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Risk Assessment Protocol for Existing Bridge Infrastructure Considering Climate Change

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Abstract: The escalating impact of climate change on global weather patterns threatens the functionality and resilience of infrastructure systems. This paper presents a rigorous risk assessment protocol tailored to existing bridge infrastructure, integrating climate change projections, structural integrity, and socioeconomic factors. The protocol's application involves five sequential steps: selecting a bridge, disassembling the structure into components, calculating utilization factors for design and projected temperatures, evaluating severity factors encompassing structural and socioeconomic aspects, and ultimately determining an overall risk rating. To demonstrate the protocol's effectiveness, a case study was conducted on the Westminster Drive Underpass in London, Ontario. This study shows how the protocol systematically evaluates the vulnerability of each bridge component to projected temperatures under the Representative Concentration Pathway 6.0 model. The protocol provides a holistic risk assessment by incorporating both the structural response and socioeconomic implications of failure. The results rank the bridge's risk level and highlight the urgency of intervention. The protocol emerges as a robust tool for decision-makers, practitioners, and engineers, offering a comprehensive approach to strengthen bridge infrastructure against the challenges of climate change.

Keywords: risk assessment; bridge infrastructure; impact of climate change; structural impact; socioeconomic impact

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1. Introduction

The global landscape is dramatically transforming due to climate change-induced severe weather events. These phenomena threaten the operational efficiency and effectiveness of infrastructure systems worldwide and exacerbate the strain on these systems due to pre-existing structural vulnerabilities. The gravity of the situation was highlighted in a critical press release by the Intergovernmental Panel for Climate Change (IPCC) [1]. The IPCC report revealed changes to Earth's climate across all climatic systems, emphasizing rising sea levels, increasing global surface temperature, flash floods, wildfires, and other climatic disruptions. The proliferation of these increasingly severe and frequent weather events has been extensively documented by news outlets, stressing the urgent need for action.

Climate change has a severe impact on infrastructure systems globally. According to Nasr et al. [2], extreme climatic events such as droughts, floods, heatwaves, and increased precipitations pose a new risk to bridge infrastructures, creating significant challenges for decision-makers in managing the portfolio of bridge assets.

Considering this unstable reality, decision-makers and policymakers must take a proactive approach to address these issues and ensure that infrastructure systems are adequately prepared to handle the increasing severity and frequency of extreme weather events. Therefore, there is a pressing need for protocols that can be easily applied by practitioners. A risk assessment protocol requires integrating the impact of projected temperatures in terms of the structural integrity of a bridge and socioeconomic factors to be considered due to the risk. Only through such comprehensive measures can we strive to safeguard our infrastructure systems against the exponential increase in forces of nature and ensure a resilient future.

This paper presents a practical methodology (protocol) to assess the risks of climate change to existing bridges. The protocol evaluates projected temperature effects on bridge structures and their socioeconomic aspects, facilitating the practical application for risk-informed decision-making. A case study was used to exemplify the methodology's implementation. This paper first reviews the Representative Concentration Pathway (RCP) models for temperature projections and examines climate change's impact on bridge structures. In addition, it compares this new approach to existing risk assessment frameworks. Overall, the methodology offers a comprehensive, adaptable tool for addressing climate-induced risks to bridges, integrating predictive models, structural analysis, and socioeconomic considerations.

2. Materials and Methods

The climate is changing at an unprecedented rate, presenting a significant challenge to global sustainability [1]. Climate models are computational simulations of the Earth's global climate system that are used to predict future climatic conditions driven by various greenhouse gas (GHG) emission possibilities. These models effectively depict climate system elements such as the atmosphere, oceans, ice and snow, land surface, and biogeochemical cycles. Through numerical mathematical frameworks, these models simulate the complex physical interactions within each component, despite limitations imposed by temporal and spatial resolutions, as well as gaps in our understanding of governing processes. Consequently, the combination of GHG emission scenarios and the characteristics of climate models introduce uncertainty into the future projections of climatic design data.

