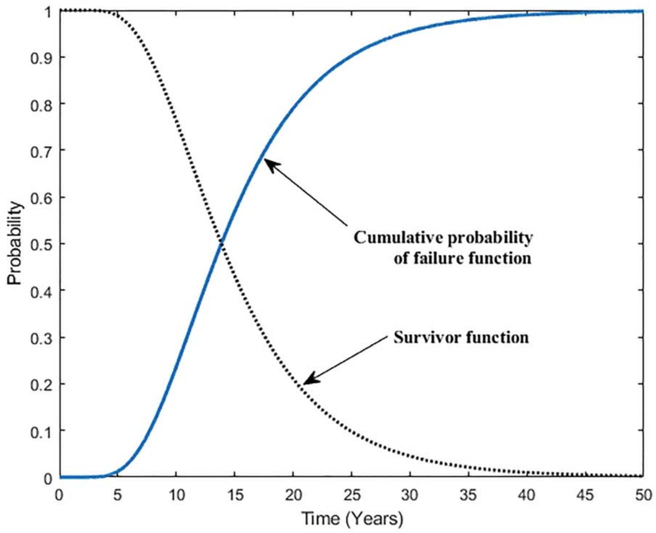

Fig. 2. Lifetime functions: cumulative probability of failure and survivor function.

Table 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 noy 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.

threshold is reached, an inspection should be conducted. Bayesian updating was utilized to update the fatigue model parameters using inspection outcomes and to 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, it did not provide a methodology to choose the predefined threshold values. Table 4 summarizes the key outcomes of the studies analyzed in this category.

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 and 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. In addition, 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 and 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 and Frangopol 2003). 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 influence the serviceability of the bridge (Frangopol et al. 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, requires immediate attention and remediation.

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 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, 2012c). 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.

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 and Cornell 1970). The VoI, along with Bayesian updating, can help in choosing an inspection plan with the least risk (i.e., cost of failure) and highest value of information and utility (Luque and 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 preposterior 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 and 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 and 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 et al. 2018). 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 an inspection scheduling that will assist decision makers to achieve maximum VoI. Bayesian updating was used to integrate inspection results into the fatigue deterioration model. The results showed that UT will provide higher VoI at earlier inspection times compared with 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) and Soliman et al. (2013) that NDE methods with higher PoD provided higher VoI at earlier stages of the structure service life compared with 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) and Straub and Der Kiureghian (2010), Yang and Frangopol (2018) 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 preposterior framework to predict all inspection outcomes corresponding to different inspection techniques and timing, and the associated repair action for each inspection scenario. 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 preposterior 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 drops 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 VoI provided from an inspection plan, the expected outcomes from different inspection and maintenance scenarios must 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 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 limit to a single bridge element any RBI frameworks that involve estimating the VoI.

RBI Planning Frameworks Based on Expert Judgment

In 2010, Parr et al. (2010) 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 judgment, 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. 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 RBI planning that does not require complex computations and is based on expert judgment and qualitative risk analysis.

The framework was presented in different journal articles and the NCHRP-782 report (Washer et al. 2014) and has been promoted by several scholars and FHWA officials as an efficient approach (Ekpiwhre et al. 2016; Everett et al. 2008; Hartmann 2018; Washer et al. 2016b; Washer et al. 2016a). The 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 to 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 that 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, shown in Fig. 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 judgment, experience, and typical deterioration patterns to evaluate the likelihood of the damage (i.e., OF) and the consequences of damage (i.e., CF).

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. In addition, the memorandum indicated that the risk-based process can help in scheduling inspections for bridges that must 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

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			

Fig. 3. Risk matrix indicating the inspection interval (in months) based on OF and CF of a bridge. (Data from Washer et al. 2014.)

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 judgment 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 judgment. 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 using data analysis to determine the probability of a bridge staying in a certain condition or deteriorating to a lower condition. 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 in a good condition longer, 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, overconservative, 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 judgment and risk-analysis methods, where the probability and consequence of failure are considered in the decision process. The studies presented by Nasrollahi and Washer (2015), Parr et al. (2010), and 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 5 summarizes findings of the studies included in the risk-based category.

In short, when selecting inspection time and method, risk-based approaches can help bridge inspection planners to 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 judgment. Expert-based approaches such as the one presented by Washer et al. (2014) can help bridge owners to 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

Table 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 (2018)	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.

expert judgment can be subjective. In addition, these methods consider only the performance and failure of the structure, whereas other objectives must be considered when choosing inspection time and methods, such as minimizing the delay of maintenance or maximizing the probability of detection.

Inspection Planning Frameworks Based on Optimization Methods

In inspection planning, different objectives in both single- and multiobjective 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 and Frangopol 2017, 2018; Kim et al. 2019b). 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, 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: UT, PT, and 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 optimal choice among all three NDE methods with a 3-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-interval inspection, Kim and Frangopol (2011b) presented a probabilistic approach for optimum inspection planning, considering uncertainties associated with corrosion propagation for reinforced concrete decks. 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 and Frangopol (2011a, c), and the cost of inspection was considered in formulating the multiobjective 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 be less expensive 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 and Frangopol 2012).

To consider the effect of minimizing damage detection delay on the repair process of a concrete bridge, Kim et al. (2011) extended the optimization process presented in Kim and Frangopol (2011a, b, c) and applied it on an 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 toward 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. In addition, analysis of the Pareto front solution showed 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 and are thus more cautious when 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; doing it too early will be a waste of resources. It should also be noted that this conclusion might change if other NDE methods with different reliability and detection capabilities were incorporated in the planning process or other approaches to describe the reliability of NDE inspection (other than POD) were used.

