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Understanding Critical Impacting Factors and Trends on the Future of Bridges

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UNDERSTANDING CRITICAL IMPACTING FACTORS AND TRENDS ON THE FUTURE OF BRIDGES

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A.M.M. Muhaimin

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To: Dean John Volakis
College of Engineering and Computing

This thesis, written by A.M.M. Muhaimin and entitled Understanding Critical Impacting Factors and Trends on the Future of Bridges, having been approved in respect to style and intellectual content, is referred to you for judgment.

We have read this thesis and recommend that it be approved.

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Florida International University, 2021

DEDICATION

I dedicate this thesis to my beloved parents for their endless and unconditional love and support.

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ABSTRACT OF THE THESIS

UNDERSTANDING CRITICAL IMPACTING FACTORS AND TRENDS ON THE FUTURE OF BRIDGES

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Various impacting factors, such as technology advancement, climate change, and economic shifts are occurring and evolving at an ever-increasing pace. There is also a growing realization among bridge engineers and relevant stakeholders that these changes will significantly impact bridge performance and bridge asset management over the next decades. However, there is limited research that offers a holistic understanding on what these factors are and how these factors will potentially affect bridges in the future. To address the gap, this thesis presents a study on the identification of the critical impacting factors and their trends on the future of bridges and an analysis of how these factors would impact the ways bridges are designed, constructed, and operated. This goal is achieved through in-depth interviews (N=21) and questionnaire surveys (N=108) with bridge experts from transportation agencies and a review of secondary sources of data (i.e., published literature and reports on bridges). A total of 30 factors were identified from the interview data and secondary sources of data.

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ABBREVATIONS AND ACRONYMS

AASHTO - American Association of State Highway and Transportation Officials

ASCE - American Society of Civil Engineers

BrIM - Bridge Information Modeling

CIF - Critical Impacting Factor

FHWA - Federal Highway Administration

FRP - Fiber Reinforced Polymer

HPS – High Performance Steel

LHSFNA - Labor Health and Safety Fund of North America

NOAA - National Oceanic and Atmospheric Administration

TCI - Transportation and Climate Initiative

UHPC - Ultra-High Performance Concrete

U.S.BLS - United States Bureau of Labor Statistics

U.S.EIA - United States Energy Information Administration

U.S.EPA - United States Environmental Protection Agency

CHAPTER 1

INTRODUCTION

1.1 Motivation

Over the last decade, various impacting factors, such as technology advancement, climate change, economic shifts, and evolving behaviors and preferences of travelers have driven the changes in the infrastructure sector at an unprecedented speed (Wang et al. 2018, Clewlow and Mishra 2017a, Lambert et al. 2013). Bridges are an integral and important part of transportation infrastructure systems and are inevitably being affected by these factors (Baker et al. 2016). Among the various impacting factors, technology has been the driving force of the advancements in the infrastructure sector, and the emerging technologies in materials, construction methods, transportation methods, and communications are expected to revolutionize the transportation industry and significantly impact the future of bridges. In addition, bridges are vulnerable to a range of threats from their surrounding environments, such as climate change, sea level rise, increasingly intense hurricanes and precipitation, and more frequent flooding. Research shows that, due to climate change, it is expected that there will be an increase in annual bridge failures by at least 10% over current failures (Khelifa et al. 2013). Similarly, economic activities, funding availability, demographic characteristics, social perceptions and behaviors of local communities may pose direct or indirect impacts on bridge design, construction, and operation. For example, as exogenous driving factors of transportation demand, the employment rate and personal income not only determine the overall volume of vehicles, but also the types of vehicles traveling on bridges (Brownstone and Golob 2009), both of which are important factors to consider when modeling traffic loads during bridge design and operation. The travel demand and economy may also impact the availability and sustainability of funding, which is vital for the continuous investment on maintaining and/or rehabilitating bridges (Geddes and Madison 2017).

These factors are occurring and evolving at an ever-increasing pace. There is also a growing realization among policymakers, engineers, contractors and other relevant stakeholders that these changes will reshape bridge design, construction, and operation over the next decades (Kennedy 2019, Bennett 2016). However, there is still limited research that offers a holistic and in-depth understanding of the critical impacting factors and their impacting mechanisms on the future of bridges. Existing research has mostly focused on advancing the knowledge on how bridges are/will be affected by some specific factors, such as climate change (e.g., Nasr et al. 2020, Suarez et al. 2005), public-private partnerships (P3s) (e.g., Cui et al. 2018), innovative construction materials and techniques (e.g., Farzad et al. 2019, Tomek 2018, Dong 2018), and connected and autonomous vehicles (CAVs) (Gora and Rüb 2016). Within these research efforts, some studies (e.g., Farzad et al. 2019, Dong 2018) focused on exploring how a factor would affect one aspect (e.g., bridge design) or one performance metric (e.g., structural robustness) of bridges. In addition, the majority of studies relied on theoretical analysis (e.g. Nasr et al. 2020, Duarte and Ratti 2018, Bastidas-Arteaga et al. 2013) or lab-based testing (e.g., Alexander and Kashani 2018, Gunes et al. 2012, Tonoli et al. 2010) without incorporating empirical knowledge or practical experience shared by experts from the transportation agencies. Empirical knowledge enables more in-depth understanding of these factors based on real-world cases and experiences (Zhang and El-Gohary 2015). While existing studies have collectively offered valuable knowledge on factors that may affect the future of bridges, a comprehensive study is sorely needed to integrate the full spectrum of factors from across multiple disciplines and to offer more in-depth discussion on how these factors will change different aspects of bridges.

1.2 Goal and Objectives

To address the above-mentioned knowledge gaps, the main objective of this study is to identify the critical impacting factors and understand how the various factors could affect bridges in the future. It aims to address the following research questions: (1) What are the factors that could affect bridge design, construction, and operation in the future? and (2) how will these factors affect the way that bridges are designed, constructed, and operated in the future? By addressing these questions, this research contributes to the body of knowledge in the engineering management domain by offering a more holistic and explicit understanding on the potential factors that may affect bridge asset management. It allows practitioners in the infrastructure asset management area to be more proactive in addressing the new challenges brought by these factors, and it potentially supports and enables our bridges to be managed in the way that is more resilient and adaptive to the changes in the future. The remainder of the thesis discusses about the research methodology, research findings, and concludes with the summary and contributions.

1.3 Thesis Organization

This thesis is organized into 5 chapters. Chapter 1 introduces the motivation of this thesis research, explains the problems to be solved, and describes the research goal and objectives to be achieved.

Chapter 2 presents a comprehensive review of the existing studies on different factors that may impact bridge design, construction and operation. It also identifies the knowledge gaps.

Chapter 3 describes the methodology used in this thesis for identifying and analyzing the critical impacting factors of bridge design, construction and operation.

Chapter 4 discusses the research results obtained from the analyses of the data obtained from interviews, questionnaire survey, and literatures.

Chapter 5 summarizes the findings from this thesis, highlights the research contributions, and provides recommendations for future studies.

CHAPTER 2

LITERATURE REVIEW

2.1 Existing Literature

Many research studies have been conducted to explore the effects of certain factors on bridges. These factors can be broadly classified into the areas of technological, environmental, social, and economic factors. In the area of technological factors, most of the existing studies focused on how new materials, techniques, or transportation methods could affect bridge performance or bridge asset management. For example, extensive research studies have been conducted in testing the use, impact, and performance of new construction materials, such as Ultra-High Performance Concrete (UHPC) (e.g., Dong 2018, Gunes et al. 2012), High-Performance Steel (e.g., Collins et al. 2019, Mistry 2003), or Fiber Reinforced Polymer (FRP) (e.g., Kim 2019, Mara et al. 2014), on bridge elements and structures. There are also studies that investigated the application and impacts of new construction techniques, such as Accelerated Bridge Construction (ABC) (e.g., Jia et al. 2018, Hadi et al. 2016) and Self-Propelled Modular Transporters (Shutt 2013, Ralls et al. 2005), on bridge construction. Other studies (e.g., Maizuar et al. 2020, Reagan et al. 2018) have focused on studying and testing the use of advanced structural health monitoring techniques (e.g., advanced non-destructive testing technique, unmanned aerial vehicle), which may transform the way future bridges are inspected and maintained. In terms of new transportation methods, one of the trending techniques that attract the most of attention is CAVs, and some studies (e.g., Sobanjo 2019, Sayed et al. 2020) focused on exploring the impacts of CAVs on civil infrastructure (including bridges) and the requirements needed for the infrastructure to accommodate CAVs.

In the areas of environmental factors, previous research mostly focused on understanding the future trends of environmental change and how such change would affect bridge performance and bridge asset management. For example, Kaewunruen et al. (2018) identified the influence of climate change (e.g., change in temperature and relative humidity) on the performance and durability of concrete structures using statistical analysis. Anarde et al. (2018) developed an integrative model of the combined impacts of sea-level rise, landscape changes, and coastal flooding on the vulnerability of highway bridges during extreme storms. Yuan et al. (2018) investigated the impacts of marine environments on the corrosion of coastal bridges during their service life period. Mortagi and Ghos (2020) proposed a numerical framework to evaluate the impact of chloride and carbonation-induced corrosion on the seismic response and bridge fragility.

In terms of social factors, a number of studies have been conducted to explore trending social phenomena, such as construction workforce and safety behaviors, and their potential impacts on transportation infrastructure asset management. For instance, Kumar et al. (2020) studied the workforce and occupations within the highway, street, and bridge construction industries in the State of Indiana, and they identified that some positions, such as civil engineers, surveys, health and safety engineers, are difficult to fill in the labor market, which may affect future transportation asset management. Kim et al. (2017)'s study showed that effective workforce training is one of the priorities for state transportation agencies to ensure long-term satisfactory performance in transportation infrastructure construction. Haghshenas et al. (2015) identified construction safety as a "transportation social impact indicator", which plays a major role in construction of transportation infrastructure, including bridges. Chen and Leu (2014) focused on construction worker safety and established a new model for fall risk assessment of workers in bridge construction projects.

For economic factors, previous research efforts focused on investigating how the growing economic trends may directly or indirectly affect transportation infrastructure. Some factors, such as Public Private Partnership (P3), and funding availability may have direct impacts on bridge project delivery. For instance, many studies (e.g., Ramsey and El-Asmar 2020, Mallett 2017) have been conducted to understand the impacts of P3 on transportation project delivery. There are also studies from multiple organizations (e.g., ASCE 2020, NGA 2020) that analyzed the recent impacts of funding uncertainty or availability on bridge operation and maintenance. Other factors, such as economic activities, E-commerce, fuel price, road pricing, may indirectly affect bridge asset management through their impacts on the travel demands or funding availability. For example, Rutter et al. (2017) discussed the potential impacts of E-commerce growth on the transportation network and identified challenges for transportation infrastructure planning and operation. Hakimelahi et al. (2016) studied the effects of fuel price on travel demand changes, which in turn influences transportation infrastructure planning and design.

2.2 Knowledge Gap

The above-mentioned studies have offered valuable knowledge on the potential factors that may transform the future of bridges. However, there is still limited research that offers a holistic and in-depth understanding of the critical impacting factors and their impacting mechanisms on bridges. The majority of these studies focus on investigating one specific factor or exploring how the factor affects one specific aspect (e.g., bridge operation) or performance metric of bridges (e.g., structural integrity). Without a holistic understating of the factors from different disciplines and how these factors may affect varying aspects of bridges, it is not easy to depict a clear and comprehensive picture of the future of bridges. Some factors may cause multifaced impacts on the ways that bridges are designed, constructed, and operated. For example, climate change may cause certain parameters (e.g., design floods, design rainfalls) to be altered in bridge design standards due to more frequent flooding events (Wright et al. 2012), reduce construction workers' productivity and safety due to higher chance of working in extreme temperatures (Acharya et al. 2018), and accelerate the degradation of materials due to rising temperatures (Rowan et al. 2013). Furthermore, multiple factors could interplay with each other to pose new uncertainties and/or requirements for bridges. For example, travel behaviors are affected by advancements in transportation facilities and methods (Auld et al. 2017, Clewlow and Mishra 2017b) that are regulated by policies and regulations, all of which could impact bridges in the future. It is often multiple factors that drive the changes of bridges.