The RCPs play a pivotal role in shaping our understanding of future climate scenarios. The projections outlined in the IPCC's 5th Assessment Report [3] were formulated based on a collection of future influence scenarios referred to as RCPs [4]. These RCPs were designated by approximating the radiative forcing anticipated by the close of the 21st century. In determining RCP scenarios, Earth system models and global climate models provide projections of future climate change based on a range of future scenarios incorporating GHGs, aerosols, and land-use change [4].

To elaborate, RCP2.6 corresponds to a trajectory of low emissions, aligning with the goals of the Paris Agreement, and is projected to yield a radiative forcing of about 2.6 W/m^2. Meanwhile, RCP4.5 signifies pathways characterized by moderate emission mitigation, leading to an approximate radiative forcing of 4.5 W/m^2. RCP6.0 embodies a stepwise elevation in emissions, resulting in a radiative forcing of 6.0 W/m^2. Lastly, RCP8.5 symbolizes a trajectory marked by persistent growth in GHG emissions, culminating in a radiative forcing of approximately 8.5 W/m^2 by the century's conclusion. Table 1 shows projected global mean surface air temperature change for the mid and late 21st century relative to the reference period of 1986–2005. The impact of these projected values on structural integrity is an emerging area of research that may result in changes to design codes [5]. These changes are drastically significant in higher-latitude geographies [6]. A similar effect can be felt in Canada compared to the rest of the world, as is demonstrated in Table 2 for six defined climate regions as well as nationally [7].

Table 1. IPCC Representative Concentration Pathway (RCP) models for mean temperature [5].

Scenario	2046–2065 Mean Temperature Increase (Range)	2081–2100 Mean Temperature Increase (Range)
RCP2.6	1.0 (0.4 to 1.6)	1.0 (0.3 to 1.7)
RCP4.5	1.4 (0.9 to 2.0)	1.8 (1.1 to 2.6)
RCP6.0	1.3 (0.8 to 1.8)	2.2 (1.4 to 3.1)
RCP8.5	2.0 (1.4 to 2.6)	3.7 (2.6 to 4.8)

Table 2. Projected change in annual mean surface air temperature nationally, as well as for six Canadian climate regions [7].

Scenario	RCP2.6		RCP8.5	
	2031–2050	2081–2100	2031–2050	2081–2100
British Columbia	1.3	1.6	1.9	5.2
Prairies	1.5	1.9	2.3	6.5
Ontario	1.5	1.7	2.3	6.3
Quebec	1.5	1.7	2.3	6.3
Atlantic	1.3	1.5	1.9	5.2
North	1.8	2.1	2.7	7.8
Canada	1.5	1.8	2.3	6.3

In Canada, the impact of climate change on infrastructure is particularly severe, with projections indicating annual mean surface temperature increases of up to 6.3 °C by the year 2100 compared to world average of 3.7 °C [7]. Climate change can directly and indirectly affect structural assets and the surrounding communities. Projection models have a long-lasting influence on assessing the sustainability of socioeconomic structures [8].

Bridges are an essential part of infrastructural portfolios that are critical for the continuity of services and goods to any community. However, they are increasingly vulnerable to extreme climate events such as floods, extreme winds, storm surges, and the accumulation of ice and snow, posing significant risks to their design and maintenance, as well as the surrounding areas [2]. These events require innovative solutions and models to manage the impact of climate change on bridge infrastructure, including the safety and serviceability of existing bridges. A major challenge for decision-makers in planning infrastructure programs is assessing and minimizing climate change risk. To ensure effective adaptation, it is crucial that climate change considerations are included in bridge design codes and standards [9]. There are significant economic implications for bridge vulnerabilities due to climate change. Studies have shown that proactive measures taken during the design and construction stage to improve bridge condition are more cost-effective than responding to the negative impact of climate change, including catastrophic events, on infrastructures and human lives [10]. For example, Guest et al. [11] highlighted how increased chloride exposure due to deicing salts and changing humidity levels exacerbated by climate change could significantly accelerate the deterioration of reinforced concrete (RC) bridge decks. Their research underscores the need for integrating climate data into mechanistic-empirical models to predict deterioration more accurately, particularly in the context of Canada's extreme climate.