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 et al. (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 would 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 a Metropolis–Hasting algorithm. In this study, the probability of failure was defined as the probability that the adopted inspection plan fails to detect a crack before the crack reaches its critical size. Various inspection outcomes were explored to identify the appropriate inspection and repair plan. The inspection outcomes were used to update model parameters and the fatigue damage profiles. The updated damage profiles were then used to determine the suitable inspection times that will help detect fatigue cracks before failure (Soliman and 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. 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 multiobjective probabilistic optimization framework to determine the optimal inspection time and method. Four objectives were considered in this study: (1) minimizing the expected damage detection delay, (2) minimizing the probability of failure, (3) maximizing the extended service life, and (4) 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 optimal inspection time and reduce computational time. The same conclusion was obtained in Kim and Frangopol (2018), where the objectives were weighted, but then a multiattribute 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: (1) maximizing the probability of fatigue crack damage detection, (2) minimizing the expected fatigue crack damage detection delay, (3) minimizing the expected repair delay, (4) minimizing the damage detection time-based probability of failure, (5) maximizing the expected extended service life, and (6) 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 multiattribute decision-making method. Kim et al. (2019b) explored how Bayesian updating and different inspection outcomes can affect the multiattribute decision process proposed in Kim and 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 multiattribute decision-making methods was conducted. Unlike the findings in Kim and Frangopol (2018), Kim et al. (2019b) found that incorporating Bayesian updating in the decision process will reduce the effect of multiattribute decision-making method on the obtained optimum inspection times, and the maintenance times will be highly dependent on the inspection outcomes. Table 6 summarizes the outcomes and of the optimization-based studies described in this section.

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 RBI frameworks. Other considerations, such as the cost and reliability of inspection (i.e., PoD) can be included in the management process to decide on optimal inspection time and method at the same time. As in the 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

Table 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 significantly increase the cost of inspections.
Kim et al. (2011)	The behavior of the bridge managers and their attitudes toward 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 preferred.
Soliman et al. (2013)	The optimizer chooses the low-quality inspections to be performed laterm 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 a 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 multiattribute decision-making method.
Kim et al. (2019b)	Incorporating Bayesian updating in the optimization process will reduce the effect of a multiattribute decision-making method on the obtained optimum inspection times, and the maintenance times will be highly dependent on the inspection outcomes.

significant computational cost. Further, 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 must 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.

Conclusions and Future Research Directions in Inspection Planning Frameworks

The deteriorating bridge networks in the United States 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 United States 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 and scheduling that can mitigate these challenges and assist bridge owners and inspectors. Despite the extensive research efforts in the field of bridge inspection planning, to the authors' knowledge, only the risk-based approach in the NCHRP-782 study (Washer et al. 2014) is expected to be allowed in the upcoming update of the NBIS as an alternative for scheduling inspections (FHWA 2019). Almost none of the other inspection planning 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 must 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. This study indicates that the risk-based approach published in NCHRP-782 (Washer et al. 2014) is not complex and can help bridge owners consider more than one bridge element or damage mode during inspection planning. However, most of the other bridge inspection planning approaches analyzed herein focus on a single element or similar details and consider only one deterioration mechanism in the decision-making process. In reality, 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. Also, during inspection, a bridge inspector will usually inspect the whole bridge not just a single bridge component. 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 must be analyzed and deterioration models that capture these mechanisms must 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 most bridges are existing bridges that have been operating for several years. Therefore, clear guidelines must 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 must work together in developing inspection planning frameworks that reduce the limitations of current inspection programs, that are easy to apply in practice and that 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 by avoiding delayed or unnecessary maintenance actions.

Data Availability Statement

No data, models, or code were generated or used during the study.

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References

AASHTO. 1994. *Manual for condition evaluation of bridges MCE-1*. 2nd ed. Washington, DC: AASHTO.
AASHTO. 1997. *AASHTO guide for commonly recognized (CoRe) structural elements*. Washington, DC: AASHTO.
AASHTO. 2011a. *AASHTO guide manual for bridge element inspection*. Washington, DC: AASHTO.
AASHTO. 2011b. *The manual for bridge evaluation*. Washington, DC: AASHTO.
AASHTO. 2013. *Manual for bridge element inspection*. Washington, DC: AASHTO.
AASHTO. 2016. *Manual for bridge evaluation, interim revisions*. Washington, DC: AASHTO.
AASHTO. 2019. *Manual for bridge element inspection (MBEI-2)*. 2nd ed. Washington, DC: AASHTO.
Abdelkhalek, S., and T. Zayed. 2020. "Comprehensive inspection system for concrete bridge deck application: Current situation and future needs." *J. Perform. Constr. Facil* 34 (5): 03120001. https://doi.org/10.1061/(ASCE)CF.1943-5509.0001484.
Agrawal, A., and S. Alampalli. 2010. "Inspection needs of deteriorating bridge components." In *Bridge Maintenance, Safety, Management and Life-Cycle Optimization: Proc., 5th Int. IABMAS Conf.,* 147. London: CRC Press.

Agrawal, A. K., A. Kawaguchi, and Z. Chen. 2010. "Deterioration rates of typical bridge elements in New York." *J. Bridge Eng.* 15 (4): 419–429. https://doi.org/10.1061/(ASCE)BE.1943-5592.0000123.

Agusta, A., S. Thöns, and B. J. Leira. 2017. "Value of information-based inspection planning for offshore structures." In *Proc., ASME 2017 36th Int. Conf. on Ocean, Offshore and Arctic Engineering. Volume 3B: Structures, Safety and Reliability*. New York: ASME. https://doi.org/10.1115/OMAE2017-62493.

Ahamdi, H. 2017. "Concrete bridge deck aging, inspection and maintenance." Ph.D. thesis, Dept. of Civil and Environmental Engineering, Univ. of Toledo.

Ajegba, P. 2020. *Long-Term infrastructure program letter report: January 2, 2020*. Washington, DC: Transportation Research Board.

Akgul, F. 2020. "Inspection and evaluation of a network of concrete bridges based on multiple NDT techniques." *Struct. Infrastruct. Eng.* 17 (8): 1076–1095. https://doi.org/10.1080/15732479.2020.1790016.