In addition, there is limited empirical studies that integrate the practical knowledge and evidence shared by the practitioners in the transportation sectors. Although theoretical analysis (e.g., literature review) or lab-based testing may offer valuable conceptual understanding of the factors, an empirical understanding of the impacting mechanisms based on field evidence is essential for developing possible adaptation strategies in practice. Theoretical knowledge is informative and explanatory but may also be partial and indirect because it may lack the understanding of the empirical reality (Forrester et al. 2008, Zhang and El-Gohary 2015). Empirical studies are important to verify, complement, and/or enhance the theoretical understanding of these factors. The practical nature of bridge design, construction, and operation further reinforces the need for empirical knowledge.

CHAPTER 3

RESEARCH METHODOLOGY

Exploratory research methods were used in this study. This is because of (1) the diversity and complexity of the impacting factors, and (2) unavailability of data regarding some factors and the impacting mechanisms of the factors on bridges. The objective of exploratory research is to gain understanding and collect information and data in a way that allows knowledge to emerge in response to questions of “what” and “why” (Fellows and Liu 2015, Mostaan and Ashuri 2017). The major strength of exploratory research methods is the ability to identify major factors associated with certain research problems in a specific research domain (Mostaan and Ashuri 2017). Exploratory research methods mainly include primary and secondary data collection methods, with primary methods focusing on collecting information directly from the subject (e.g., a group of people or an individual), while secondary methods focusing on collecting information from previously published primary research. In this study, the research methodology incorporates both the primary and secondary methods. It includes two main phases: data collection phase and data synthesis and analysis phase. Fig. 1 shows an overview of the research methodology used in this study.

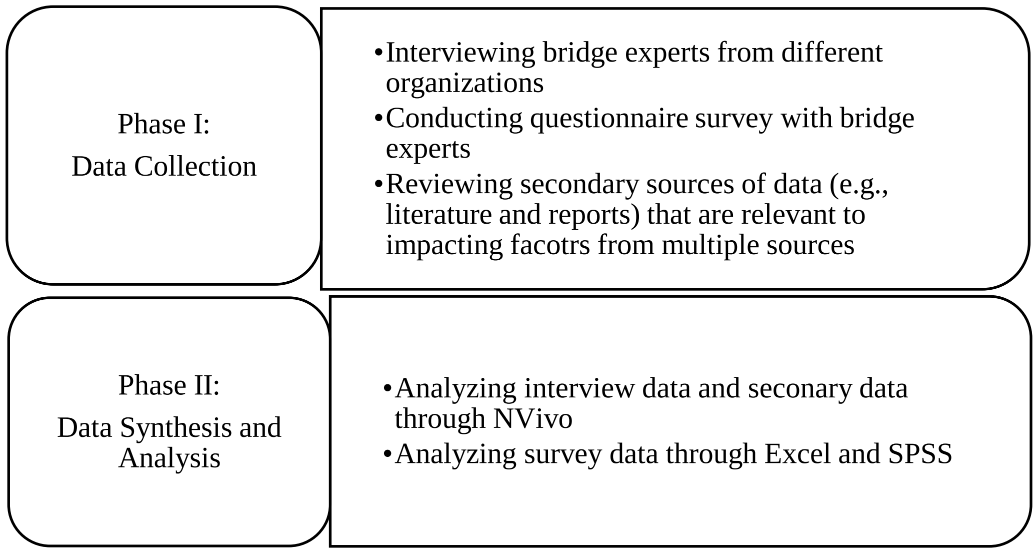

Figure 1. An Overview of Research Methodology

3.1 Phase I: Data Collection

3.1.1 Primary Data Collection

In-depth semi-structured interviews and questionnaire survey were used as primary data collection methods to solicit the opinions of experts in the bridge engineering domain on the importance, trends, and impacting mechanisms of critical impacting factors.

3.1.1.1 Semi-Structured Interview

To conduct the expert interviews, two main steps were taken. First, the interview instrument was designed. The interview instrument contains 26 questions, which were grouped into four sections: (a) bridge design, (b) bridge construction, (c) bridge operation, and (d) demographic information collection. Under each of the first three sections, a similar set of open-ended questions were asked. Some examples of the questions in the bridge design section include:

- Based on your expertise in Bridge Engineering, *what* are the critical factors that could affect the design standards/specifications of our bridges in the future?
- Can you please explain *why* you believe the factors could affect the future design standards/specifications of bridges?
- Can you please explain *how* these factors could affect the future design standards/specifications of bridges?
- How do you predict the trends of the factors you mentioned? / Do you see any particular trends in the factors you just mentioned?
- Among the factors you discussed, what are the factors that you believe are the most critical ones?
- What are the factors you have already accounted for in the design of bridges?

In the fourth section of the interview instrument, the demographic information, including age, gender, education, ethnicity, race, profession, and work experience, of the interviewees was solicited through a set of structured questions.

Second, the interviews were implemented. The interviews targeted the bridge experts from multilevel government agencies, such as State Departments of Transportation (DOTs), local (e.g., county-level, city-level) transportation agencies, and local transportation commissions. The interviews were conducted during the 2019 International Accelerated Bridge Construction Conference in Miami, Florida held from December 11, 2020 to December 13, 2020. Prior to the conference, the attendees were contacted with interview invitations via emails. Around 75 emails were sent, and 21 conference attendees agreed to participate in the interviews. During the conference, a total of 19 face-to-face interviews were conducted with 20 interviewees. One attendee agreed to provide written answers to all the interview questions. The descriptive statistics of the interviewees' demographic information is summarized in Table 1. The interviews were all conducted in a semi-structured format, which allows the researchers to modify the questions based on the backgrounds of the interviewees.

Table 1. Demographic Information of Interviewees

Demographic Information	
No of Interviewees	21
Gender	
Male	13
Female	6
Not disclosed	2
Age	
36-40	3
41-45	2
46-50	3
51-55	5
56-60	4
Above 65	2
Not disclosed	2
Highest Level of Degree	
Bachelor's degree	8
Graduate degree	11
Not disclosed	2
Years of Work at Current Workplace	
More than 1 but less than 3 years	1
More than 3 but less than 6 years	2
More than 6 but less than 9 years	1
More than 9 but less than 12 years	1
12 years or more	14
Not disclosed	2
Race	
Asian	3
White	16
Not disclosed	2
Current Region of Residency	
Northeast	2
Midwest	4
South	8
West	5
Not disclosed	2

All the face-to-face interviews were recorded upon receiving approval from the interviewees through informed consent forms approved by Institutional Review Board (IRB). The audio recordings were then transcribed using an online automatic transcribing tool SONIX (Sonix

2020). The transcribed data were checked for accuracy and potential errors and revised manually. They were then saved into digital word documents.

3.1.1.2 Questionnaire Survey

A questionnaire survey was designed to solicit the opinions of bridge experts and relevant stakeholders. A total of 32 CIFs was included in the questionnaire survey. These CIFs were identified from the interviews with bridge domain experts and a review of secondary sources of data, which include published literature and reports. The CIFs were classified into environmental, social, economic, and technological factors.

The survey aims to understand expert opinion on (1) the likelihood of impacts, and (2) possible trends in the future of these CIFs. The questionnaire survey has three main sections: (1) impact assessment, (2) trend analysis, and (3) background information of participants. Section 1 of the survey solicits experts' assessment on how likely each of the CIFs would impact the future of bridges. Examples or definitions of each CIF were provided to ensure the clarity of the CIFs. A 5-point Likert scale was used to capture the responses, with 5 being "extremely likely, followed by "very likely", "likely", "not likely" and "no impact". Section 2 of the survey aims to solicit experts' opinions on the possible trends of each CIF. Four options were provided, including "trend continues", "trend stops", "trend reverses", and "unpredictable trend". Section 3 acquired participants' demographic information, such as age, gender, race, educational background, years of experience, current job position, and regions of operation.

The survey was implemented on Qualtrics from April 2020 to October 2020. The targeted participants include bridge design, construction, and operation experts, and relevant stakeholders from different state departments of transportation (DOTs), other government agencies (e.g., AASHTO, FHWA), private construction companies, and academic researchers from different universities. Potential respondents were purposively sampled from different open online sources, such as government websites, websites of public agencies, and online address books, etc. Survey invitations with a link to the online questionnaire were sent through emails to all potential participants. A total of 763 emails were sent. A total of 132 participants responded to the survey, and 108 of them completed the survey. The response rate is about 17%, and the completion rate is approximately 82%. Table 2 summarizes the demographic information of the participants.

Table 2: Demographic Information of the Survey Participants

Demographic Parameters	**Number of Survey Participants**
Total number of participants	108
Gender	
Male	93
Female	15
Age	
26-40	25
41-55	50
56-65	26
Above 65	7
Education	
Some college credit, no degree	1
Bachelor's degree	41
Graduate degree	46
Doctoral degree (e.g., PhD, Research doctorate)	16
Professional degree (e.g., MD, JD)	3
Other	1
Employment	
Private-for-profit company, business or individual, for wages, salary or commissions	9
Not-for-profit, tax-exempt, or charitable organization	1
State government employee	68
Federal government employee	11
University	16
Others	3
Job Position	
Design Engineer	65
Construction and Maintenance Engineer	24
Researcher	19
Work Experience (years)	
1 to 10 years	26
11 to 20 years	21
21 to 30 years	28
More than 30 years	33
Race	
Asian	16
White	84
Black or African American	2
American Indian or Alaska Native	1
Do not know	2
Other	3
Regions of U.S. by Coastline	
Coastal regions	58
Inland regions	50

3.1.2 Secondary Data Collection

The primary data collected through interviews and surveys were supplemented with secondary data, including published literature and reports. To collect the secondary data, a set of data sources was first identified; the data sources include Google Scholar search engine, Science Direct database, American Society of Civil Engineers library, Journal Storage (JSTOR), Scopus database, and Research Gate website. These databases or virtual libraries were commonly used in the civil engineering and engineering management domain to identify relevant literature (Leitner et al. 2020). In addition, the virtual library of the first author's university (Florida International University) was used to supplement the above-mentioned databases.

Two rounds of search were then conducted. In the first round, the keywords or keyword combinations were derived through a deductive approach. The deductive approach identifies the keyword combinations based on a predefined framework that (1) focuses on exploring technological, environmental, social, and economic factors and (2) the impacts on bridge design, construction, and operation. The keyword combinations include (1) one of "technological factor", "environmental factor", "social factor", and "economic factor", and (2) one of "bridge design", "bridge construction", and "bridge operation". In the second round, the keyword combinations were derived through an inductive approach. The inductive approach identifies the keyword combinations based on the observation or analysis of the literature data obtained from the first round and the interview data. In this round, the keywords contain specific factors identified from the literature and interview data, such as "climate change and bridges design", "new construction materials and bridge design", and "public-private partnerships and bridge construction".

From the search results, the titles and abstracts of the articles were first reviewed to determine if the articles are relevant to this study. The review of the complete text was then conducted to identify those articles that are helpful in identifying certain factors and understanding their impacting mechanisms on bridges.

3.2 Phase II: Data Synthesis and Analysis

3.2.1 Analyses of Interview Data

The interview transcription data and the secondary data were imported into and analyzed through NVivo Pro 12. NVivo Pro 12 is a software program which is used for analyzing unstructured text, audio, and image data including interviews, focus groups, surveys, and literature (Phillips and Lu 2018). It is very useful for qualitative and mixed-methods research because of its features. The collected data were read manually and were analyzed through the hierarchal nodes function of NVivo. The following analyses were then conducted using one or multiple groups of data.