Additionally, Guest et al. [11] observed that climate change could shorten the service life of RC bridge decks due to increased exposure to environmental stressors. These findings reinforce the importance of early interventions to mitigate climate-related degradation, particularly when using high-resolution climate projections to anticipate and address the most pressing vulnerabilities. Akomea-Frimpong et al. [12] underscores that sustainable adaptation strategies, such as adaptive maintenance schedules and the use of durable materials, are critical for prolonging the life of bridges and ensuring resilience. Their work suggests that multi-criteria decision-making frameworks that integrate environmental, social, and economic factors can play a pivotal role in strengthening infrastructure resilience in the face of climate stressors.

Various climatic risk factors can create vulnerability in bridge structures. With projected higher temperatures, extreme winds, increased precipitation, and changes in relative humidity in some areas, bridges can be directly and indirectly impacted. These factors can lead to degradation and the failure of bridge components, including the deck, substructure, and superstructure, compromising their performance and structural integrity.

Palu and Mahmoud [13] conducted a comprehensive study on the vulnerability of infrastructure, focusing on the impact of climate change on simply supported steel girder bridges in the U.S. by focusing on the main load-carrying girder. The National Oceanic and

Atmospheric Administration models were used to study the potential impact of changes in temperature on the clogging of joints in these bridges' main load-carrying girders. They found that unpredicted thermal stress can significantly impact the structure's stability and performance. Their study revealed that a small increase in temperature, by 1 °C, can lead to a 2% increase in the interaction equation value, resulting in a continuous reduction in bridge capacity as the climate continues to warm. Therefore, without proactive interventions, the impact of climate change could have a devastating effect on these bridges' ability to carry loads, posing significant risks to public safety and transportation systems [13].

Projected temperature increases can result in increased thermal stresses that can cause significant damage to bridges, especially in steel structures, where tensile stress is impacted by larger temperature gradients than those due to the entire live load [14]. Furthermore, projected increases in snowfall, wind, and precipitation can lead to an increase in demand and possibly overwhelm the drainage system and capacity of a bridge. Increased precipitation can also result in floods that directly impact the flow control systems, abutments, and piers, possibly along with hydraulic structures. Additionally, several other factors may represent a risk to the bridge structure, such as accidents resulting from unexpected loads due to decreased visibility during fog [15]. There are risks due to extreme, intense, and frequent floods and storms [16]. This includes costs associated with removing snow, temporary full and partial closures, unexpected maintenance costs, and additional preventative maintenance programs, with both direct and indirect impacts on the community and local economy.

Currently, most design standards estimate climatic loads based on an extreme value analysis of past observations of natural phenomena. Design codes are applied based on the assumption of stationary climate conditions and disregard the potential effects of climate change, which is progressing at a rapid rate as outlined by the IPCC [1]. To ensure the long-term structural reliability of new and existing structures, it is crucial that the influence of climate change is considered in load estimation [17]. The increasing risk of extreme weather events due to climate change poses a significant challenge to the engineering community. The impact of climate change on infrastructure design and maintenance needs to be evaluated using models and techniques that incorporate climate change scenarios and are easily applied in the field. This evaluation should also consider the potential risks to public safety for the economy and surrounding environment through protocols that integrate structural and socioeconomic factors.