Alampalli, S., and F. Jalinoos. 2009. "Use of NDT technologies in US bridge inspection practice." *Mater. Eval.* 67 (11): 1236–1246.

ASCE. 2020. "Report card for Colorado's infrastructure." Accessed April 18, 2020. https://www.infrastructurereportcard.org/state-item/colorado-infrastructure.

ASCE. 2021. "2021 infrastructure report card." Accessed January 4, 2021. https://infrastructurereportcard.org/cat-item/bridges/.

ASCE/SEI-AASHTO-Ad-hoc. 2009. "White paper on bridge: Inspection, rating, rehabilitation, replacement." *J. Bridge Eng.* 14 (1). https://doi.org/10.1061/(ASCE)1084-0702(2009)14:1(1).

ASNT (American Society for Nondestructive Testing). 2020. *Personnel qualification and certification in nondestructive testing*. Recommended Practice No. SNT-TC-1A. Columbus, OH: ASNT.

Atadero, R. A., G. Jia, A. Abdallah, and M. E. Ozbek. 2019. "An integrated uncertainty-based bridge inspection decision framework with application to concrete bridge decks." *Infrastructures* 4 (3): 50. https://doi.org/10.3390/infrastructures4030050.

Ben-Akiva, M., and D. Gopinath. 1995. "Modeling infrastructure performance and user costs." *J. Infrastruct. Syst.* 1 (1): 33–43. https://doi.org/10.1061/(ASCE)1076-0342(1995)1:1(33).

Benjamin, J. R., and C. A. Cornell. 1970. *Decision for civil engineers*. New York: MacGraw-Hill Book Company.

Biondini, F., and D. M. Frangopol. 2016. "Life-cycle performance of deteriorating structural systems under uncertainty: Review." *J. Struct. Eng.* 142 (9): F4016001. https://doi.org/10.1061/(ASCE)ST.1943-541X.0001544.

Brooks, C., R. Dobson, D. Banach, D. Dean, T. Oommen, R. Wolf, T. Havens, T. Ahlborn, and B. Hart. 2015. *Evaluating the use of unmanned aerial vehicles for transportation purposes*. Rep. No. RC-1616. Michigan, MI: Michigan Dept. of Transportation.

Bu, G., J. Lee, H. Guan, M. Blumenstein, and Y.-C. Loo. 2014. "Development of an integrated method for probabilistic bridge-deterioration modeling." *J. Perform. Constr. Facil* 28 (2): 330–340. https://doi.org/10.1061/(ASCE)CF.1943-5509.0000421.

Campbell, L. E., R. J. Connor, J. M. Whitehead, and G. A. Washer. 2020. "Benchmark for evaluating performance in visual inspection of fatigue cracking in steel bridges." *J. Bridge Eng.* 25 (1): 04019128. https://doi.org/10.1061/(ASCE)BE.1943-5592.0001507.

Campbell, L. E., C. N. Perry, R. J. Connor, and J. B. Lloyd. 2016. *Element level bridge inspection. Benefits and use of data for bridge management*. Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2016/13. West Lafayette, IN: Purdue Univ.

Chen, C. 1987. "Bridge management under a level of service concept providing optimum improvement action, time, and budget prediction." Ph.D. thesis, Dept. of Civil Engineering, North Carolina State Univ.

Chung, H.-Y., L. Manuel, and K. H. Frank. 2006. "Optimal inspection scheduling of steel bridges using nondestructive testing techniques." *J. Bridge Eng.* 11 (3): 305–319. https://doi.org/10.1061/(ASCE)1084-0702(2006)11:3(305).

Coe, J. T., J. E. Nyquist, B. Kermani, and L. Sybrandy. 2013. *Application of nondestructive testing to evaluate unknown foundations for Pennsylvania bridges*. FHWA-PA-2013-003-TEM 002. Harrisburg, PA: Dept. of Transportation, Bureau of Planning and Research.

Dietrich, J. I., M. A. Inkala, and V. J. Männistö. 2005. "Bridge inspection quality management." *Transp. Res. Rec.* 1933 (1): 2–8. https://doi.org/10.1177/0361198105193300101.

Dong, Y., and D. M. Frangopol. 2015. "Risk-informed life-cycle optimum inspection and maintenance of ship structures considering corrosion and fatigue." *Ocean Eng.* 101: 161–171. https://doi.org/10.1016/j.oceaneng.2015.04.020.

Dorafshan, S., and M. Maguire. 2018. "Bridge inspection: Human performance, unmanned aerial systems and automation." *J. Civ. Struct. Health Monit.* 8 (3): 443–476. https://doi.org/10.1007/s13349-018-0285-4.

Ekpiwhre, E. O., K. F. Tee, S. A. Aghagba, and K. Bishop. 2016. "Risk-based inspection on highway assets with category 2 defects." *Int. J. Saf. Secur. Eng.* 6 (2): 372–382. https://doi.org/10.2495/SAFE-V6-N2-372-382.

Emal, M. 2017. "Application of lean philosophy to routine inspection of bridges." Ph.D. thesis, Dept. of Civil and Environmental Engineering, Univ. of Delaware.

Enright, M. P., and D. M. Frangopol. 1999. "Condition prediction of deteriorating concrete bridges using Bayesian updating." *J. Struct. Eng.* 125 (10): 1118–1125. https://doi.org/10.1061/(ASCE)0733-9445(1999)125:10(1118).

Estes, A. C., and D. M. Frangopol. 2003. "Updating bridge reliability based on bridge management systems visual inspection results." *J. Bridge Eng.* 8 (6): 374–382. https://doi.org/10.1061/(ASCE)1084-0702(2003)8:6(374).

Everett, T. D., P. Weykamp, H. A. Capers Jr, W. R. Cox, T. S. Drda, L. Hummel, P. Jensen, D. A. Juntunen, T. Kimball, and G. A. Washer. 2008. *Bridge evaluation quality assurance in Europe*. FHWA-PL-08-016. Alexandria, VA: American Trade Initiatives.