(1) Identification of Critical Impacting Factors

This analysis aimed to understand *what* factors may cause impacts on bridges. The group of data on "identification and description of critical impacting factors" were reviewed and analyzed. In this process, a combination of top-down and bottom-up data analysis methods was used to identify the critical impacting factors. The top-down data analysis starts by defining the high-level categories and then extends to more specific factors, and the bottom-up data analysis starts by identifying the most specific factors first and then categorizes them into high-level categories (Pathak et al. 2020, Zhang and El-Gohary 2016). In this study, three main categories were first defined by benchmarking the triple bottom line (TBL)-sustainability framework (Goh et al. 2020) to include environmental, social, and economic factors, and a fourth category of technological factors was added due to the extensive discussion on technological advancements by the interviewees. Based on these four categories, the data were analyzed to identify the critical impacting factors. For example, environmental factors include climate change, change in intensity and frequency of extreme events, sea level rise, and change in soil quality, etc. To code the data in NVivo, the high-level categories (e.g., environmental factors, social factors) were coded as parent nodes, and the specific factors (e.g., sea level rise, labor shortage) were coded as child nodes. All the interview transcriptions were then reviewed and labeled using the child nodes.

(2) Importance of Impacting Factors

This analysis investigated the importance of impacting factors based on expert opinion. The primary data collected through the interviews were reviewed and analyzed. Frequency analysis was conducted to quantitatively interpret the interview data. In this study, the importance of the factors was interpreted through their frequencies, which refer to the number/percentage of interviewees who mentioned or discussed about the factors during the interviews. Frequency analysis is a commonly used content analysis method (Ahmad et al. 2021). It allows for the interpretation of the relative importance of different factors, criteria, or patterns identified in the interview data in a quantitative manner (Ahmad et al. 2021, Elliott 2018). For each factor identified from the interview, the number/percentage of interviewees who mentioned it was counted and tabulated.

3.2.2 Analyses of Survey Data

The collected survey data were first imported to an excel file for preprocessing. The options for the impact ratings and trend ratings were transformed into sequential numerical values for statistical analysis. For impact ratings, the five options in the Likert scale were transformed into the following values: “Extremely Likely” = 5, “Very Likely” = 4, “Likely” = 3, “Not Likely” = 2, and “No impact” = 1. For trend ratings, the options were transformed as follows: “Trend Continues” = 1, “Trend Stops” = 0, and “Trend Reverses” = -1. The “Unpredictable Trend” option was not assigned a numerical value. Rather, an acronym of “UT” was used. The number of participants who chose “Unpredictable Trend” as a response for each factor was counted and tabulated.

Based on the numerical values, mean indexing was calculated to rank the CIFs based on their (1) likelihood of impacts on bridges, and (2) future trends. Mean indexing is commonly used in exploratory and descriptive data analysis (Goh and Yang 2013). In addition, the uncertainty of trend for each CIF is determined by calculating the percentage of participants who chose the “UT” in the options.

Kruskal-Wallis H and Mann-Whitney U tests were conducted to find out if there were differences in response or opinions among various groups of participants. Kruskal-Wallis H test is a nonparametric test that is used for comparing the differences between three or more independent samples (Zhang and El-Gohary 2016). Mann-Whitney U test is used to compare differences between two independent groups, which have dependent variable that is ordinal or continuous (but not normally distributed) (Laerd Statistics 2020). The participants are grouped according to three criteria, including job position of the participants, years of experience related to bridge engineering, and regions of operation. Based on the collected data, for job positions, there are three groups, which are “Design Engineer (G1)”, “Construction and Maintenance Engineer (G2)”, and “Academic Researcher (G3)”. For years of experience, there are four groups, which are “1 to 10 Years of Experience (E1)”, “11 to 20 Years of Experience (E2)”, “21 to 30 Years of Experience (E3)”, and “More than 30 Years of Experience (E4)”. Lastly, depending on the region where the participants are from, two groups are identified: “Coastal State (R1)” and “Inland State (R2)”. “Coastal State (R1)” category includes states that have coastlines (e.g., Florida, Delaware, Georgia), and the “Inland State” category includes states that do not have coastlines (e.g., Iowa, Arizona, Arkansas). This categorization was selected because it was assumed that the experts who worked in coastal states might have different opinions about the impact of environmental factors than the experts from states which are inland regions. This assumption is based on a report by Babcock (2013), which observed that the inland or landlocked states are most likely to ignore climate hazards and climate change. The Kruskal-Wallis H tests were performed on groups classified based on job positions and years of experience. The Mann-Whitney U test was conducted on groups classified based on regions where the participants are from.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Identification of Critical Impacting Factors

Based on the expert interviews and a review of secondary sources of data, a total of 30 factors were identified and classified into environmental, social, economic, and technological categories (Fig. 2). Benchmarking the literature in the relevant domains (e.g., NASA 2014, Kozak and Nield 2001, Kenton 2020, NOAA 2020, Boller 2009), the definitions of these factors are presented in Table 3. As per Fig. 2, among these factors, 4 factors were identified solely from expert interviews, 7 factors were collected solely from existing literature, and 19 factors were identified from both sources.

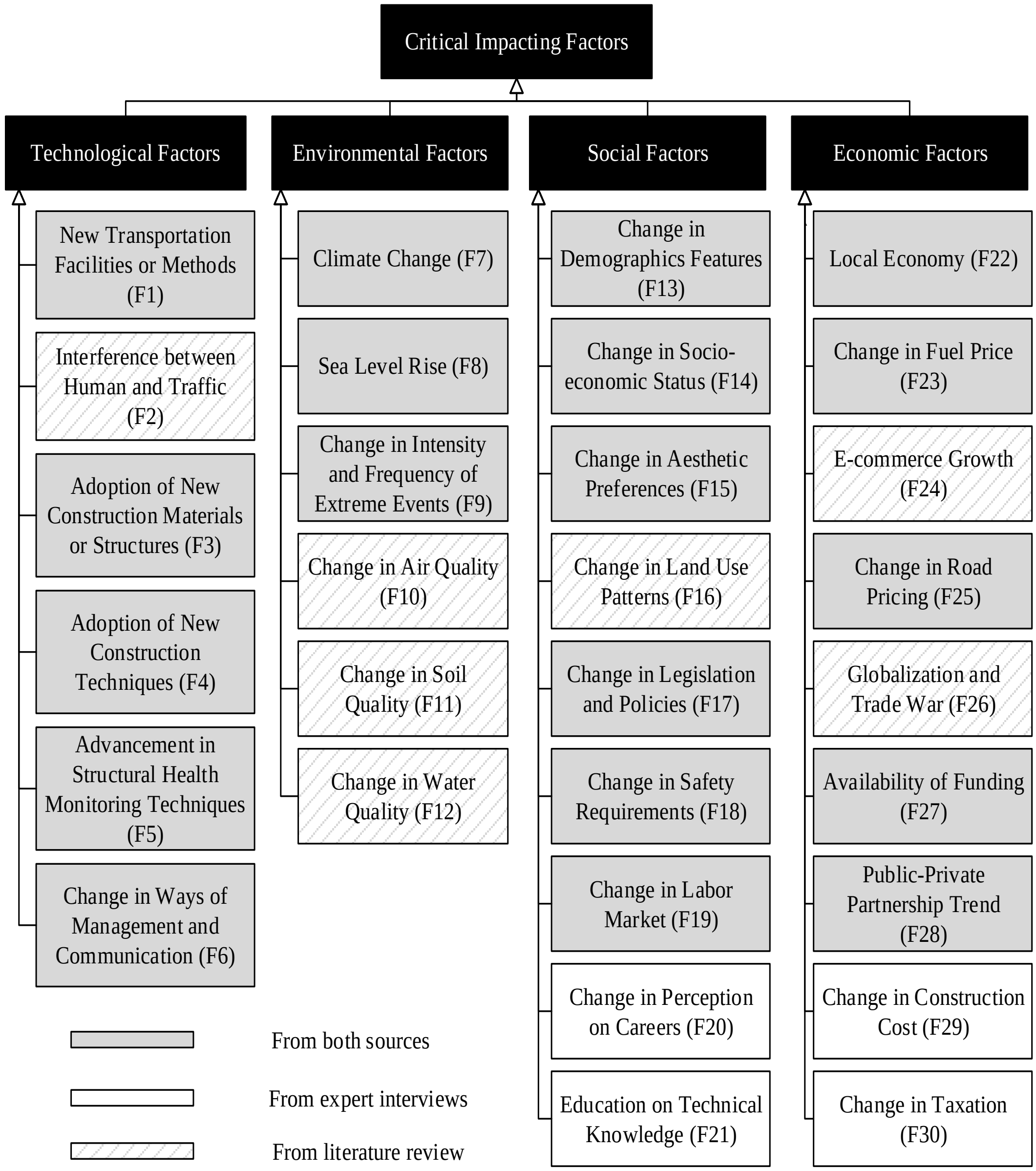

Figure 2. A hierarchy of Critical Impacting Factors

Table 3. Definitions of Critical Impacting Factors.

No.	Factor	Definition
Technological Factors		
F1	New transportation facilities or methods	It refers to new and advanced methods and facilities of transportation, such as connected and autonomous vehicles (CAVs), hyperloop, shared mobility, urban transport pod, and maglev train, etc.
F2	Interference between human and traffic	It refers to the interrelations between humans and transportation networks, such as communications between vehicles and road infrastructure, and advanced computing systems for navigation.
F3	Adoption of new construction materials or structures	It refers to the acceptance and use of new and advanced construction materials and structures, such as thermoplastic materials, composite materials, geo-synthetic reinforced soil-integrated bridge system, high performance steel, ultra-high performance concrete, and elastomeric bridge bearings, etc.
F4	Adoption of new construction techniques	It refers to the enactment and use of new and advanced construction techniques, such as accelerated bridge construction technology, and self-propelled modular transporters (SPMTs) for bridge construction.
F5	Advancement in structural health monitoring techniques	It refers to new and innovative technologies on monitoring of structural health of bridges, such as acoustic imaging for inspecting substructure, smart sensors for active monitoring, and machine learning for structural health prediction, etc.
F6	Change in ways of management and communication	It refers to the adoption of new methods of management and communication, such as building information modeling, cloud-based management software or tools, and digital supply chain management platforms, etc.
Environmental Factors		
F7	Climate change	It refers to a long-term unprecedented change in the average weather patterns of local, regional, and global climates.
F8	Sea level rise	It refers to an increase in the level of the oceans due to the effects of global warming.
F9	Change in intensity and frequency of extreme events	It refers to the change in unexpected, unusual, severe, or unseasonal weather or seismic activities with intensity and frequency that has not been seen in the past.
F10	Change in air quality	It refers to the change in air quality indices and increase of pollutant particles in atmosphere due to use of fossil fuels and emissions of greenhouse gases and pollutant particulates.
F11	Change in soil quality	It refers to the increase of salinity, toxic chemicals, pollutants and contaminants in the soils, which could pose a risk to human health and/or the ecosystem.
F12	Change in water quality	It refers to the increase of salinity, toxic chemicals and biological agents that exceed normal and tolerable limits and may pose a threat to human health and the environment.
Social Factors		
F13	Change in demographic features	It refers to the change in the characteristics of populations in a certain area with regard to age, gender, birth rate, nationality, ethnicity, and religion.
F14	Change in socioeconomic status	It refers to the change in the social standing or class of populations in a certain area. It is often measured as a combination of education, income, employment rate, and occupation.