Structural assessments rely on historical climatic data to determine load factors and assess the health of a bridge structure. As per the IPCC [1], data clearly demonstrated that the climate is changing, and the overall temperature is warming up. Historical data no longer accurately presenting future climatic conditions. There has been some effort by practitioners and scholars to assess the impact of climate change on bridge structures. However, research and work are needed to develop a framework and methodology to assess the long-term health of bridge structures due to climate change. Table 3 presents a summary of the different infrastructure methodologies employed for assessing climate change risk, using the following key criteria:

- Structural Assessment: This criterion considers whether a given methodology evaluates the health of the bridge structure to determine its rating (e.g., fair, poor, etc.).
- Impact of Projected Climatic Data: This criterion considers whether a methodology incorporates an assessment of projected climate data (e.g., future projected temperature data or wind speed data).
- Economic Impact: This criterion considers whether a methodology evaluates the economic impact of non-serviceable bridges (e.g., cost to replace or cost of limited traffic or restricted traffic flow).
- Societal Impact: This criterion considers whether a methodology evaluates the societal impact of the restricted or limited flow of goods and services to surrounding communities.

- Ease of Use: This criterion considers the level of ease in the implementation and utilization of a methodology by practitioners and decision-makers from different knowledge backgrounds (e.g., technical, management, policymakers, etc.).

Methodologies that were reviewed are categorized as follows:

- Considering two or more criteria;
- Considering climate change;
- Quantitative, qualitative, and easy to apply.

The overall goal of the various methodologies reviewed and summarized in Table 3 is to develop robust risk assessment frameworks that can equip practitioners with the necessary tools to make informed decisions about interventions. The objective of Table 3 is to create a literature review of various assessment methodologies on this topic. Various methodologies may assess structural impact from different lenses such as exposure to extreme weather events or operational and maintenance challenges. Decision modeling is a critical component of this process, as it provides a structured and systematic approach to tackling complex decisions. As Clemen and Reilly [18] note, decision analysis can make the process of decision-making easier by breaking down complex decisions into more manageable components. It is important for decision-makers to identify key uncertainties and assess the potential risks and benefits associated with different courses of action. By leveraging decision modeling and analysis, practitioners can develop risk assessment frameworks that are both rigorous and effective in informing decision-making in the face of climate change and other complex challenges.

Table 3. Climate change impact on structures—comparison.

	Criteria				Application		
Methodology	**Structural**	**Projected Climatic Data**	**Economic Impact**	**Societal Impact**	**Quantitative**	**Qualitative**	**Ease of Application**
Wang et al. [19]	Yes	No	Yes	Yes	Yes	Yes	No
Johnson and Weaver [20]	Yes	Yes	No	No	Yes	Yes	Yes
Deco and Frangopol [21]	Yes	Yes	No	No	Yes	Yes	No
Nelson and Freas [22]	Yes	No	Yes	Yes	No	Yes	Yes
Khelifa et al. [23]	Yes	No	Yes	Yes	Yes	Yes	No
Ghile et al. [24]	Yes	Yes	No	No	Yes	Yes	No
Ontario Bridge Index [25]	Yes	No	No	No	Yes	Yes	Yes
Dawson et al. [26]	Yes	Yes	No	No	Yes	Yes	Yes
Markogiannaki [27]	Yes	Yes	No	No	Yes	Yes	Yes
Hawchar et al. [28]	Yes	Yes	No	No	Yes	Yes	Yes
Chang et al. [29]	Yes	Yes	No	No	Yes	Yes	Yes
Kumar et al. [30]	Yes	Yes	No	No	Yes	Yes	Yes
PIEVC Protocol [31]	Yes	Yes	No	No	Yes	Yes	Yes
This Paper	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Through the literature review analysis, it was concluded that many of the methodologies considered more than one of the following criteria: (1) structural impact, (2) projected climatic data, (3) economic impact, and (4) societal impact. While most of the methodologies considered structural assessment and, to some degree, projected climate change, few extend their analysis to incorporate societal and economic impacts. Some of the methodologies in the literature were of particular interest for their practical application to current research. Markogiannaki [27] introduced a framework to assess the risk to cable-stayed bridges due to climate change. The method considered new and existing bridge structures and incorporated the determination of potential hazards due to climate change effects. The hazards were determined based on failure modes for each natural hazard, and the vulnerability in each scenario was analyzed to determine the probability of failure. The risk was then calculated and classified based on the mean annual frequency of extreme events. The natural hazards considered in this framework were seismic and hurricane occurrences and their downstream effect on sea-level rise and increased intensity. The methodology is limited to a specific type of bridge and does not consider the economical and societal impact.