Faber, M. H. 2002. "Risk-based inspection: The framework." *Struct. Eng. Int.* 12 (3): 186–195. https://doi.org/10.2749/101686602777965388.

Farhangdoust, S., A. B. Mehrabi, and S. F. A. Mowsavi. 2018. "NDT methods applicable to health monitoring of ABC closure joints." In *Proc., 27th Research Symp.*, 75–87. Orlando, FL: American Society for Nondestructive Testing (ASNT).

Farrar, M. M., and B. Newton. 2014. *The AASHTO manual for bridge element inspection*. Winter, FL: ASPIRE.

FHWA (Federal Highway Adminstration). 1995. *Recording and coding guide for the structure inventory and appraisal of the nation's bridges*. Rep. No. FHWA-PD-96-001. Washington, DC: FHWA.

FHWA (Federal Highway Adminstration). 2012a. *Errata sheet-recording and coding guide for the structure inventory and appraisal of the nation's bridges*. Washington, DC: FHWA.

FHWA (Federal Highway Adminstration). 2012b. *National bridge inspection standards (NBIS)*. Washington, DC: Federal Highway Adminstration.

FHWA (Federal Highway Administration). 2012c. *Moving ahead for progress in the 21st century act (MAP-21), a summary of highway provisions*. Washington, DC: FHWA.

FHWA (Federal Highway Adminstration). 2015. *Federal highway administration nondestructive evaluation (NDE) Web manual*. Washington, DC: FHWA.

FHWA (Federal Highway Adminstration). 2018. *Memorandum: Risk-based interval, determination for routine bridge inspections*. Washington, DC: FHWA.

FHWA (Federal Highway Adminstration). 2019. *Proposed changes to the national bridge inspection standards (NBIS)*. Washington, DC: FHWA.

Frangopol, D. M., Y. Dong, and S. Sabatino. 2017. "Bridge life-cycle performance and cost: Analysis, prediction, optimisation and decision-making." *Struct. Infrastruct. Eng.* 13 (10): 1239–1257. https://doi.org/10.1080/15732479.2016.1267772.

Friedland, I. M., H. Ghasemi, and S. B. Chase. 2007. *The FHWA long-term bridge performance program*. McLean, VA: F. Turner-Fairbank Highway Research Center.

Gamerman, D., and H. F. Lopes. 2006. *Markov chain Monte Carlo: Stochastic simulation for Bayesian inference*. Boca Raton, FL: CRC Press.

Ghasemi, H. 2008. *FHWA long-term bridge performance program*. Wasinhgton, DC: Federal Highway Administration.

Graybeal, B, Moore, M, Phares, B, Rolander, D, & Washer, G. (2001). *Reliability of visual inspection for highway bridges, volume II: Appendices*. No. FHWA-RD-01-021, Appendices. Washington, DC: Federal Highway Administration.

Gucunski, N., B. Basily, J. Kim, J. Yi, T. Duong, K. Dinh, S.-H. Kee, and A. Maher. 2017a. "RABIT: Implementation, performance validation and integration with other robotic platforms for improved management of bridge decks." *Int. J. Intell. Rob. Appl.* 1 (3): 271–286. https://doi.org/10.1007/s41315-017-0027-5.

Gucunski, N., A. Imani, F. Romero, S. Nazarian, D. Yuan, H. Wiggenhauser, P. Shokouhi, A. Taffe, and D. Kutrubes. 2013. *The second strategic highway research program*. Washington, DC: Federal Highway Administration.

Gucunski, N., A. Maher, H. Ghasemi, and F. S. Ibrahim. 2012. "Segmentation and condition rating of concrete bridge decks using NDE for more objective inspection and rehabilitation planning." In *Proc., 6th Int. Conf. on Bridge Maintenance, Safety and Management*, 617–624. Rotterdam, Netherlands: Balkema.

Gucunski, N., B. Pailes, J. Kim, H. Azari, and K. Dinh. 2017b. "Capture and quantification of deterioration progression in concrete bridge decks through periodical NDE surveys." *J. Infrastruct. Syst.* 23 (1): B4016005. https://doi.org/10.1061/(ASCE)IS.1943-555X.0000321.

Haladuick, S., and M. R. Dann. 2018. "Value of information-based decision analysis of the optimal next inspection type for deteriorating structural systems." *Struct. Infrastruct. Eng.* 14 (9): 1283–1292. https://doi.org/10.1080/15732479.2018.1433692.

Hallermann, N., and G. Morgenthal. 2014. "Visual inspection strategies for large bridges using unmanned aerial vehicles (UAV)." In *Proc., 7th IABMAS, Int. Conf. on Bridge Maintenance, Safety and Management*, 661–667. London: Taylor & Francis Group.

Hartmann, J. L. 2018. *Risk-based interval, determination for routine bridge inspections*. Washington, DC: Federal Highway Administration.

Harzing, A.-W., and S. Alakangas. 2016. "Google Scholar, Scopus and the web of science: A longitudinal and cross-disciplinary comparison." *Scientometrics* 106 (2): 787–804. https://doi.org/10.1007/s11192-015-1798-9.

Hasan, S., and E. Elwakil. 2020. "National bridge inventory data-based stochastic modeling for deck condition rating of prestressed concrete bridges." *Pract. Period. Struct. Des. Constr.* 25 (3): 04020022. https://doi.org/10.1061/(ASCE)SC.1943-5576.0000505.

Hearn, G. 2007. Vol. 375 of *Bridge inspection practices (NCHRP-375)*. Washington, DC: National Cooperative Highway Research Program.

Hesse, A. A., R. A. Atadero, and M. E. Ozbek. 2015. "Uncertainty in common NDE techniques for use in risk-based bridge inspection planning: Existing data." *J. Bridge Eng.* 20 (11): 04015004. https://doi.org/10.1061/(ASCE)BE.1943-5592.0000733.

Hubbard, B., and S. Hubbard. 2020. "Unmanned aircraft systems (UAS) for bridge inspection safety." *Drones* 4 (3): 40. https://doi.org/10.3390/drones4030040.