F15	Change in aesthetic preferences	It refers to the change in aesthetic preferences on bridge design by the stakeholders.
F16	Change in land use patterns	It refers to the change in utilization of the available lands in an urban or suburban area as dictated by urban and regional planning and socio-economic context in that area.
F17	Change in legislation and policies	It refers to the change in the preparation and enaction of laws by local, state, or national legislatures on bridges and/or transportation.
F18	Change in safety requirements	It refers to the change in requirements on occupational and work zone safety in a bridge construction project.
F19	Change in labor market	It refers to the change in labor and job market, such as the change in supply of and demand for construction labor.
F20	Change in perceptions on careers	It refers to the change in working-class people's understanding, impression and persuasion of careers and jobs that are relevant to bridges (e.g., structural engineer).
F21	Education on new technical knowledge	It refers to the education on new, innovative, and advanced technologies and the development on relevant skills to create more skilled workforce.
Economic Factors		
F22	Economic growth	It refers to the change in production and distribution of economic goods and services, which is measured in terms of gross national product (GNP) or gross domestic product (GDP).
F23	Change in fuel price	It refers to the change in gasoline and diesel prices that are usually determined by the global demand for and supply of crude oil.
F24	E-commerce growth	It refers to the increase in buying and selling of goods or services and the associated transaction of money and data using the internet.
F25	Change in road pricing	It refers to the change in charges of road tolls, distance or time-based fees, congestion charges, and charges on certain vehicles.
F26	Globalization and trade war	It refers to the interaction and integration among people, companies, and governments worldwide, and the potentially rising conflicts between two or more countries marked by rising tariffs and other protectionist actions.
F27	Availability of funding	It refers to sufficient funds provided by the owners of bridges to develop new bridges and/or manage existing bridges.
F28	Public-private partnership trend	It refers to collaborations between government agencies and private-sector companies to fund, construct, operate and maintain bridge projects.
F29	Change in construction cost	It refers to the change in costs during construction of bridges which include labor, material, equipment, services, utilities costs and contractor's profit.
F30	Change in taxation	It refers to the change on taxes that are relevant to bridge projects.

4.2 Importance of Critical Impacting Factors based on Interview Data

The importance of the 23 factors identified through the expert interviews were analyzed based on the percentage of interviewees who mentioned the factors during the interviews. Fig. 3 shows the importance of the factors based on how these factors were well recognized or widely discussed by the experts. By integrating findings from the expert interviews and literature review, the following sections present detailed discussion on the top ranked factors in each category with a focus on the impacting mechanisms of these factors on bridges in the future.

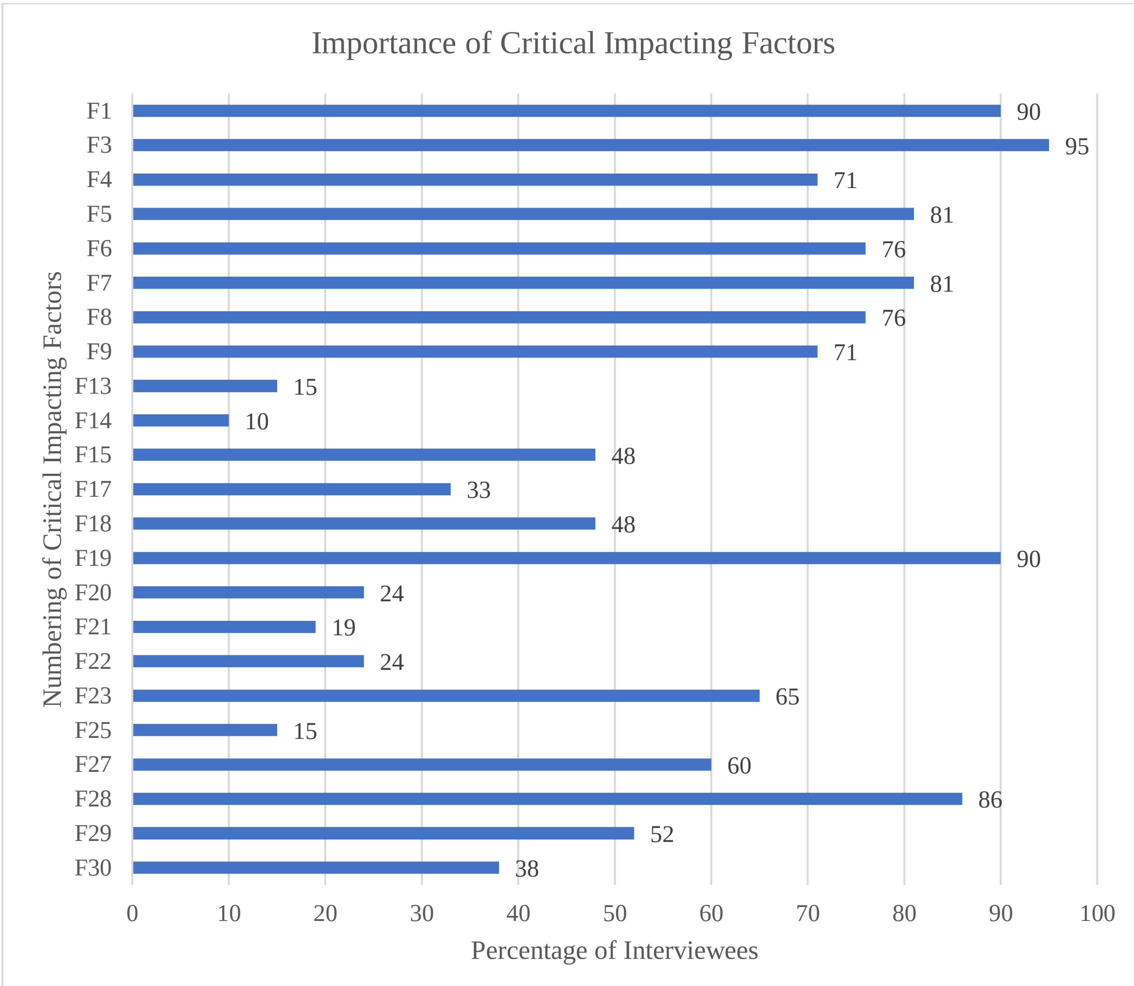

Figure 3. Importance of Critical Impacting Factors based on Expert Interviews

4.2.1 Technological Factors

4.2.1.1 Adoption of New Construction Materials or Structures

Among all the interviewees, approximately 95% (20 out of 21) of them emphasized that the adoption of new construction materials or structures would bring significant impacts to bridges in the future. New advanced materials or innovative structural systems feature highly desirable attributes for bridges, such as long-life expectancy, fewer maintenance requirements, and lower life-cycle cost. Some examples of the newly developed advanced materials or structures mentioned by the interviewees are UHPC, HPS, elastomeric bridge bearings, and composite materials.

As all levels of government have prioritized the efforts on reducing the number of structurally deficient bridges (i.e., bridges that require significant maintenance, rehabilitation, or replacement), the demand for high-performance construction materials and/or structures is on the rise (FHWA 2020). According to the interviewees, these new materials could “bring major changes and opportunities” to the next generation of bridges. For example, UHPC, which has a minimum specified compressive strength of 17,000 pounds per square inch (120 MPa), is becoming popular in bridge construction for its exceptional properties of strength, durability, tensile ductility, and toughness requirements (PCA 2020). In the interviews, a structural engineer from Delaware DOT explained that, with the use of UHPC, we expect to see more bridges with longer spans and reduced number of required substructures in the future. UHPC has already been used for different bridge construction applications, such as prestressed girders, precast waffle panels for bridge decks, precast concrete piles, seismic retrofits of bridges, thin bonded overlays of bridge decks, and joint fills for prefabricated bridge elements (Zhou et al. 2018, Plevny 2020). Compared with traditional concrete, UHPC offers distinguishable benefits, such as shorter length of rebar embedment, accelerated construction schedule, improved durability, reduced maintenance, extended usage life, and improved resiliency (Gunes et al. 2012, Russel and Graybeal 2013).

Besides UHPC, another highly mentioned advanced material is HPS for bridges. HPS has better properties such as strength, toughness, weldability, ductility, and corrosion resistance, to allow for maximum performance of bridge structures while remaining cost-effective (Collins et al. 2019). The two main outstanding properties compared to conventional steels are improved weldability and toughness. Similar to UHPC, the advantages of HPS for bridges include longer span lengths and fewer piers, lower foundation and superstructure cost, wider beam spacing and fewer beams, fewer maintenance requirements, and longer service life (Mistry 2003). An interviewee from New Mexico DOT highlighted that existing practices have already shown that new types of HPS, which require less amount of protective coatings, have significantly reduced the maintenance cost of bridge structures.

However, when new materials are brought into the market, it often takes years for the materials to gain inclusion in the modern practices of bridge design and construction. The higher initial cost associated with these new materials become the most challenging factor that hinders the adoption of new materials in practice. This opinion was echoed by several interviewees. An interviewee from Virginia DOT provided an example of carbon fiber, which is a material that has high tensile strength, low weight, and high chemical resistance. According to the interviewee, the adoption of this material for bridges has been slow as industry-based research on developing and utilizing carbon fiber for bridges is limited, which leads to limited production and high cost. Although advanced materials that are introduced to the market have an expanded array of benefits, the high cost and the lack of skilled workforce for handling the materials are hindering the pace of adopting them for bridge construction. However, research shows that adoption of advanced materials will eventually decrease the life cycle costs of bridges (Dong 2018, Yang et al. 2020).

4.2.1.2 New Transportation Facilities or Methods

Approximately 90% (19 out of 21) of the interviewees agreed to the significant impacts of new transportation facilities and methods on the future of bridges. Over the last three decades, the transportation industry is excelling in the development of new transportation facilities, such as connected and automated vehicles (CAVs), shared mobility, and hyperloop, etc (Chan 2017, Robinson 2020). Several studies (e.g., Duarte and Ratti 2018) highlighted that it is uncertain whether technological advancements in transportation methods will lead to an increase or decrease in road traffic, which eventually affect the design and rehabilitation of bridge infrastructure. Understanding this trend is critical to determine whether the current bridge infrastructure can sustain the ever-changing transportation demand.

During the interviews, the interviewees mostly discussed about the potential impacts of CAVs on the future of bridges. Although the majority of the interviewees agreed that CAVs will bring significant changes in future bridge design standards, "it is difficult to determine what the changes are going to be in the future", as mentioned by an interviewee from Arizona DOT. On one hand, CAVs, which feature a high level of automation with lower human error rates, could potentially increase safety, efficiency, and convenience in travel and decrease traffic congestions, thus bringing a positive mitigation in transportation infrastructure (Kutgun et al. 2018, Anderson et al. 2014). CAVs' artificial intelligence-based navigation systems are expected to enable driving through narrower traffic lanes and eventually reduce the number of lanes needed for traffic (Kockelman et al. 2017). On the other hand, CAVs create opportunities for platooning of heavy freight vehicles, which could significantly change the loading on long-span bridges. Reevaluating and updating the load model in the design standards of bridge structures are needed to accommodate the drive of CAVs on the future bridges (CATAPULT 2017).

Besides CAVs, other recently proposed and/or developed transportation facilities, such as Hyperloops and Maglev trains, may also bring significant impacts to future bridges. Hyperloop is a new form of transportation method that allows passengers to travel at over 700 mph in floating pod inside giant low-pressure tubes, usually below ground (Ranger 2019). The thermal expansion of supporting steel bridges for Hyperloop tube causes the tube to physically change its size. There is, thus, a need for more efficient thermal expansion joints that allow the bridges to expand and shrink without compromising the structural integrity (Alexander and Kashani 2018). Maglev train is a system of train transportation that travels at a high speed (around 200 to 400 mph) by using two sets of magnets where one set of magnet is used to repel and push the train up off the track, and another set is used to move the elevated train ahead – to reduce the friction. Compared to traditional wheel/rail trains, Maglev trains may lead to significant differences between the coupling vibration mechanism of the trains and bridges, calling for structural design changes of the bridges (Wang et al. 2020, Li et al. 2018).

4.2.2 Environmental Factor

4.2.2.1 Climate Change

Among the six environmental factors, climate change (with emphasis on temperature and precipitation change) was considered as the most critical impacting factor by the experts; it was emphasized or mentioned by 81% (17 out of 21) of the interviewees. Climate change has multifaceted impacts on the design, construction, and maintenance of bridges. Accounting for all these possible impacts is a prerequisite for ascertaining risks and developing hazard mitigation strategies for bridges. Extensive studies (e.g., Mondoro et al. 2017, Volosciuk et al. 2016, Ishida et al. 2018) have been conducted to analyze the trends of climate change, and it is likely that climate change will increase global average temperature, alter extreme temperatures in different regions of the world, and change the precipitation rates and patterns as well as the relative humidity (Meyer et al. 2014). In the U.S., the annual average temperature of the contiguous 48 states is projected to rise throughout the century. It is projected that the average temperature will rise up to 2.5°F (1.4°C) to 2.9°F (1.6°C) in the next 30 years (Wuebbles et al. 2017). The total annual precipitation has also increased due to climate change. Since 1901, the precipitation has increased at an average rate of 0.08 inches per decade over the contiguous U.S. However, shifting weather patterns could cause certain regions, such as the Southwest region, to experience less precipitation than usual (U.S. EPA 2020).