Nelson and Freas [22] introduced a risk assessment planning methodology that incorporates climate change and its impact on water infrastructure planning. The methodology considers average annual precipitation, heavy precipitations (extremes), and sea-level rise as the most impactful climatic events for water infrastructures. Their approach integrates the "threshold risk assessment approach," which relies on professionals' judgments, and the "scenario risk assessment approach," a quantitative approach. They provided a balanced methodology of qualitative and quantitative methods for planning purposes considering expert judgement on the impact of climate change. Wang et al. [19] introduced a methodology that integrated two useful tools, data envelopment analysis (DEA) [32] with the analytic hierarchy process (AHP) [33,34] to solve a problem with 15 alternatives. Even though Wang et al. [19] did not discuss climate change, they provided a framework to perform a risk assessment of structural criteria such as safety, functionality, sustainability, and environment by comparing multiple bridge structures at a time and therefore provide a ranking of most to least critical of portfolio of bridges. The methodology available through the Public Infrastructure Engineering Vulnerability Committee Protocol (PIEVC Protocol) [31] provides an approach that considers projected climate data, and it also benefits from its ease of use in practice and industry. However, it falls short in assessing economic and societal impacts. Therefore, a more comprehensive approach that considers not only the physical impact of climate change on infrastructure, but also the economic and social implications is needed to adequately address climate change in infrastructure planning.

Researchers such as Omer and Nehdi [35] and Hajializadeh et al. [36] emphasized the challenges in assessing climate change risk on bridge infrastructure. However, developing a methodology and tool to help practicing engineers and decision-makers assess the risk of climate change on existing infrastructure, considering both structural and socioeconomic vulnerability, is an emerging area of research. Bridge infrastructure managers and practicing engineers need improved tools to assess the relative risks of climate change to various aspects of the bridge infrastructure network, evaluate and develop response strategies, and allocate resources effectively. Decision-makers also need efficient techniques to incorporate climate change data and projections into transportation infrastructure planning, construction, retrofitting, and operation.

These factors motivated the development of the methodology presented in this paper to provide a comprehensive tool that assesses bridge infrastructure and contributes to decision-making on incorporating risk management issues in the transport and logistic sectors to improve quality of life and maintain economic growth. Analyzing risk on an existing bridge structure in this format starts to assess the risk at a component level while also considering the overall health of the bridge structurally and its serviceability, including assessing the socioeconomic impact of bridge failure on the surrounding community. Nethwani et al. [37] noted, "risk management is about improving the overall public welfare and reducing the risk to life in a cost-effective manner".

The presented protocol evaluates the risk of climate change for a simple bridge structure. As Palu and Mahmoud [13] assessed, as was discussed earlier, temperature values are critical to any bridge's structural integrity and serviceability, and have direct and indirect impacts on its overall performance. A bridge acts as a whole system, and our objective was to create a risk evaluation of each component of a bridge to determine an overall risk level for the entire bridge. The protocol assesses a bridge structure through integrating the impact of projected temperature as modeled by a selected RCP model and calculating the governing utilization factors at the selected RCP projected temperature values. The selection of the RCP model and projection is based on geographic relevance and application. Further, the protocol accounts for the impact of the bridge structure's failure on the socioeconomics of the region it services. The proposed approach is easy to implement and provides an indication of risk factors to inform decision-makers of the next steps. Figure 1 shows a schematic diagram of the proposed five step assessment protocol to conduct a risk assessment on an existing bridge structure, considering the impact of climate change on temperature.