Irizarry, J., and E. N. Johnson. 2014. *Feasibility study to determine the economic and operational benefits of utilizing unmanned aerial vehicles (UAVs)*. Atlanta: Georgia Institute of Technology.

Irwin, G. R., and P. C. Paris. 1971. "Fundamental aspects of crack growth and fracture." In *Engineering fundamentals and environmental effects*, edited by H. Liebowitz, 1–46. Amsterdam, Netherlands: Elsevier.

Jia, G., and P. Gardoni. 2018. "State-dependent stochastic models: A general stochastic framework for modeling deteriorating engineering systems considering multiple deterioration processes and their interactions." *Struct. Saf.* 72: 99–110. https://doi.org/10.1016/j.strusafe.2018.01.001.

Jung, S., S. Song, S. Kim, J. Park, J. Her, K. Roh, and H. Myung. 2019. "Toward autonomous bridge inspection: A framework and experimental results." In *Proc., 2019 16th Int. Conf. on Ubiquitous Robots*, 208–211. Piscataway, NJ: IEEE.

Khan, M. S. 2000. "Bridge-management systems past, present and future." *Concr. Int.* 22 (8): 53–56.

Kim, J., N. Gucunski, and K. Dinh. 2019a. "Deterioration and predictive condition modeling of concrete bridge decks based on data from periodic NDE surveys." *J. Infrastruct. Syst.* 25 (2): 04019010. https://doi.org/10.1061/(ASCE)IS.1943-555X.0000483.

Kim, S., and D. M. Frangopol. 2011a. "Cost-based optimum scheduling of inspection and monitoring for fatigue-sensitive structures under uncertainty." *J. Struct. Eng.* 137 (11): 1319–1331. https://doi.org/10.1061/(ASCE)ST.1943-541X.0000365.

Kim, S., and D. M. Frangopol. 2011b. "Inspection and monitoring planning for RC structures based on minimization of expected damage detection delay." *Probab. Eng. Mech.* 26 (2): 308–320. https://doi.org/10.1016/j.probengmech.2010.08.009.

Kim, S., and D. M. Frangopol. 2011c. "Optimum inspection planning for minimizing fatigue damage detection delay of ship hull structures." *Int. J. Fatigue* 33 (3): 448–459. https://doi.org/10.1016/j.ijfatigue.2010.09.018.

Kim, S., and D. M. Frangopol. 2012. "Probabilistic bicriterion optimum inspection/monitoring planning: Applications to naval ships and bridges under fatigue." *Struct. Infrastruct. Eng.* 8 (10): 912–927. https://doi.org/10.1080/15732479.2011.574811.

Kim, S., and D. M. Frangopol. 2017. "Efficient multi-objective optimisation of probabilistic service life management." *Struct. Infrastruct. Eng.* 13 (1): 147–159. https://doi.org/10.1080/15732479.2016.1198405.

Kim, S., and D. M. Frangopol. 2018. "Decision making for probabilistic fatigue inspection planning based on multi-objective optimization." *Int. J. Fatigue* 111: 356–368. https://doi.org/10.1016/j.ijfatigue.2018.01.027.

Kim, S., D. M. Frangopol, and M. Soliman. 2013. "Generalized probabilistic framework for optimum inspection and maintenance planning." *J. Struct. Eng.* 139 (3): 435–447. https://doi.org/10.1061/(ASCE)ST.1943-541X.0000676.

Kim, S., D. M. Frangopol, and B. Zhu. 2011. "Probabilistic optimum inspection/repair planning to extend lifetime of deteriorating structures." *J. Perform. Constr. Facil.* 25 (6): 534–544.

Kim, S., B. Ge, and D. M. Frangopol. 2019b. "Effective optimum maintenance planning with updating based on inspection information for fatigue-sensitive structures." *Probab. Eng. Mech.* 58: 103003. https://doi.org/10.1016/j.probengmech.2019.103003.

Kwon, K., and D. M. Frangopol. 2011. "Bridge fatigue assessment and management using reliability-based crack growth and probability of detection models." *Probab. Eng. Mech.* 26 (3): 471–480. https://doi.org/10.1016/j.probengmech.2011.02.001.

Lee, S., and N. Kalos. 2015. "Bridge inspection practices using nondestructive testing methods." *J. Civ. Eng. Manage.* 21 (5): 654–665. https://doi.org/10.3846/13923730.2014.890665.

Lee, S., N. Kalos, and D. H. Shin. 2014. "Non-destructive testing methods in the U.S. for bridge inspection and maintenance." *KSCE J. Civ. Eng.* 18 (5): 1322–1331. https://doi.org/10.1007/s12205-014-0633-9.

Lethanh, N., J. Hackl, and B. T. Adey. 2017. "Determination of Markov transition probabilities to be used in bridge management from mechanistic-empirical models." *J. Bridge Eng.* 22 (10): 04017063. https://doi.org/10.1061/(ASCE)BE.1943-5592.0001101.

Li, M., and G. Jia. 2020. "Bayesian updating of bridge condition deterioration models using complete and incomplete inspection data." *J. Bridge Eng.* 25 (3): 04020007. https://doi.org/10.1061/(ASCE)BE.1943-5592.0001530.

Liberati, A., D. G. Altman, J. Tetzlaff, C. Mulrow, P. C. Gøtzsche, J. P. Ioannidis, M. Clarke, P. J. Devereaux, J. Kleijnen, and D. Moher. 2009. "The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate health care interventions: Explanation and elaboration." *J. Clin. Epidemiol.* 62 (10): e1–e34. https://doi.org/10.1016/j.jclinepi.2009.06.006.

Lin, Z., H. Pan, X. Wang, and M. Li. 2019. *Improved element-level bridge inspection criteria for better bridge management and preservation*. Fargo, ND: Mountain-Plains Consortium.