During the interviews, the interviewees expressed their concerns about the adverse impacts of both the higher temperatures and increased precipitation caused by climate change. For example, a bridge engineer from Wisconsin DOT explained that the bridges that were built 20 to 30 years ago with the projection of 50 to 60 years of service life might have to be replaced sooner due to the impacts from climate change. Studies have found that, due to climate change, the structural elements of a bridge have higher chances of being damaged through corrosion (Kallias and Imam 2013). The rising temperatures will accelerate the corrosion rates. The increase in CO_2 levels which is associated with global warming will also increase the likelihood of carbonation-induced corrosion. Carbonation is one of the major physiochemical processes caused by atmospheric CO_2 levels to concrete structures; it can deteriorate the chemical composition of concrete and impact the service life of concrete structures (Tonoli et al. 2010).

Another interviewee from Texas DOT explained that the excessive rainfall due to climate change could result in a higher flow of stream water and more frequent flooding events. This could increase the scour rates to an abnormal level. Scouring is the removal of underwater sediment (e.g., sand, earth) from around the substructures of bridges (Johnson and Ayyub 1992). Many studies have shown scouring is a common triggering event for bridge failures (Cook et al. 2015, Flint et al. 2017). Failures due to scour, are particularly strong during floods, and this can eventually weaken and ultimately undermine the integrity of bridges (Warren 1993). For example, a study by Taricska (2014) indicates that around 50% of bridge failures between 2000 and 2012 in the U.S. were caused by scouring.

4.2.2.2 Sea Level Rise

Sea level rise is considered as the second highest ranked environmental factor by the interviewees. The results of the interviews show that 76% (16 out of 21) of experts expressed their concerns about the impacts of sea level rise on future bridges with special focus on design standards and maintenance activities. The global average sea level has been rising since the start of the 20th century; the sea level rose by 16cm to 21cm between 1990 and 2016. This trend will likely to accelerate as a study shows that the global average sea level is expected to rise by 9cm to 18 cm by 2030 compared to the year 2000 (Wuebbles et al. 2017), which is a trend of roughly 30 cm per century. The acceleration is mainly caused by two human-induced global warming factors: (1)

increased volume of sea with thermal expansion of water in higher ocean temperatures, and (2) increased mass of water from the melting of mountain glaciers (Lindsey 2020).

Sea level rise has been posing major threats to low-lying coastal communities including bridges in these communities. According to an interviewee from the Delaware DOT, the old bridges which were built before 1980s and are located over coastal streams need to be replaced within 35 to 50 years. This is due to rising water levels in coastal streams during tidal activities. Because of the rising water levels, old bridges will be left with less than required clearance underneath the decks, where salt water could cause severe corrosion in bridge bearings and compromise the structural integrity of these bridges (Gao and Wang 2017). Sea level rise even threatens some of the newly constructed bridges. An example provided by an interviewee is the San Francisco-Oakland Bay Bridge, which is a complex of bridges spanning across San Francisco Bay in California. The new eastern span of the bridge opened in 2013, and it cost $6.4 billion and took nearly six years to build. However, after less than two years of its opening, a report by the Metropolitan Transportation Commission (MTC 2014) finds that sea level rise will probably inundate several parts of the new span of the Bay Bridge permanently, and additional construction projects to protect the bridge will cost another $17 million. In the interviews, the experts highlighted the importance of accounting for rising sea levels and climate science in all infrastructure planning processes, and they agreed that, the rising water levels will eventually bring changes to the design standards of future bridges, especially for the coastal communities.

In addition, combined with the effects of increased precipitation, sea level rise further exacerbates the impacts of flooding events and increases the scour rates of bridges, causing structural safety concerns of the structures. Besides these impacts, rising sea levels pose a major threat to the corrosion of prestressed concrete members of reinforced concrete bridges in two ways. First, it may cause corrosion of steel fibers in prestressed members. For example, a study in Japan found that the minimum cover depth for concrete members (70 mm) currently used in coastal bridges of Japan is insufficient in preventing the corrosion of steel fiber in prestressed members (Li et. al. 2001). Second, the joints of precast members in bridges will face corrosion due to salt ingress in the joints caused by rising sea levels and infiltration of sea water in coastal streams (Nasr et al. 2019). Salt ingress occurs when there are pathways leading to the interior of the bridge structures due to improperly designed and maintained joints and drainage systems.

4.2.3 Social Factors

4.2.3.1 Changes in Labor Market

Change in the labor market was identified as one of the most impactful social factors by the experts, and 90% (19 out of 21) of experts discussed about the effects and challenges that changing labor market may pose on bridges in the future. Over the last few decades, labor shortage in the infrastructure and construction sector has evolved as an important societal challenge (Cilia 2019). In the aftermath of the 2008 recession, an estimated 600,000 workers switched their careers away from the construction sector (Kalleberg and Von Watcher 2017). Labor shortage is partially caused by the overall career perceptions of construction and/or civil engineering-related careers as these careers are commonly linked with requiring manual efforts, outdoor activities, and lower wages (Ellis 2020). The aging and retiring of the existing workforce further exacerbate the severity of skilled labor shortage. According to the Bureau of Labor Statistics, about 32% of construction laborers were between 45-64 years old in 2019 (U.S.BLS 2020a).

During the interviews, the experts believed that lack of labor, especially the skilled ones, will negatively impact bridge construction and maintenance in the future. Labor shortage may pose major threats to long-term economic viability and bridge construction project performance. A scarcity of skilled labors can substantially affect bridge construction productivity, resulting a prolonged schedule to achieve project targets (Karimi et al., 2018). Moreover, labor shortages lead to poor quality of project performance and higher cost (Karimi et al. 2018), which are also impacted by the increase in the expenses on recruitment, training, and retaining the labor force in the construction industry (Han et al. 2008). In addition, with the advancement in the bridge construction methods, techniques, and materials, some interviewees called for a higher level of education and training for existing construction workers, field supervisors, and inspectors. The experts anticipate that if this shortage is not addressed soon, the productivity, safety, and cost of construction and maintenance works on bridges will be severely affected. A bridge engineer from Virginia DOT shared his/her observation of an apparently imminent labor shortage in ongoing maintenance works of bridges, which results in higher labor cost and longer time to complete the projects.

Labor shortage could also interplay with certain technological factors to affect bridges in the future. Some interviewees voiced their concerns about the lack of skilled engineers and experienced contractors in adopting new construction techniques in practice. Although there are emerging construction techniques, such as accelerated bridge construction and prefabricated bridge construction, there is currently a lack of engineers who have the relevant knowledge and experience. As a result, the reluctance in adopting these new techniques partially comes from the lack of capable personnel.

4.2.3.2 Changes in Safety Requirements

The change in safety requirements and preferences of safety precautions have been considered as a positive impacting factor on the future of bridges by 48% (10 out of 21) of interviewees. Approximately 2,000 fatal vehicle crashes occur in the construction work zones, and 44% of bridge construction worker injuries involve crashes with a vehicle traveling through a work zone and 67% of these injuries are fatal injuries (FHWA 2020). Thus, safety has always been identified as a “transportation social impact indicator” (Haghshenas et al., 2015); previous studies revealed that safety weigh over other societal desire and priorities and has a major impact on infrastructure-related activities and decisions (Haghshenas et al., 2015). Additionally, improvement of occupational safety and health is of the utmost importance to the construction industry and the prevention of serious incidents and fatalities has been at the forefront of project planning (Hallowell 2010).

During the interviews, the interviewees highlighted that there is a trend of implementing more stringent policies on traffic safety and work zone safety in construction and maintenance works along with utilizing more effective methods or tools to increase safety. In the interview, a construction engineer from Washington County Highway Department explained that, along with the advancement on construction techniques, the legislations and policies on transportation safety have become more stringent, and the methods to ensure public safety are becoming more effective. An example he/she provided is that offering additional lanes for emergency response has now become part of the design standards for new transportation infrastructure (e.g., highways and highway bridges); it allows emergency vehicles to travel without taking detours or reducing speeds due to traffic. Other measures, such as the implementation of traffic calming process for reducing vehicle speeds and the use of portable traffic signals, are also being increasingly adopted during bridge construction. Additionally, new construction techniques, such as accelerated bridge construction, can reduce the exposure to work zone crashes and increase safety for both construction workers and traveling public by limiting the duration of traffic impacts, as emphasized by a senior supervising engineer from Virginia DOT.

Despite increasingly stringent safety policies and tremendous efforts made by different stakeholders (e.g., OSHA, policymakers, contractors) on improving safety, injury and fatality rates in the construction industry have plateaued over the last 5 years (LHSFNA 2020). Therefore, as highlighted by several interviewees, safety remains “a key challenge” in bridge construction and more research is needed to continuously improve safety in infrastructure construction and operation.

4.2.4 Economic Factors

4.2.4.1 Public-Private Partnership (P3) Trend

Approximately 86% (18 out of 21) of the interviewees discussed about P3 as one of the new funding sources for bridge projects. P3 is a cooperative arrangement that is formed between two or more public and private-sector partners. Through the P3, a government agency typically contracts with one or more private partners to renovate, construct, operate, maintain, and/or manage a bridge (AGCA 2020, Mallett 2017). The growing demand for modernization of infrastructure asset management and the constraints on public resources have led to calls for more private-sector involvement in bridge infrastructure through P3 (Kirk and Mallet 2013).

In the interviews, several interviewees considered P3 to be one of the most likely economic trends for the bridge infrastructure; they explained that P3 projects are gaining popularity among government agencies and the general public as it offers several benefits, such as enabling more efficient and easy financing for projects by pooling funds from multiple sources, reducing the demand on existing public funds, transferring the risks from taxpayers to the private sectors, accelerating project schedule, and facilitating on-time delivery. P3 often encourages the private partners to come up with innovative and improved methods to meet project requirements. An interviewee from Pennsylvania DOT pointed out that they managed to bundle the replacement of 558 structurally deficient bridges in a P3 agreement, which took advantages of standardized bridge designs and mass prefabrication of bridge components, resulting in significant time and cost savings to taxpayers. In addition, an interviewee from Washington State DOT highlighted, besides the widely known benefits of P3, one hidden benefit of adopting P3 is that it can potentially increase project quality and reduce maintenance needs by appointing and engaging the same private partners in both construction and future operation and maintenance. This would motivate the private partners to manage and deliver high-quality projects, and eventually lead to high life-cycle value of the projects.

However, there are some disadvantages of P3, such as private partners claiming compensation for risks identified by them. This may lead to overcompensation, limited competition among private partners, and heavy dependency of government agencies on private partners. Some interviewees also explained that P3 is only suitable for certain types of bridge projects. For example, an interviewee from Indiana DOT mentioned that, P3 is generally used for large bridge projects with higher expected average daily traffic or bridge projects that are located in the urban transportation network. This may become one major limitation of adopting P3 in practice. The expert also pointed out that more research on P3 modeling is needed to identify new models that are suitable for rural bridge projects.

4.2.4.2 Change in Fuel Prices

Approximately 65 % (13 out of 21) of the experts emphasized that change in fuel prices can potentially affect the future of bridges through its impact on gas taxes, travel demand, and construction cost. According to the latest information from Energy Information Administration (EIA) (U.S.EIA 2020), the national average retail fuel price has decreased for an average of $0.46/gallon compared to its price from a year ago. Such drastic fall in fuel prices was last observed in the recession of 2008 in the U.S. (Baffes et al. 2015). The downward trend of fuel prices may be caused by multiple factors, including global COVID-19 pandemic, global trade wars, political tensions in crude oil producing countries, and on-going warfare in the Middle East (U.S.BLS 2020b).