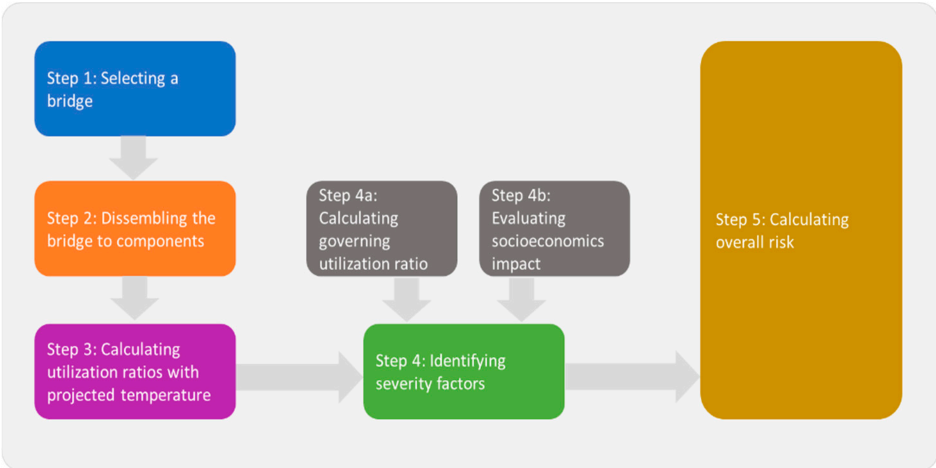

Figure 1. Schematic of risk assessment protocol.

1. Step 1: Selecting a Bridge

This step involves selecting and characterizing an existing bridge by providing descriptions such as location, dimensions, material, servicing area, and overall condition. Once the bridge is selected, the various components of the bridge are identified in preparation for Step 2. As described in Figure 2, the bridge is identified in terms of three major components:

- Superstructure, which includes bearings, bridge deck, cast-in-place slab, and girders.
- Substructure, which includes the abutment, wing and return walls, piers, pier cap, and foundation.
- Non-structure, which includes parapets, joints, and drainage systems.

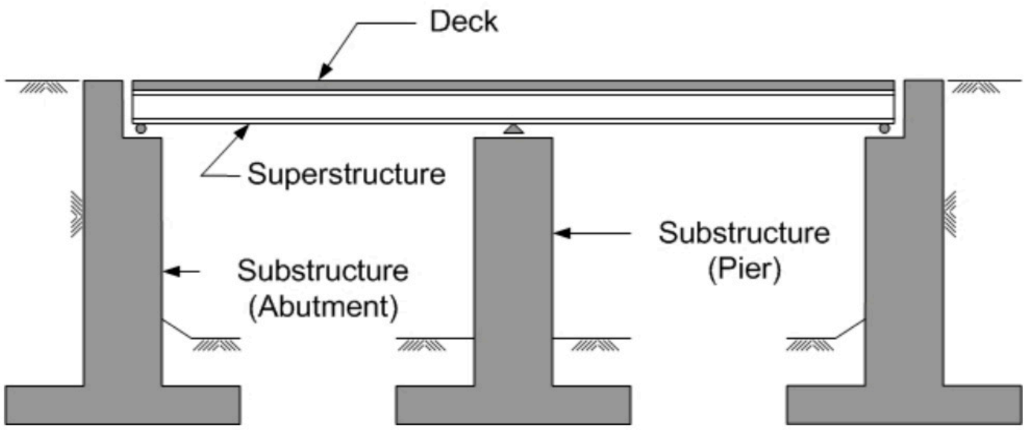

Figure 2. Simple bridge structure.

2. Step 2: Disassembling the Bridge to Components

Using a specific simple bridge infrastructure, each selected bridge system is then disassembled into its individual components. The impact of temperature on its functionality for each bridge component will also be identified, as illustrated in Table 4.