Liu, Y., and D. M. Frangopol. 2019. "Utility and information analysis for optimum inspection of fatigue-sensitive structures." *J. Struct. Eng.* 145 (2): 04018251. https://doi.org/10.1061/(ASCE)ST.1943-541X.0002257.

Luque, J., and D. Straub. 2019. "Risk-based optimal inspection strategies for structural systems using dynamic Bayesian networks." *Struct. Saf.* 76: 68–80. https://doi.org/10.1016/j.strusafe.2018.08.002.

Mauch, M., and S. Madanat. 2001. "Semiparametric hazard rate models of reinforced concrete bridge deck deterioration." *J. Infrastruct. Syst.* 7 (2): 49–57. https://doi.org/10.1061/(ASCE)1076-0342(2001)7:2(49).

McGuire, B., R. Atadero, C. Clevenger, and M. Ozbek. 2016. "Bridge information modeling for inspection and evaluation." *J. Bridge Eng.* 21 (4): 04015076. https://doi.org/10.1061/(ASCE)BE.1943-5592.0000850.

Melchers, R. E., and A. T. Beck. 2018. *Structural reliability analysis and prediction*. Hoboken, NJ: John Wiley & Sons.

Memarzadeh, M., and M. Pozzi. 2016. "Integrated inspection scheduling and maintenance planning for infrastructure systems." *Comput.-Aided Civ. Infrastruct. Eng.* 31 (6): 403–415. https://doi.org/10.1111/mice.12178.

Mohamed, H. A., A. O. Abd El Halim, and A. G. Razaqpur. 1995. "Use of neural networks in bridge management systems." *Transp. Res. Rec.* 1490: 1–8.

Morcous, G., Z. Lounis, and Y. Cho. 2010. "An integrated system for bridge management using probabilistic and mechanistic deterioration models: Application to bridge decks." *KSCE J. Civ. Eng.* 14 (4): 527–537. https://doi.org/10.1007/s12205-010-0527-4.

Morcous, G., H. Rivard, and A. M. Hanna. 2002. "Case-based reasoning system for modeling infrastructure deterioration." *J. Comput. Civil Eng.* 16 (2): 104–114. https://doi.org/10.1061/(ASCE)0887-3801(2002)16:2(104).

Nasrollahi, M., and G. Washer. 2015. "Estimating inspection intervals for bridges based on statistical analysis of national bridge inventory data." *J. Bridge Eng.* 20 (9): 04014104. https://doi.org/10.1061/(ASCE)BE.1943-5592.0000710.

Nguyen, T. T., and K. Dinh. 2019. "Prediction of bridge deck condition rating based on artificial neural networks." *J. Sci. Technol. Civ. Eng.* 13 (3): 15–25. https://doi.org/10.31814/stce.nuce2019-13(3)-02.

Nickless, K., and R. A. Atadero. 2018. "Mechanistic deterioration modeling for bridge design and management." *J. Bridge Eng.* 23 (5): 04018018. https://doi.org/10.1061/(ASCE)BE.1943-5592.0001223.

Okasha, N. M., and D. M. Frangopol. 2010. "Redundancy of structural systems with and without maintenance: An approach based on lifetime functions." *Reliab. Eng. Syst. Saf.* 95 (5): 520–533. https://doi.org/10.1016/j.ress.2010.01.003.

Olson, L. D., F. Jalinoos, and M. F. Aouad. 1995. *Final report: Determination of unknown subsurface bridge foundations*. NCHRP 21-05. Washington, DC: Transportation Research Board.

Omar, T., M. L. Nehdi, and T. Zayed. 2017. "Performance of NDT techniques in appraising condition of reinforced concrete bridge decks." *J. Perform. Constr. Facil* 31 (6): 04017104. https://doi.org/10.1061/(ASCE)CF.1943-5509.0001098.

Omer, M., L. Margetts, M. Hadi Mosleh, S. Hewitt, and M. Parwaiz. 2019. "Use of gaming technology to bring bridge inspection to the office." *Struct. Infrastruct. Eng.* 15 (10): 1292–1307. https://doi.org/10.1080/15732479.2019.1615962.

Onoufriou, T., and D. M. Frangopol. 2002. "Reliability-based inspection optimization of complex structures: A brief retrospective." *Comput. Struct.* 80 (12): 1133–1144. https://doi.org/10.1016/S0045-7949(02)00071-8.

Orcesi, A. D., and D. M. Frangopol. 2011. "Use of lifetime functions in the optimization of nondestructive inspection strategies for bridges." *J. Struct. Eng.* 137 (4): 531–539. https://doi.org/10.1061/(ASCE)ST.1943-541X.0000304.

Paris, P., and F. Erdogan. 1963. "A critical analysis of crack propagation laws." *J. Basic Eng.* 85 (84): 528–533. https://doi.org/10.1115/1.3656900.

Parr, M. J., R. J. Connor, and M. Bowman. 2010. "Proposed method for determining the interval for hands-on inspection of steel bridges with fracture critical members." *J. Bridge Eng.* 15 (4): 352–363. https://doi.org/10.1061/(ASCE)BE.1943-5592.0000057.

Perry, B. J., Y. Guo, R. Atadero, and J. W. van de Lindt. 2020. "Streamlined bridge inspection system utilizing unmanned aerial vehicles (UAVs) and machine learning." *Measurement* 164: 108048. https://doi.org/10.1016/j.measurement.2020.108048.

Petroff, S. M., M. W. Halling, and P. J. Barr. 2011. "Monitoring of long term bridge performance (LTBP) program bridges." In *Structures Congress 2011*, edited by D. Ames, T. L. Droessler, and M. Hoit, 65–76. Reston, VA: ASCE.

Phares, B. M., G. A. Washer, D. D. Rolander, B. A. Graybeal, and M. Moore. 2004. "Routine highway bridge inspection condition documentation accuracy and reliability." *J. Bridge Eng.* 9 (4): 403–413. https://doi.org/10.1061/(ASCE)1084-0702(2004)9:4(403).

