ABC-UTC GUIDE FOR:

UNDERSTANDING CRITICAL IMPACTING FACTORS AND TRENDS ON BRIDGE DESIGN, CONSTRUCTION, AND MAINTENANCE FOR FUTURE PLANNING

Start Date: October 1, 2019

End Date: April 30, 2021

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ABSTRACT

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 project focuses on identifying the factors that may affect the future of bridges and analyzing how these factors would impact the ways bridges are designed, constructed, and operated. In-depth interviews (N=21) and questionnaire surveys (N=108) were conducted with bridge experts from transportation agencies. A total of 30 factors were identified. Some highly discussed factors include “Adoption of New Construction Materials or Structures”, “New Transportation Facilities or Methods”, “Climate Change”, “Sea Level Rise”, “Changes in Labor Market”, “Changes in Safety Requirements”, “Public-Private Partnership (P3) Trend”, “Change in Fuel Prices”, and “Availability of Funding”. This research offers a holistic and explicit understanding of the multifaceted factors that could affect bridge design, construction, and operation in the future. Such understanding is important for highway officials, bridge construction, safety, design, and research engineers to introduce more proactive and timely policies and strategies that address the new challenges brought by these factors.

ACKNOWLEDGMENTS

The research study resulting in development of this Guide was supported by the US Department of Transportation through the Accelerated Bridge Construction University Transportation Center (ABC-UTC).

1. INTRODUCTION

1.1. BACKGROUND

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 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. SCOPE OF THE GUIDE

The main objective of this guide is to provide information about the critical impacting factors and how these factors may impact the way that bridges are designed, constructed, and maintained.

Section 1 of this guide offers a brief overview of this project. Section 2 summarizes the identified critical impacting factors. Section 3 presents the discussion of these factors by the bridge domain experts, who participated in the project. Section 4 offers the recommendations based on the findings from this project. Section 5 provides a summary of the project and describes the benefits of the project.

1.3. INTENDED USERS

This guide can offer useful information to highway officials, bridge construction, design, operation engineers, and academic researchers.

2. CRITICAL IMPACTING FACTORS

A total of 30 factors were identified and classified into environmental, social, economic, and technological categories (Figure 1). 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 1.