Table 4. Disassembling a bridge to components.

	System	Sub-Item #	Component	Critical to Structural Integrity? (Y/N)	Impacted by Temperature? (Y/N)
1	Superstructure	1.1	Deck	Y	Y
		1.2	Girders	Y	Y
		1.3	Cast-in-place slab	Y	Y
2	Substructure	2.1	Abutment	Y	Y
		2.2	Piers (Columns)	Y	Y
3	Non-structure	3.1	Joints	Indirectly	Y
		3.2	Drainage System	Indirectly	Y

3. Step 3: Calculating Utilization Ratios

This step involves the calculation of the utilization factor (also known as utilization ratio, U/R) for each component based on the design temperature (per code) and projected temperature (based on a selected and geographically relevant RCP model). The utilization factor is defined as the ratio between the actual performance value and maximum allowable capacity:

$$\text{Utilization factor} = \text{performance value}/\text{maximum allowable capacity} \quad (1)$$

Determining the overall U/R ratio of the bridge entails calculating individual component U/R ratio and identifying the governing U/R value, which signifies the component most susceptible to failure.

4. Step 4: Identifying Severity Factors

In this step, the severity factors are determined for all the components. The severity factors are calculated as a qualitative measure by first calculating the governing utilization ratio and evaluating the socioeconomic impact. Once the severity factors are determined, climate change risk can be determined. It is essential to determine the severity factors due to climate change at each failure mode at the component level of a bridge. This level of microassessment is the foundation of the assessment protocol. The process involves two key sub steps: Step 4a: Calculating the governing utilization ratio. As described in Step 3, the utilization factor is critical to estimating the likelihood of failure. The utilization ratio (U/R) is calculated for each component in this step, and the highest ratio is then considered for the evaluation of risk. The highest value of U/R is identified as the limiting component and weakest link of the system. Step 4b: Evaluating the socioeconomic impact. Part b of Step 4 involves evaluating the potential socioeconomic impact of climate change on the existing bridge structure. Nathwani et al. [37] explained that welfare economics had inspired the conceptual development of decision tools to improve life safety and quality beyond the traditional sphere of political and economic policies, and into science and engineering technology decision-making. They identified that risk management (relative to the risk of climate change on bridge structures) is about improving overall public welfare and reducing the risk to life in a cost-effective manner. Thus, it is important to determine the severity of the impact on socioeconomic factors due to climate change. To measure the severity of the impact, the methodology considers several factors:

- How long is the bridge out-of-service? The protocol assesses the duration of the bridge being out-of-service, setting a cut-off time of 10 days. In determining the impact of service disruption, it is important to identify the categorization of a bridge to the community the bridge services. Experts would assess if the specific bridge was categorized as “critical” or “non-critical”. Critical bridges, such as those connecting major transportation corridors or servicing remote communities, will require a shorter service interruption, while non-critical bridges can withstand a longer period of service interruption. Therefore, the threshold may vary depending on the specific criticality of the bridge function. It is important to recognize that there are no universal, one-size-fits-all standards for determining the threshold on bridge out-of-service duration. The protocol suggests a 10-day cutoff as a starting point in the absence of a categorization of a specific bridge.

- What is the magnitude of the damage to the surrounding ecosystem? The methodology evaluates the magnitude of damage to the surrounding ecosystem and identifies whether the damage is permanent or not. Understanding the ecological impact of the bridge failure is critical in determining the overall severity of the impact.
- What is the magnitude of damage to the bridge structure? The protocol considers the magnitude of the damage to the bridge structure and determines the impact of damage for rebuilding, repairing, or managing through regular maintenance and repair programs.

5. Step 5: Calculating the Overall Risk Rating

This final step involves determining the overall risk rating of the existing bridge structure considering the impact of climate change. Risk is quantified as the product of the probability of failure and the subsequent consequences resulting from the failure. This calculation follows the equation of risk [38]:

$$R = P \times C \quad (2)$$

where R is risk, P is probability of failure, and C is consequence resulting from failure.