The change in fuel prices mainly affects the construction and maintenance of bridges through gas taxes, which is one of the major funding sources for transportation infrastructure projects. According to the interviewees, gas taxes collected from the fuel sale and consumption are the major source of Highway Trust Fund, which finances construction and maintenance of bridges. With fixed rate since 1993 and rising construction cost, the purchase power of gas taxes had severely declined even before reduced travel demand during the COVID-19 pandemic. As the increasing need of modernizing aging bridges has placed greater strains on the funds, Highway Trust Fund has been on the brink of insolvency for twelve years, and the amount of other new federal assistance funds remain unclear (Mcnichol 2019). This leaves a large uncertainty on the available funds that can be used for maintaining existing structurally deficient bridges and/or constructing new ones. Second, fuel prices can potentially affect the design of bridges through its impact on people's travel behaviors and overall travel demand. An interviewee from Iowa DOT discussed that, fuel prices may have a lasting impact on both the travel behaviors of commuters and freight demand, which significantly affect the traffic loading on bridge structures. From a long-term perspective, this could affect the modes of transportation and the development of transportation infrastructure. For example, the drop of fuel prices has the potential to benefit trucking companies; it reduces the operation cost of trucking companies and allows trucking to be more competitive compared to other freight transportation methods (e.g., rail) (Tipping et al. 2015). This may potentially lead to change in freight demand in the long run. Third, fuel prices may affect the construction operation and cost for bridge projects as the transportation cost of moving construction materials and other necessary supplies to construction sites is one of the major components of construction cost (Mineer 2015). Additionally, the purchase and use of construction equipment can be affected by fuel prices as making investments in new equipment requires the estimation of fuel cost and the potential value of equipment in the future (Mineer 2015).

4.3 Systematic Evaluation of Critical Impacting Factors

The analysis of the survey results aimed at addressing the following research questions:

(1) What are the rankings of the critical impacting factors based on their likelihood of impacts on bridges in the future?

(2) What are the future trends of the critical impacting factors based on the participants' opinions?

(3) What are the factors that are most impactful and most likely to happen?

(4) Do different groups of experts have different opinions based on their (a) job positions, (b) years of experience, (c) regions of operation?

4.3.1 Likelihoods of Impacts of Critical Impacting Factors

The CIFs were ranked based on the mean index of impact ratings provided by the respondents. Table 4 shows the mean impact rating and the ranking of CIFs based on the mean index of impact ratings.

Table 4: Ranking of CIFs based on Mean Indexing of Impact Ratings.

Numbering	**Name of Factors**	**Impact Rating**	**Ranking by Impact Rating**
F1	New transportation facilities or methods	3.36	11
F2	Interference between human and traffic	3.41	9
F3	Adoption of new construction materials or structures	3.74	4
F4	Adoption of new construction techniques	3.71	5
F5	Advancement in structural health monitoring techniques	3.49	6
F6	Change in ways of management and communication	3.44	7
F7.1	Change in temperature	2.95	22
F7.2	Change in relative humidity	2.55	29
F7.3	Change in precipitation	3.44	7
F8	Sea level rise	3.32	14
F9	Change in intensity and frequency of extreme events	3.81	3
F10	Change in air quality	2.32	30
F11	Change in soil quality	2.58	28
F12	Change in water quality	2.71	24
F13	Change in demographic features	3.20	17
F14	Change in socioeconomic status	2.64	26
F15	Change in aesthetic preferences	2.66	25
F16	Change in land use patterns	3.31	15
F17	Change in legislation and policies	3.43	8
F18	Change in risk tolerance	3.14	18
F19	Change in labor market	3.34	12
F20	Change in perceptions on careers	2.85	23
F21	Education on new technical knowledge	3.33	13
F22	Economic growth	3.25	16
F23	Change in fuel price	3.02	20
F24	E-commerce growth	2.98	21
F25	Change in road pricing	3.10	19
F26	Globalization and trade war	2.59	27
F27	Availability of funding	4.21	1
F28	Public-private partnership trend	3.31	15
F29	Change in construction cost	3.90	2
F30	Change in taxation	3.37	10

As per Table 4, the respondents attached the highest importance to "Availability of Funding (F27)". Research shows that, availability of funding is one of the most critical factors that may impact transportation infrastructure project delivery. In the United States, bridges are typically funded by Federal-Aid Highway Program (FAHP), taxes and fees which include general taxes (sales or income taxes not designated for specific purpose), taxes designated for infrastructure (e.g. motor fuel taxes), tolls collected at expressways and bridges, and private investors from P3 type projects (Mcnichol 2019). As the major source of federal investment on bridges, highway trust fund has been on the brink of insolvency for twelve years, which creates a lot of uncertainties for state and local government to finance the needed bridge projects (Mcnichol 2019). This can complicate long-term planning for new bridge and delay the repair and rehabilitation of critical existing bridges. Moreover, COVID-19 has left significant impact on transportation infrastructure construction and maintenance. There is a shortage of budget due to states allocating more funds to healthcare and prevention against COVID-19. In addition, the mandatory shutdown has caused drastic decrease in the number of vehicles on roads and bridges and as a result states are collecting less gas tax and tolls (U.S. Bridge 2021). A report produced by American Road and Transportation Builders Association (ARTBA) using data from July 2020 states that, 14 states announced project delays or cancellations and in at least 39 states, transportation authorities and local governments have publicly projected declining revenues. In that report, it is estimated that, years of budget deficiency and the sudden impact of COVID-19 has resulted in revenue declines, budget cuts and diverted funds of $30.34 billion approximately (Black 2020).

"Change in Construction Cost (F29)" has the second highest average impact rating. According to the bridge design manual of Wisconsin DOT (WisDOT 2021), the construction cost of bridges depends on the type of bridge structures, project locations, project sizes, foundation requirements, and sequencing of projects. The National Highway Construction Cost Index 2.0 developed by FHWA (FHWA 2017) shows that, the construction cost of transportation infrastructure almost doubled in 2019 compared to the cost in 2003. Research (e.g., Rahman et al. 2013, Wang et al. 2021) shows that, in recent years, the changes in construction costs are mostly caused by the increase in material prices, labor costs, and shipping and logistics, and advancements on construction management methods. Furthermore, the most recent Engineering and Construction Cost Index published by IHS MarkitPEG (Zarenski 2020) shows that, material and labor costs in all sectors of the construction industry have increased due to the COVID-19 pandemic. The use of new and advanced construction materials has also impacted the overall construction costs as these materials have higher initial costs but lower life-cycle costs (Berg et al. 2006, Wang et al. 2020). On the other hand, research (e.g., Powell 2019, Hearns 2019) shows that advanced bridge construction techniques, such as slide-in bridge construction, prefabricated bridge components, and use of self-propelled modular transporter, are helping transportation agencies to reduce direct and indirect costs of bridge construction.

"Change in Intensity and Frequency of Extreme Events (F9)" has the third highest impact rating. Different types of extreme events increase the vulnerability of bridge structures. For example, extreme wind loads caused by hurricanes and tornadoes can damage bridge structures and even lower wind speeds can hamper traffic flow and maintenance work (Rowan et al. 2013). Excessive rainfalls can increase the speed and volume of stream flows, causing scouring around bridge foundations.

"Adoption of New Construction Materials or Structures (F4)" and "Adoption of New Construction Techniques (F5)" are the following factors that have significant impacts on design and construction of bridges.

4.3.2 Potential Trends of Critical Impacting Factors

All the CIFs were also ranked based on the mean index of trend ratings provided by the respondents. Table 5 shows the average trend ratings and the ranking of CIFs based on the mean index of trend ratings.

Table 5: Ranking of CIFs based on Mean Indexing of Trend Ratings

Numbering	Name of Factors	Trend Rating	Ranking by Trend Rating
F1	New transportation facilities or methods	0.93	4
F2	Interference between human and traffic	0.94	3
F3	Adoption of new construction materials or structures	0.95	2
F4	Adoption of new construction techniques	0.94	3
F5	Advancement in structural health monitoring techniques	0.89	8
F6	Change in ways of management and communication	0.96	1
F7.1	Change in temperature	0.94	3
F7.2	Change in relative humidity	0.87	10
F7.3	Change in precipitation	0.89	8
F8	Sea level rise	0.90	7
F9	Change in intensity and frequency of extreme events	0.91	6
F10	Change in air quality	0.56	19
F11	Change in soil quality	0.55	20
F12	Change in water quality	0.46	22
F13	Change in demographic features	0.83	12
F14	Change in socioeconomic status	0.61	17
F15	Change in aesthetic preferences	0.67	16
F16	Change in land use patterns	0.81	13
F17	Change in legislation and policies	0.87	10
F18	Change in risk tolerance	0.85	11
F19	Change in labor market	0.83	12
F20	Change in perceptions on careers	0.46	23
F21	Education on new technical knowledge	0.93	4
F22	Economic growth	0.53	21
F23	Change in fuel price	(-) 0.09	25
F24	E-commerce growth	0.88	9
F25	Change in road pricing	0.85	11
F26	Globalization and trade war	0.69	15
F27	Availability of funding	0.57	18
F28	Public-private partnership trend	0.77	14
F29	Change in construction cost	0.92	5
F30	Change in taxation	0.38	24

As per Table 5, “Change in Ways of Management and Communication (F6)” has the highest mean trend rating among all the CIFs. The adoption of new digital technologies, such as

Bridge Information Modeling (BrIM), cloud-based management software or tools (e.g., Procore, Penta), and digital supply chain management platforms (e.g., Oracle Supply Chain Management, Infor Supply Chain Management, is growing in the bridge/infrastructure sector, and these new technologies may change the way future projects are delivered. This result is consistent with a number of recent studies. For example, according to Xu and Turkan (2019), BrIM is currently revolutionizing bridge design and inspection sector. The move towards constructible BrIM will hold even greater importance as the stakeholders of bridge of design, construction and operation are embracing its use and DOTs are promoting it for all future bridge projects (Northcutt 2019). "Adoption of New Construction Materials or Structures (F3)" has the second highest mean trend rating. There is a rise of the demand for high-performance construction materials and/or structures (FHWA 2020). New construction materials such as UHPC, HPS, fiber-reinforced polymer (FRP), and elastomeric bridge bearing are becoming popular in bridge construction (Zhou et al. 2018, Plevny 2020, Collins et al. 2019, Zou et al. 2020, LaFave et al. 2013).

Table 5 also shows that, the factors of "Interference between Human and Traffic (F2)", "Adoption of New Construction Techniques (F4)", and "Change in temperature (F7.1)" have the same trend rating, and they are tied as the third highest factors based on trend ratings. Increasing labor shortages and rising construction costs are challenging the industry to innovate advanced technologies and new ideas for bridge construction and these advanced technologies are usually popular for having higher strength and ductility, greater durability and flexibility, and reduced margin for error and waste (Zitzman 2021). The implementation of accelerated bridge construction, self-propelled modular transporters (SPMTs) in bridge construction, modular and prefabricated construction for bridge components are increasing (Lomax and Duffy 2013). According to the survey results, it is observed among the 10 highest ranked factors based on trend ratings, six of them are technological CIFs. This result coincides with several studies (e.g., Lomax and Duffy

2013, Stocking 2017) that shows a rise in usage of different new technologies in bridge design and construction.

In contrast, the survey results show that "Change in Fuel Price (F23)" is the only factor that shows a negative mean trend rating. This result implies that the majority of respondents expect the trend on fuel price change to reverse in the near future. Although it is difficult to determine or predict the trend of fuel prices in the future, some recent reports show that the fuel price has started to rise as of January 2021, and it may rise at a steady pace in the near future (Kumar and Hiller 2021).