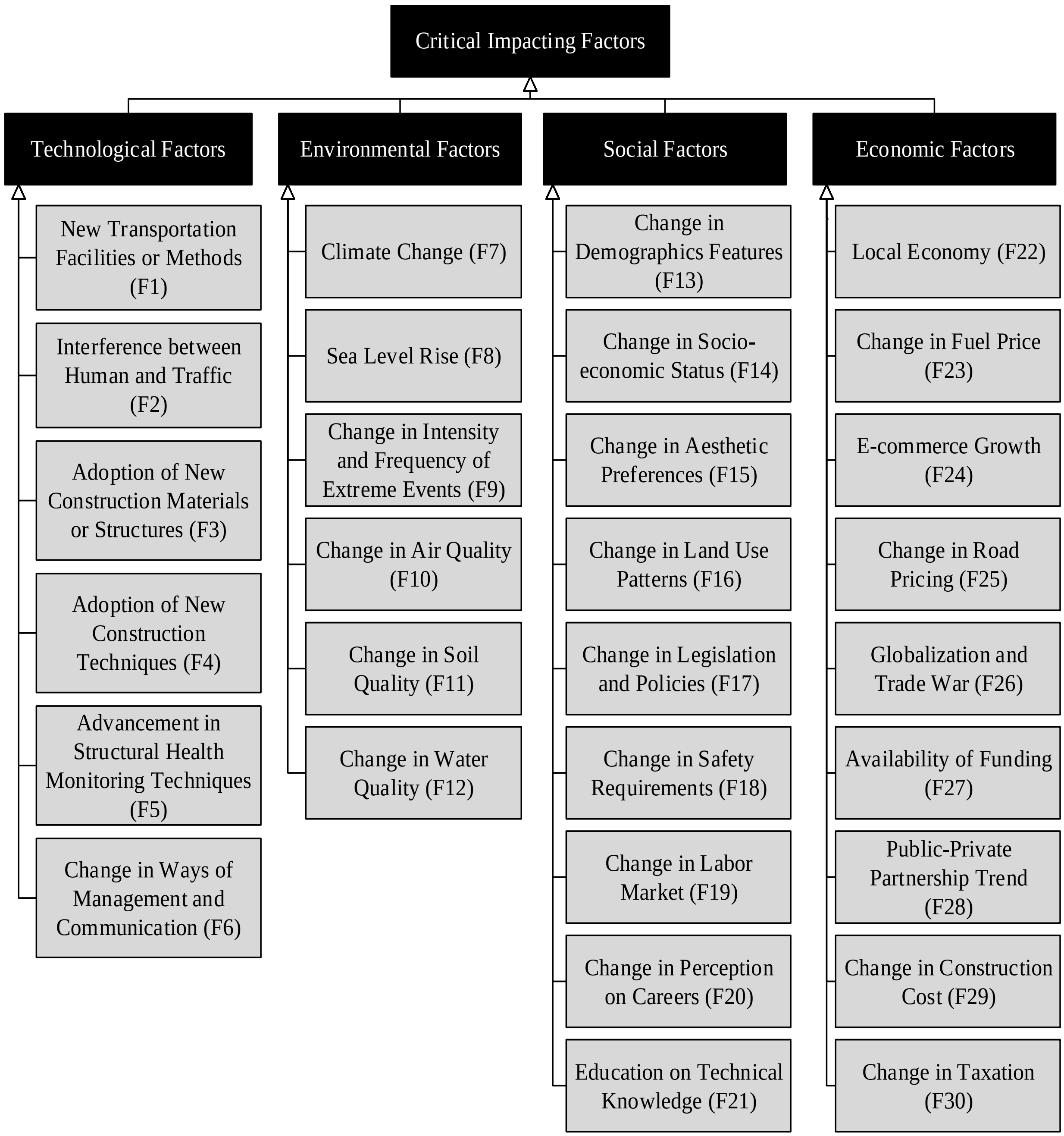

Figure 1. A hierarchy of Critical Impacting Factors

Table 1. 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 including slide-in bridge construction 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.

3. IMPORTANCE OF CRITICAL IMPACTING FACTORS

The following sections offer some discussions about the most important (highly discussed) factors.

3.1. TECHNOLOGICAL FACTORS

(1) Adoption of New Construction Materials or Structures

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 experts 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 bridge experts, these new materials could "bring major changes and opportunities" to the next generation of bridges. For example, a typical UHPC material for bridges has a design compressive strength of 29,000 pounds per inch (200 MPa) (Gunes et al. 2012) and it 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 service 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). A bridge expert 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 experts. A bridge expert 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 expert, 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).

(2) New Transportation Facilities or Methods

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 experts mostly discussed about the potential impacts of CAVs on the future of bridges. Although the majority of the experts 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 a bridge expert 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 reduce 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).

3.2. ENVIRONMENTAL FACTOR

(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. 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. 2018, 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 experts 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 expert 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.

(2) Sea Level Rise

Sea level rise is considered as the second highest ranked environmental factor by the experts. 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 a bridge expert 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 a bridge expert 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.

3.3. SOCIAL FACTORS

(1) Changes in Labor Market

Change in the labor market was identified as one of the most impactful social factors by the experts. 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 experts 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 experts 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 slide-in 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.

(2) Changes in Safety Requirements

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 experts 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 experts, safety remains “a key challenge” in bridge construction and more research is needed to continuously improve safety in infrastructure construction and operation.

3.4. ECONOMIC FACTORS

(1) Public-Private Partnership (P3) Trend

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 experts 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. A bridge expert 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, a bridge expert 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 experts also explained that P3 is only suitable for certain types of bridge projects. For example, a bridge expert 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.

(2) Change in Fuel Prices

The 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 experts, 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 bridges that are in poor conditions 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. A bridge expert 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).

(3) Availability of Funding

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).

4. RECOMMENDATIONS

As discussed in the previous sections, a variety of technological, environmental, social, and economic factors may impose considerable impacts on bridge design, construction, and operation in the future. There is, thus, a need for the transportation policymakers and decision makers to be adaptive to these impacts and be proactive to potential changes for better planning purposes. Based on the results of the interviews and literature review, some possible actions for adapting to the top-ranked technological, environmental, social, and economic factors are recommended as follows:

(1) Technological Factors

The following strategies for addressing the changes brought by the technological factors are recommended: First, although adoption of new construction materials is critical to increase the life expectance and reduce maintenance needs, the high initial cost could become a primary barrier for adoption. A “top down” approach, which requires the higher administrative-level policymakers to support industry research on new material or technique adoption, was recommended by a few experts. In addition, more research on the life-cycle cost analyses for new materials is recommended as they would offer new knowledge and evidence for demonstrating the long-term economic effectiveness of using new materials. These analyses can also be integrated into current material purchase standards to facilitate “best value” purchase. Second, the experts and researchers (e.g., Alexander and Kashani 2018, Kockelman et al. 2017) have been calling for the need of changing existing bridge design standards to accommodate and accelerate the deployment of new transportation facilities or travel methods (e.g., CAVs, hyperloops), which may require fundamental research on how these new methods could potentially affect the traffic loads, including both passenger travel and freight delivery. New load models may be integrated into the design of future bridge structures or the retrofit of existing ones. Third, for integration of any new technologies (e.g., structural health monitoring techniques, new communication or navigation tools) into the bridge sector, there is a need for multi-sector stakeholder collaboration that engages government agencies, private industries, and multi-disciplinary researchers to comprehensively facilitate the development and deployment of new technologies from both technical and policy-making perspectives.