Pines, D., and A. E. Aktan. 2002. "Status of structural health monitoring of long-span bridges in the United States." *Prog. Struct. Mater. Eng.* 4 (4): 372–380. https://doi.org/10.1002/pse.129.

Quirk, L., J. Matos, J. Murphy, and V. Pakrashi. 2018. "Visual inspection and bridge management." *Struct. Infrastruct. Eng.* 14 (3): 320–332. https://doi.org/10.1080/15732479.2017.1352000.

Rens, K. L., T. J. Wipf, and W. F. Klaiber. 1997. "Review of nondestructive evaluation techniques of civil infrastructure." *J. Perform. Constr. Facil* 11 (4): 152–160. https://doi.org/10.1061/(ASCE)0887-3828(1997)11:4(152).

Rolander, D. D., B. M. Phares, B. A. Graybeal, M. E. Moore, and G. A. Washer. 2001. "Highway bridge inspection: State-of-the-practice survey." *Transp. Res. Rec.* 1749 (1): 73–81. https://doi.org/10.3141/1749-12.

Ryan, T. W., J. E. Mann, Z. M. Chill, and B. T. Ott. 2012. *Bridge inspector's reference manual (BIRM)*. Publication No. FHWA NHI 12-049. Washington, DC: Federal Highway Administration.

Sacks, R., A. Kedar, A. Borrmann, L. Ma, I. Brilakis, P. Hüthwohl, S. Daum, U. Kattel, R. Yosef, and T. Liebich. 2018. "Seebridge as next generation bridge inspection: Overview, information delivery manual and model view definition." *Autom. Constr.* 90: 134–145. https://doi.org/10.1016/j.autcon.2018.02.033.

Sanders, P., R. Atadero, and M. Ozbek. 2018. *Methodology for uncertainty-based inspection planning of concrete bridge decks using mechanistic models of crack formation and propagation*. Technical Rep. No. MPC-18-346. Fargo, ND: Upper Great Plains Transportation Institute.

Scherer, W. T., and D. M. Glagola. 1994. "Markovian models for bridge maintenance management." *J. Transp. Eng.* 120 (1): 37–51. https://doi.org/10.1061/(ASCE)0733-947X(1994)120:1(37).

Seo, J., J. P. Wacker, and L. Duque. 2018. *Evaluating the use of drones for timber bridge inspection*. Gen. Tech. Rep. FPL-GTR-258. Madison, WI: US Dept. of Agriculture, Forest Service, Forest Products Laboratory.

Shahin, M. Y. 1994. *Pavement maintenance management for airports, roads, and parking lots*. London: Chapman & Hall.

Shiraki, N., M. Shinozuka, J. E. Moore, S. E. Chang, H. Kameda, and S. Tanaka. 2007. "System risk curves: Probabilistic performance scenarios for highway networks subject to earthquake damage." *J. Infrastruct. Syst.* 13 (1): 43–54. https://doi.org/10.1061/(ASCE)1076-0342(2007)13:1(43).

Shirolé, A. M. 2010. "Bridge management to the year 2020 and beyond." *Transp. Res. Rec.* 2202 (1): 159–164. https://doi.org/10.3141/2202-19.

Sohanghpurwala, A. A. 2006. *Manual on service life of corrosion-damaged reinforced concrete bridge superstructure elements*. Washington, DC: Transportation Research Board.

Soliman, M., and D. M. Frangopol. 2013. "Reliability and remaining life assessment of fatigue critical steel structures: Integration of inspection and monitoring information." In *Structures Congress 2013: Bridging Your Passion with Your Profession*, edited by B. J. Leshko, and J. McHugh, 709–720. Reston, VA: ASCE.

Soliman, M., and D. M. Frangopol. 2014. "Life-cycle management of fatigue-sensitive structures integrating inspection information." *J. Infrastruct. Syst.* 20 (2): 04014001. https://doi.org/10.1061/(ASCE)IS.1943-555X.0000169.

Soliman, M., D. M. Frangopol, and S. Kim. 2013. "Probabilistic optimum inspection planning of steel bridges with multiple fatigue sensitive details." *Eng. Struct.* 49: 996–1006. https://doi.org/10.1016/j.engstruct.2012.12.044.

Soliman, M., D. M. Frangopol, and A. Mondoro. 2016. "A probabilistic approach for optimizing inspection, monitoring, and maintenance actions against fatigue of critical ship details." *Struct. Saf.* 60: 91–101. https://doi.org/10.1016/j.strusafe.2015.12.004.

Soltangharaei, V., R. Anay, L. Ai, E. R. Giannini, J. Zhu, and P. Ziehl. 2020. "Temporal evaluation of ASR cracking in concrete specimens using acoustic emission." *J. Mater. Civ. Eng.* 32 (10): 04020285. https://doi.org/10.1061/(ASCE)MT.1943-5533.0003353.

Sorel, T. 2019. *Long-term infrastructure program letter report: January 30, 2019*. Washington, DC: Transportation Research Board.

Stewart, M. G. 2004. "Spatial variability of pitting corrosion and its influence on structural fragility and reliability of RC beams in flexure." *Struct. Saf.* 26 (4): 453–470. https://doi.org/10.1016/j.strusafe.2004.03.002.

Straub, D. 2009. "Stochastic modeling of deterioration processes through dynamic Bayesian networks." *J. Eng. Mech.* 135 (10): 1089–1099. https://doi.org/10.1061/(ASCE)EM.1943-7889.0000024.

Straub, D. 2014. "Value of information analysis with structural reliability methods." *Struct. Saf.* 49: 75–85. https://doi.org/10.1016/j.strusafe.2013.08.006.

Straub, D., and A. Der Kiureghian. 2010. "Bayesian network enhanced with structural reliability methods: Methodology." *J. Eng. Mech.* 136 (10): 1248–1258. https://doi.org/10.1061/(ASCE)EM.1943-7889.0000173.