4.3.3 Uncertainty of Trends of Critical Impacting Factors

Table 6 shows the ranking of CIFs based on the percentage of uncertainty ratings. This result analysis shows that how unpredictable or uncertain the trends of the CIFs are, according to the survey respondents. It demonstrates that, even though these factors are critical they may have fluctuations and uncertainty in their future trends.

Table 6: Ranking of CIFs based on Uncertainty Ratings

Numbering	Name of Factors	Uncertainty of Trend (%)	Ranking by Uncertainty of Trend
F1	New transportation facilities or methods	9.26	21
F2	Interference between human and traffic	12.04	20
F3	Adoption of new construction materials or structures	3.70	25
F4	Adoption of new construction techniques	6.48	23
F5	Advancement in structural health monitoring techniques	5.56	24
F6	Change in ways of management and communication	7.41	22
F7.1	Change in temperature	19.44	13
F7.2	Change in relative humidity	34.26	6
F7.3	Change in precipitation	32.41	7
F8	Sea level rise	17.59	15
F9	Change in intensity and frequency of extreme events	20.37	12
F10	Change in air quality	17.59	15
F11	Change in soil quality	32.41	7
F12	Change in water quality	25.93	11
F13	Change in demographic features	14.81	17
F14	Change in socioeconomic status	31.48	8
F15	Change in aesthetic preferences	44.44	3
F16	Change in land use patterns	18.52	14
F17	Change in legislation and policies	29.63	9
F18	Change in risk tolerance	19.44	13
F19	Change in labor market	27.78	10
F20	Change in perceptions on careers	31.48	8
F21	Education on new technical knowledge	12.96	19
F22	Economic growth	35.19	5
F23	Change in fuel price	46.30	2
F24	E-commerce growth	14.81	17
F25	Change in road pricing	15.74	16
F26	Globalization and trade war	43.52	4
F27	Availability of funding	43.52	4
F28	Public-private partnership trend	32.41	7
F29	Change in construction cost	13.89	18
F30	Change in taxation	49.07	1

The results show that, “Change in Taxation (F30)” has the highest percentage of uncertainty ratings. Recent reports (e.g., Patent 2020, Slowey 2020) show that uncertainties and fluctuations in taxes in the construction industry are likely to happen in the upcoming years. In 2017, the Tax Cut and Job Act (TCJA) was implemented, which benefitted the construction industry by lowering the tax rates, increasing threshold of postponing taxation, deductions for business assets (e.g., new construction equipment), and setting opportunities for alternative minimum tax (Cotney 2018). However, tax policies are subject to change for a number of reasons such as development of economy, shift of administration, and etc. The CIF with the second highest percentage of uncertainty is “Change in Fuel Price (F23)”. It is a well-established fact that fuel prices have frequent fluctuations, and it is a nearly volatile market (Lioudis 2021, Barnett and Barron 2020). It is observed that, CIFs with higher percentage of uncertainty ratings tend to have lower mean trend ratings, which further confirms that the trend of these CIFs are uncertain as they received varying responses from the survey participants.

Collectively, it is observed that technological factors have lower percentages of uncertainty ratings, and economic factors have higher percentages of uncertainty ratings. The high uncertainty on economic factors may be partially due to the COVID-19 pandemic, as the COVID-19 pandemic has largely increased the volatility and uncertainty of global economy (Sanghai 2020) . For example, the COVID-19 pandemic has increased the uncertainty of construction budget and funding availability. It has reduced the traffic flow on roads and bridges, which caused a huge plunge in funds from gas tax. In addition, due to lockdowns in most of the countries around the world, there was disruption in global shipping and distribution, which caused a shortage of construction materials in certain places of the world (Phillips 2020). This shortage caused the prices of construction materials to increase. Researchers are expecting that this crisis will continue throughout 2021 (Phillips 2020, DBSG 2021).

4.3.4 Most Impactful and Trending Factors

Among the 32 CIFs, some factors have higher impact ratings and trend ratings. This means these factors have higher impact on different aspects of bridge and they have higher possibility of having a continuous trend in the future. The most impactful and trending factors among the 32 CIFs were identified through a factor index. This index was calculated by multiplying mean impact rating of a CIF by its mean trend rating. Table 7 shows the Factor Index and the ranking of CIFs based on it.

The factor index accounts for both the impact rating and the trend rating. This result analysis identifies which of the CIFs have higher impacts on bridges as well as higher possibility of continuing the trends. It, thus offers a better understanding on the importance of these factors for bridges. It can be observed that, some factors that have higher impact rating may have lower trend rating with higher rates of uncertainty. For example, “Availability of Funding (F27)” has the highest impact rating, but it has a lower factor index and is only ranked as the 20th factor based on the factor index. This is due to its lower trend rating and higher uncertainty. Factor index can be used to prioritize those factors based on their index values when considering the impacts of these factors on bridges.

Table 7: Ranking of CIFs by Factor Index

Numbering	Name of Factors	Factor Index (Impact x Trend)	Ranking by Factor Index
F1	New transportation facilities or methods	3.12	7
F2	Interference between human and traffic	3.19	6
F3	Adoption of new construction materials or structures	3.56	2
F4	Adoption of new construction techniques	3.49	3
F5	Advancement in structural health monitoring techniques	3.11	8
F6	Change in ways of management and communication	3.31	5
F7.1	Change in temperature	2.78	14
F7.2	Change in relative humidity	2.22	21
F7.3	Change in precipitation	3.06	10
F8	Sea level rise	2.99	11
F9	Change in intensity and frequency of extreme events	3.46	4
F10	Change in air quality	1.31	28
F11	Change in soil quality	1.42	26
F12	Change in water quality	1.25	30
F13	Change in demographic features	2.65	16
F14	Change in socioeconomic status	1.60	25
F15	Change in aesthetic preferences	1.77	23
F16	Change in land use patterns	2.67	15
F17	Change in legislation and policies	2.98	12
F18	Change in risk tolerance	2.67	15
F19	Change in labor market	2.79	13
F20	Change in perceptions on careers	1.31	27
F21	Education on new technical knowledge	3.09	9
F22	Economic growth	1.72	24
F23	Change in fuel price	(-) 0.27	31
F24	E-commerce growth	2.63	17
F25	Change in road pricing	2.62	18
F26	Globalization and trade war	1.79	22
F27	Availability of funding	2.42	20
F28	Public-private partnership trend	2.54	19
F29	Change in construction cost	3.60	1
F30	Change in taxation	1.29	29

According to the results shown in Table 7, “Change in Construction Cost (F29)” is the highest ranked factor based on factor index, followed by “Adoption of New Construction Materials or Structures (F3)”, “Adoption of New Construction Techniques (F4)”, “Change in Intensity and Frequency of Extreme Events (F9)”, and “Change in Ways of Management and Communication (F6)”. In bridge construction, the costs associated with the materials and labor for the structures in a bridge is the predominant part (approx. 90%) (Mladjov 2016). Changes in construction cost due to changes in cost of materials and labor affect time and quality of construction. It is important to maintain cost, time, and quality of construction of transportation infrastructure as it has significant impact on national economy (Mladjov 2016).

“Adoption of New Construction Materials or Structures (F3)” and “Adoption of New Construction Techniques (F4)” have the second and third highest ratings based on Factor Index, respectively. Researchers are continuously working to find more advanced and efficient construction materials and techniques for sustainable bridge construction which will reduce the life-cycle costs of bridge structures. Among the top 5 CIFs according to the Factor Index, 3 of them are technological factors. It can be assumed that advancements in construction materials, techniques and management are significantly important to practitioners and academic researchers. Although traditional construction materials have the disadvantages of lower initial costs and consumer reliability, studies by Long et al. (2008) and Kumar and Kumar (2016) show that innovative construction materials can lower the life cycle costs and improve sustainability compared to traditional materials.

“Change in Intensity and Frequency of Extreme Events (F9)” has the fourth highest ratings in factor index. According to a recent report (McClean 2020), there has been a staggering rise in the number of extreme weather events over the past 20 years. Researchers have found out that rising global temperatures and other climatic changes are responsible for this drastic increase. Climate-related disasters jumped 83 percent in 2000-2019 period when compared with 1980-1999 period (Gardiner 2020). From 2000 to 2019, there were 7,348 major natural disasters around the world. The death toll from these disasters is 1.23 million people and the economic losses are $2.97 trillion globally (Gardiner 2020). Bridges are more prone to extreme events, such as hurricanes, flooding, extremely high temperatures (Meyer et al. 2014). These extreme events can have individual or combined effects on bridges. For example, hurricanes can damage bridge cables and road beds;

extreme temperatures can cause thermal expansion of joints in superstructures; and frequent flooding events can cause scouring at substructures of bridges (Meyer et al. 2014).

4.3.5 Differences in Expert Opinions on the Likelihoods of Impacts

Kruskal-Wallis H tests and Mann-Whitney U tests were conducted to investigate if there are any differences in opinions of various groups of experts. Following Kruskal-Wallis H tests, pairwise comparisons were conducted to further identify which two groups are significantly different from one another (Salkind 2010). Impact rating data of the CIFs are used to find out whether a group of participants rated the impacts of the CIFs which are significantly different when compared to corresponding groups. Table 8 shows the list of groups based on job positions, years of experience, and regions. Table 9 shows the p-values obtained from the Kruskal-Wallis H test.

Table 8: List of Groups

Groups based on Job Position	
G1	Design Engineers
G2	Construction and Maintenance Engineers
G3	Academic Researchers
Groups based on Years of Experience	
E1	1 to 10 years
E2	11 to 20 years
E3	21 to 30 years
E4	More than 30 years
Groups based on Regions	
R1	Coastal States
R2	Inland States

Table 9: P-values from Kruskal-Wallis H Test and Mann-Whitney U Test

Numbering	Name of Factors	G1 vs. G2 vs. G3[a]	E1 vs. E2 vs. E3 vs. E4[a]	R1 vs. R2[b]
F1	New transportation facilities or methods	**0.009**[c]	0.306	0.653
F2	Interference between human and traffic	0.059	0.248	0.790
F3	Adoption of new construction materials or structures	0.258	0.896	0.883
F4	Adoption of new construction techniques	0.229	0.931	0.351
F5	Advancement in structural health monitoring techniques	**0.048**[c]	0.289	0.533
F6	Change in ways of management and communication	0.245	0.645	0.679
F7.1	Change in temperature	0.104	**0.022**[c]	0.608
F7.2	Change in relative humidity	**0.002**[c]	**0.008**[c]	0.497
F7.3	Change in precipitation	0.245	0.872	0.703
F8	Sea level rise	0.135	0.306	**0.002**[c]
F9	Change in intensity and frequency of extreme events	0.440	0.137	0.124
F10	Change in air quality	0.131	0.454	0.099
F11	Change in soil quality	**0.022**[c]	0.081	0.969
F12	Change in water quality	**0.006**[c]	**0.017**[c]	0.095
F13	Change in demographic features	0.531	0.667	0.056
F14	Change in socioeconomic status	0.595	0.484	0.061
F15	Change in aesthetic preferences	0.465	0.124	0.447
F16	Change in land use patterns	0.281	0.864	0.063
F17	Change in legislation and policies	0.880	0.174	**0.005**[c]
F18	Change in risk tolerance	0.723	0.173	0.332
F19	Change in labor market	0.706	0.445	0.255
F20	Change in perceptions on careers	0.306	0.393	0.503
F21	Education on new technical knowledge	0.178	0.331	0.110
F22	Economic growth	0.424	0.343	0.453
F23	Change in fuel price	0.925	0.634	0.793
F24	E-commerce growth	0.947	0.826	0.221
F25	Change in road pricing	0.997	0.955	0.650
F26	Globalization and trade war	0.873	0.694	0.449
F27	Availability of funding	0.658	0.751	0.455
F28	Public-private partnership trend	0.099	0.754	0.524
F29	Change in construction cost	0.779	0.955	0.695
F30	Change in taxation	0.281	0.415	0.529

[a]p-values from Kruskal-Wallis H Test; [b]p-values from Mann-Whitney U Test; [c]The p-value is significant at 0.05 level (2-tailed).