(2) Environmental Factors

The following strategies to reduce the probability and/or consequences associated with environmental impacts on bridges are recommended: First, the existing design standards or building codes need to be constantly re-evaluated and updated to adapt bridge design and construction to the changing climate and rising sea levels. For example, the design rainfalls or design floods need to be re-evaluated on an annual basis and uncertainty parameters can be introduced for design criteria (e.g., design wave forces) that are largely impacted by the changing environmental factors. Second, the use of new materials (e.g., UHPC, HPS) or construction techniques (e.g., ABC) are recommended by the experts as they could either allow the structures to be more durable and resistant to environmental impacts or reduce the impacts of bridge construction on the environments. Third, for the existing bridges, retrofitting strategies such as using corrosion inhibitors, cathodic protection, increasing concrete thickness, or using protective surface coating and barriers (Nasr et al. 2020, Stewart et al. 2012) could potentially control the increased corrosion rates caused by several environmental factors (e.g., climate change, sea level rise). Other strategies, such as the use of anchorage bars, concrete shear tabs, and increasing continuity, can be adopted for adapting to increased scour rates (Mondoro et al. 2018). Fourth, considering the availability of multiple adaptation strategies, cost-benefit analyses, or life-cycle cost analyses are needed to better understand which strategy to implement and when to implement it (Nasr et al. 2020).

(3) Social Factors

Societal preferences can change over time and since bridges and other infrastructure are built to outlive ever-emerging societal changes, meticulous study of societal factors is critical for bridge design, construction and operation. The following recommended strategies are offered: First, uplifting the technical skill level and preserving the dignity of the existing construction workforce while enticing the best minds of future generations to pursue a career in construction are essential to avoid the current labor shortage in construction. In addition, according to several experts, introducing new technologies, such as robotic and artificial intelligence, into the construction field could partially address the shortage of labor for certain construction activities, especially those that require repetitive works. Second, safety of human workers during construction and maintenance of bridges and safety of the community throughout the life cycles of bridges should be prioritized in all bridge projects, as highlighted by the experts. Construction work zones have long been associated with disruptions to regular activities, road closures, dust, and noise. While the construction workforce is exposed to all these nuisances and hazards, commuters and people living in the surrounding communities are also impacted depending upon their contact with the construction work zones. New real-time monitoring and preventive technologies can radically enhance the safety of construction work zones; deployment of modern technologies to track construction resources and activities can assist in avoiding hazards, regulating road closures and warning people on what to expect. In addition, the experts suggested that, new bridge construction techniques (e.g., ABC) can potentially improve the safety of construction processes by reducing hazard exposure time and area, and they could also improve the overall societal perceptions on bridge construction as they facilitate minimal disruptions to regular activities. With the development of new techniques and technologies, risk tolerance of the society is ever narrowing. Bridges are eventually constructed for societal good; safety of communities must be embodied into the bridge construction works that it becomes a part of the community and culture.

(4) Economic Factors

The following strategies for adapting to the economic factors are recommended: First, according to the experts, when considering P3 for potential projects, governments may want to account for the benefits and cost throughout the project's entire life cycle. In addition, government agencies can take more efforts to standardize the P3 project assessment and development process, including how to determine if P3 is appropriate for a project, how to develop a comprehensive request for proposals for P3 projects, and how to decide which proposal to accept. Second, to cope with the budget shortfalls due to the reduced sales and gas tax revenue, state and local transportation agencies may need to reevaluate their typical project planning and programming policies to better align funding with decision making, achieve the best and highest use of infrastructure assets and revenues, and provide cost-effective solutions to current and future transportation needs. One potential solution is through right-sizing transportation infrastructure, which involves reassessing the size and composition of transportation infrastructure to reflect the current economic reality, such as relaxing or waiving standards, replacing infrastructure with more economical options, or decommissioning infrastructure to allow for land reuse (NASEM 2019). Third, to provide much-needed investment on critical bridge infrastructure and stimulate the economy, state and local governments are encouraged to leverage the private capital through adopting P3, asset recycling, evaluating underutilized bridges or renegotiating lease arrangements. State and local governments are also recommended to integrate greater economic considerations into their project planning and evaluation process; they may prioritize bridge projects that support the local economy, enable job creation or retention, improve connectivity, amenity or other factors that lead to increases in local tax revenues (Falk et al. 2020).

5. CONCLUSIONS

5.1. PROJECT SUMMARY

This project focuses on identifying the critical impacting factors and analyzing how these factors may affect bridge design, construction, and operation in the future. A total of 20 interviews were conducted with 21 bridge-domain experts, and a total of 108 bridge experts participated in the expert survey. 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. Some highly important factors were discussed in detail, including “Adoption of New Construction Materials or Structures”, “New Transportation Facilities or Methods”, “Climate Change”, “Sea Level Rise”, “Changes in Labor Market”, “Changes in Safety Requirements”, “Public-Private Partnership (P3) Trend”, “Change in Fuel Prices”, and “Availability of Funding”.

5.2. PROJECT BENEFITS

This project offers a holistic and explicit understanding of the multifaceted critical impacting factors that could affect bridges in the future. 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.

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.

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