Straub, D., and M. H. Faber. 2004. "On the relation between inspection quantity and quality." *In e-Journal of Nondestructive Testing*. 9 (7): 1–14. Accessed May 14, 2019. http://www.ndt.net.

Sultana, M., G. Chai, S. Chowdhury, T. Martin, Y. Anissimov, and A. Rahman. 2018. "Rutting and roughness of flood-affected pavements: Literature review and deterioration models." *J. Infrastruct. Syst.* 24 (2): 04018006. https://doi.org/10.1061/(ASCE)IS.1943-555X.0000413.

Swenson, D. V., and A. R. Ingraffea. 1991. "The collapse of the schoharie creek bridge: A case study in concrete fracture mechanics." In *Current trends in concrete fracture research*, edited by Z. P. Bažant, 73–92. Dordrecht, Netherlands: Springer.

Tao, W., and N. Wang. 2019. "A novel markovian framework for optimum maintenance of deteriorating bridges in earthquake-prone areas." In *Proc., 13th Int. Conf. on Applications of Statistics and Probability in Civil Engineering (ICASP13)*. https://doi.org/10.22725/ICASP13.330.

Tarighat, A., and A. Miyamoto. 2009. "Fuzzy concrete bridge deck condition rating method for practical bridge management system." *Expert Syst. Appl.* 36 (10): 12077–12085. https://doi.org/10.1016/j.eswa.2009.04.043.

Taylor, B. R., Y. Qiao, M. D. Bowman, and S. Labi. 2016. *The economic impact of implementing nondestructive testing of reinforced concrete bridge decks in Indiana*. FHWA/IN/JTRP-2016/20. West Lafayette, IN: Indiana Dept. of Transportation.

Thompson, P. D., and R. W. Shepard. 2000. "AASHTO commonly recognized bridge elements—Successful applications and lessons learned." In *Proc., National Workshop on Commonly Recognized Measures for Maintenance*, 1–13. McLean, VA: Booz-Allen & Hamilton.

Thompson, P. D., E. P. Small, M. Johnson, and A. R. Marshall. 1998. "The Pontis bridge management system." *Struct. Eng. Int.* 8 (4): 303–308. https://doi.org/10.2749/101686698780488758.

Tokdemir, O. B., C. Ayvalik, and J. Mohammadi. 2000. "Prediction of highway bridge performance by artificial neural networks and genetic algorithms." In *Proc., 17th Int. Symp. on Automation and Robotics in Construction (ISARC)*, 1091–1098. Taipei, Taiwan: National Taiwan University.

Ullidtz, P. 1993. *Mathematical model of pavement performance under moving wheel load*. Washington, DC: Transportation Research Board.

Ullidtz, P. 1999. "Deterioration models for managing flexible pavements." *Transp. Res. Rec.* 1655 (1): 31–34. https://doi.org/10.3141/1655-05.

Vaghefi, K., R. C. Oats, D. K. Harris, T. M. Ahlborn, C. N. Brooks, K. A. Endsley, C. Roussi, R. Shuchman, J. W. Burns, and R. Dobson. 2012. "Evaluation of commercially available remote sensors for highway bridge condition assessment." *J. Bridge Eng. 17*(6): 886–895. https://doi.org/10.1061/(ASCE)BE.1943-5592.0000303.

Vu, K. A., and M. G. Stewart. 2005. "Predicting the likelihood and extent of reinforced concrete corrosion-induced cracking." *J. Struct. Eng.* 131 (11): 1681–1689. https://doi.org/10.1061/(ASCE)0733-9445(2005)131:11(1681).

Washer, G., R. Connor, M. Nasrollahi, and J. Provines. 2016a. "New framework for risk-based inspection of highway bridges." *J. Bridge Eng.* 21 (4): 04015077. https://doi.org/10.1061/(ASCE)BE.1943-5592.0000818.

Washer, G., R. Connor, M. Nasrollahi, and R. Rebecca. 2016b. "Verification of the framework for risk-based bridge inspection." *J. Bridge Eng.* 21 (4): 04015078. https://doi.org/10.1061/(ASCE)BE.1943-5592.0000787.

Washer, G., M. Hammed, H. Brown, R. Connor, P. Jensen, J. Fogg, J. Salazar, B. Leshko, J. Koonce, and C. Karper. 2019. *Guidelines to improve the quality of element-level bridge inspection data*. Washington, DC: Transportation Research Board.

Washer, G., M. Nasrollahi, C. Applebury, R. Connor, A. Ciolko, R. Kogler, P. Fish, and D. Forsyth. 2014. *Proposed guideline for reliability-based bridge inspection practices (national academy of sciences*. Project 12-82 (01). Washington, DC: Transportation Research Board.

Wells, J., and B. Lovelace. 2018. *Improving the quality of bridge inspections using unmanned aircraft systems (UAS)*. No. MN/RC 2018-26. St. Paul, MN: Collins Engineers.

Xu, Y., and Y. Turkan. 2019. "Bridge inspection using bridge information modeling (BrIM) and unmanned aerial system (UAS)." In *Advances in Informatics and Computing in Civil and Construction Engineering*, edited by I. Mutis, and T. Hartmann, 617–624. Cham, Switzerland: Springer.

Yang, D. Y., and D. M. Frangopol. 2018. "Probabilistic optimization framework for inspection/repair planning of fatigue-critical details using dynamic Bayesian networks." *Comput. Struct.* 198: 40–50. https://doi.org/10.1016/j.compstruc.2018.01.006.

Yehia, S., O. Abudayyeh, S. Nabulsi, and I. Abdelqader. 2007. "Detection of common defects in concrete bridge decks using nondestructive evaluation techniques." *J. Bridge Eng.* 12 (2): 215–225. https://doi.org/10.1061/(ASCE)1084-0702(2007)12:2(215).

Zink, J., and B. Lovelace. 2015. *Unmanned aerial vehicle bridge inspection demonstration project*. No. MN/RC 2015-40. St. Paul, MN: Collins Engineers.