The factors with p-values less than 0.05 are the factors whose impacts ratings were rated significantly differently across various groups of participants. For example, the impact rating of "New Transportation Facilities or Methods (F1)" and "Advancement in Structural Health Monitoring Techniques (F5)" were rated significantly differently across the groups based on job positions, and "Change in Temperature (F7.1)" and "Change in Relative Humidity (F7.2)" were rated significantly differently across the groups based on years of experience. CIFs with p-values less than 0.05 are identified. Then, the mean impact rating of those identified factors across various groups are obtained from the survey results. Table 10 summarizes the mean impact rating of the CIFs with p-values less than 0.05 across various groups.

Table 10: Mean Impact Rating of CIFs across Different Groups

Numbering	**Name of Factors**	**Job Positions**			**Years of Experience**				**Regions by Coastline**	
		G1	G2	G3	E1	E2	E3	E4	R1	R2
F1	New transportation facilities or methods	3.38	2.96	3.79	-	-	-	-	-	-
F5	Advancement in structural health monitoring techniques	3.35	3.58	3.84	-	-	-	-	-	-
F7.1	Change in temperature	-	-	-	3.38	3.14	2.71	2.70	-	-
F7.2	Change in relative humidity	2.40	2.46	3.16	2.92	2.71	2.36	2.30	-	-
F8	Sea level rise	-	-	-	-	-	-	-	3.69	2.90
F11	Change in soil quality	2.45	2.50	3.16	-	-	-	-	-	-
F12	Change in water quality	2.52	2.75	3.32	3.12	2.90	2.46	2.48	-	-
F17	Change in legislation and policies	-	-	-	-	-	-	-	3.64	3.18

Note: Some cells are blank because not all groups rated the impact of CIFs significantly different. It means their p-value is 0.05 or greater.

4.3.5.1 Differences in Expert Opinions based on Job Positions

For those CIFs with p-values less than 0.05 in the Krukal-Wallis H test, pairwise comparisons were further conducted to identify which two groups of respondents based on job positions rated the factors significantly differently. Table 11 shows the p-values of pairwise comparisons across groups with different job positions.

Table 11: Pairwise Comparisons of Groups with Different Job Positions.

Numbering	**Name of Factors**	**G1 vs. G2**	**G1 vs. G3**	**G2 vs. G3**
F1	New transportation facilities or methods	0.040[c]	0.088	0.002[c]
F5	Advancement in structural health monitoring techniques	0.251	0.017[c]	0.255
F7.2	Change in relative humidity	0.717	0.000378[c]	0.006[c]
F11	Change in soil quality	0.897	0.007[c]	0.028[c]
F12	Change in water quality	0.242	0.001[c]	0.073

For “New transportation facilities or methods (F1)”, it is observed that “Construction and Maintenance Engineers (G2)” rated the impact of this factor significantly lower than the other two groups (G1, G3). Recent research (e.g., Sobanjo 2019, Sayed et al. 2020) shows that new transportation methods such as CAVs have significant impacts on bridges, mostly on the design of bridges. Therefore, academic researchers and design engineers may attach higher importance to this factor as compared to construction and maintenance engineers.

In the case of “Advancement in Structural Health Monitoring Techniques (F5)”, there is a significant difference between design engineers (G1) and academic researchers (G3). Design engineers (G1) attached a lower impact rating compared to academic researchers (G3) and construction and maintenance engineers (G2). Research in the field of structural health monitoring is exploring innovative methods of structural inspection and health monitoring techniques, such as non-destructive testing technique, and using unmanned aerial vehicles for bridge inspections (Maizuar et al. 2020, Reagan et al. 2018). Academic researchers are involved in developing and testing these advanced structural health monitoring techniques. In addition, these methods are used during maintenance of bridge structures, and maintenance engineers are involved in these operations. Therefore, construction and maintenance engineers and academic researchers may develop a better understand of advanced structural health monitoring techniques than design engineers, which lead to their higher ratings of impact.

4.3.5.2 Differences in Expert Opinions based on Years of Experience

Table 12 shows the p-values of pairwise comparison across groups with different years of experience. For “Change in Temperature (F7.1)”, participants with “1 to 10 Years of Experience (E1)” rated the impact of this factor significantly differently compared to participants with “21 to 30 Years of Experience (E3)” and participants with “More than 30 Years of Experience (E4)”. Group E1 rated the impact of F7.1 higher than the other three groups. Group E3 and E4 have rated the impact of F7.1 lower compared to E1 and E2. The results show that the rating of impact for

F7.1 is higher among participants with less years of experience compared to participants with more years of experience. Similarly, the impact rating of "Change of Relative Humidity (F7.2)" was rated significantly higher by group E1 compared to E3 and E4. In addition, group E2 attached a significantly higher impact rating of F7.2 than group E4 did. Research studies that show relative humidity is responsible for accelerating the degradation of construction materials, the loss of prestressing force in prestressed bridges, damages to adhesive or coating materials, and decreasing the compressive strength of concrete (Jiang and Yuan 2013, Nasr et al. 2020, Cadoni et al. 2001).

In general, these results imply that participants with less experience are more concerned about the impacts of environmental factors when compared to the participants with more years of experience. It is observed from the demographic information that, participants with less experience are younger, and obviously participants with more experience are older. This result is consistent with a number of studies that show, there are significant differences in perception of climate change among existing 4 generations (baby boomers, generation X, generation Y and generation Z). A study by Frumkin and Moody (2012) shows that older people (55 years or older) are less concerned about climate change due to information gap, political views, and personal beliefs. An extensive report by Reinhart (2018) shows that, approximately 70% of 18- to 34-year-old people are concerned about the impact of global warming whereas 56% of people who are 55 or older are concerned about global warming. In addition, around 75% of 18- to 34-year-old people think that global warming is caused by human activities whereas about 55% of people who are 55 or older think the same (Reinhart 2018).

Table 12: P-values of Pairwise Comparison of Groups based on Years of Experience

Numbering	**Name of Factors**	**E1 vs. E2**	**E1 vs. E3**	**E1 vs. E4**	**E2 vs. E3**	**E2 vs. E4**	**E3 vs. E4**
F7.1	Change in temperature	0.356	0.010[c]	0.008[c]	0.138	0.129	0.987
F7.2	Change in relative humidity	0.590	0.009[c]	0.005[c]	0.053	0.037[c]	0.929
F12	Change in water quality	0.600	0.009[c]	0.014[c]	0.052	0.079	0.779

4.3.5.3 Differences in Expert Opinions based on Regions

Results in Table 9 show that "Sea Level Rise (F8)" and "Change in Legislation and Policies (F17)" were rated significantly differently between respondents from "Coastal States (R1)" and respondents from "Inland States (R2)". As there are only two groups, a Mann-Whitney U test was performed. Table 10 shows that, for both factors, respondents from "Coastal States (R1)" rated the impact of these two factors higher than participants from "Inland States (R2)". This observation can be backed up by a study (Babcock 2013), which shows that the stakeholders of infrastructure in the inland or landlocked states are most likely to ignore the impacts of sea level rise and climate change. In addition, in the United States, one factor that drives the changes in legislation and policies in coastal states is environmental factor, such as climate change, sea level rise, and increasing intensity of extreme events. Twelve states in Northeast and Mid-Atlantic have formed the Transportation and Climate Initiative (TCI) which are attempting to solve climate change challenges on transportation infrastructure (Gatti 2019). TCI is focusing on implementing policies to lower vehicle emissions, encourage use of clean transportation technologies, such as electric vehicles, and upgrade transportation networks to reduce vulnerability to climate change, etc. Furthermore, there is a rising concern among the policy makers and legislatures to modernize the transportation networks in Northeast and Mid-Atlantic regions (Descant 2018, Ho 2018). For example, policy makers are pushing implementation of truck platooning laws in various states (Roberts 2019, Mele 2017). In addition, the coastal states have higher density of transportation infrastructure, according to highway statistics of 2017 provided by Federal Highway Administration (FHWA 2017). Considering the above-mentioned facts, participants from the coastal states may have observed higher impacts of changing legislation and policies than the participants from inland states.

CHAPTER 5

CONCLUSIONS

5.1 Research Summary

This thesis presents an exploratory study on identifying the critical impacting factors and analyzing how these factors may affect bridge design, construction, and operation in the future. A combination of primary and secondary research methods was employed for conducting this exploratory study. The primary research method focuses on collecting information directly from bridge-domain experts. A total of 20 interviews were conducted with 21 bridge-domain experts. In addition, a total of 108 bridge experts participated in the expert survey. The secondary research method focuses on gathering information from previously published primary research, including published literature and reports on bridges. Based on the results from both the expert interview and literature review, a total of 30 critical impacting factors were identified, and these factors were classified into four main categories, including environmental, social, economic, and technological factors. The identified factors were then included in the expert survey to systematically solicit expert opinion on the likelihood and trends of impacts. The results show that, the factors that are most likely to cause impacts are “Availability of Funding (F27)”, “Change in Construction Cost (F29)”, “Change in Intensity and Frequency of Extreme Events (F9)”, “Adoption of New Construction Materials or Structures (F3)”, and “Adoption of New Construction Techniques (F4)”. The factors whose trends are more likely to continue include “Change in Ways of Management and Communication (F6)”, “Adoption of New Construction Materials or Structures (F3)”, “Adoption of New Construction Techniques (F4)”, and “Change in Temperature (F7.1)”, while the factor that may have a reverse trend is “Change in Fuel Price (F23)”, according to the survey participants. In addition, experts who have different job positions, years of experience, or are from different regions attached significantly different impact ratings on certain factors.

5.2 Contributions to the Body of Knowledge

This research contributes to the body of knowledge on three primary levels. First, on a theoretical level, it offers a holistic and explicit understanding of the multifaceted critical impacting factors that could affect bridges in the future by identifying and explicitly defining these factors. Second, on an empirical level, the empirical knowledge obtained through interviewing and surveying experts from transportation agencies bridges the gap between a theoretical understanding of the factors with actual bridge design, construction, and operation practices, thus offering practical insights on how to better manage our bridges in a way that adapts to the impacts. Third, on a practical level, a comprehensive understanding of the critical impacting factors is important for decision makers and policymakers in the transportation agencies to introduce more proactive and timely standards, regulations, and policies that address the new challenges brought by these factors. The findings from this study may offer insights to decision makers and drive a rethinking of how to better manage our bridge assets to prepare for the technological, environmental, social, and economic changes that will likely to happen and/or cause impacts. For example, decision makers may want to prioritize actions when only limited resources are available by focusing on the factors that are more important or more likely to cause impacts. This research can also spur more dialogue and research on important practical questions: How to systematically incorporate these factors into technical considerations for the future of bridges? How to facilitate the implementation of adaptation strategies for bridge asset management in the future? How to measure the performance of bridges when adapting to the changes brought by these factors? This research together with future research in this area will eventually support and enable our bridges to be designed, constructed, and operated in a way that is more resilient and adaptive to the changes in the future.

5.3 Future Work

The study presented in this thesis may indicate several directions for future research. In this thesis, the CIFs of bridge design, construction and operation are identified, and their potential impacts are analyzed and discussed based on interviews and surveys with experts in the bridge engineering domain. Future data collection can expand the scope to invite experts from other domains of interest; these experts may offer assessments on the trends of the identified factors. For example, social scientists whose research involves transportation infrastructure can provide knowledge about the impacts of social factors on bridges. Similarly, economists can offer assessments on the impacts of economic factors on bridges. In addition, this research can be extended to include other types of data to offer more robust information about these factors and the ways they are impacting bridges. For example, real data regarding climate change and bridge performance can be collected and analyzed in an integrated manner. Advanced data analytics methods (e.g., machine learning, deep learning) can be used to predict bridge performance given impacts from these factors. Such information will be useful to provide a comprehensive list of adaptive strategies that allow bridge engineers and decision makers to account for these factors in future bridge management. The adaption strategies may include plans and schemes on how to adjust, modify, and adapt policies and standards of bridges considering the impacts of every CIF.

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