The two criteria to assess the above risk are socioeconomic and utilization factors. These two criteria form the consequences of climate change on a structure, and the product of these two factors yields a severity factor of the risk of climate change, as illustrated in Figure 3, and the severity factor equation, defined in Equation (3).

$$\text{Severity factor} = \text{Socioeconomic factor} \times \text{Bridge utilization factor}. \quad (3)$$

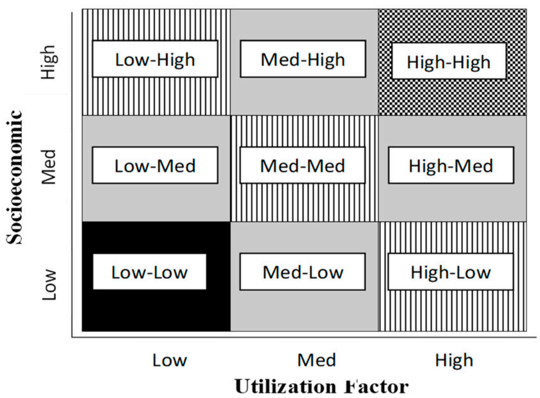

Figure 3. Categorization of severity factor in terms of socioeconomic and utilization factors.

The severity factor equation was developed based on two critical dimensions: the socioeconomic impact and the structural utilization factor of the bridge. These two criteria were selected because they represent the significant consequences of projected temperature on bridge infrastructure. The socioeconomic factor measures the societal consequence of bridge service interruption, including disruption to transportation networks, economic costs to the surrounding region, damage to the surrounding ecosystem, and potential harm to public welfare. It captures the idea that climate change-induced damage to infrastructure has ripple effects beyond the physical structure itself, affecting economic productivity, emergency response capabilities, the local ecology, and social stability. The rationale for incorporating this factor is drawn from the welfare economics and infrastructure risk management literature, which emphasizes that the cost of infrastructure failure is often felt most acutely in economic and social terms [39]. The utilization factor reflects the structural performance of the bridge, specifically the relationship between the bridge's current usage and its design capacity under projected climate (temperature) conditions. It represents the direct physical impact of climate change (e.g., temperature) on the structural integrity of the bridge. This factor is essential for understanding how the projected temperature may push the bridge beyond its intended operational limits. The product of these two factors (Severity factor = Socioeconomic factor × Utilization factor) is used to quantify the severity of the risk posed by climate change to the bridge. This multiplication of factors is conceptually similar to the way risk is calculated (e.g., Risk = Probability × Consequence), and it allows for a more holistic assessment by accounting for both the direct physical risks and the broader societal impacts of infrastructure failure. The combination ensures that even if a bridge remains structurally sound under projected climate conditions, significant socioeconomic disruptions could still indicate a high severity of risk.

The probability of failure in this assessment is the likelihood of failure occurrence on the bridge components specific to a climate change factor such as temperature. This gives a probability factor defined as the likelihood of failure occurrence of a specific component of a bridge. Thus, the overall risk rating is determined by multiplying the severity factor by the occurrence factor, as shown in Equation (4):

$$\text{Risk rating} = \text{Severity factor} \times \text{Occurrence}. \quad (4)$$

The overall risk rating of a given bridge is determined based on the predefined categorization shown in Figure 4. The categorization in Figure 4 is then applied in the assessment protocol and is used to complete Table 5 to determine the overall risk rating. Table 5 was developed as a tool for calculating the risk rating. The risk rating in Table 5 was calculated using Equation (4) where the socioeconomic factor rating and the utilization factor rating are determined. The occurrence is then assessed based on the probability of occurrence to determine a rating. The ratings for the socioeconomic factor, utilization factor, and occurrence are multiplied to obtain the overall risk rating.

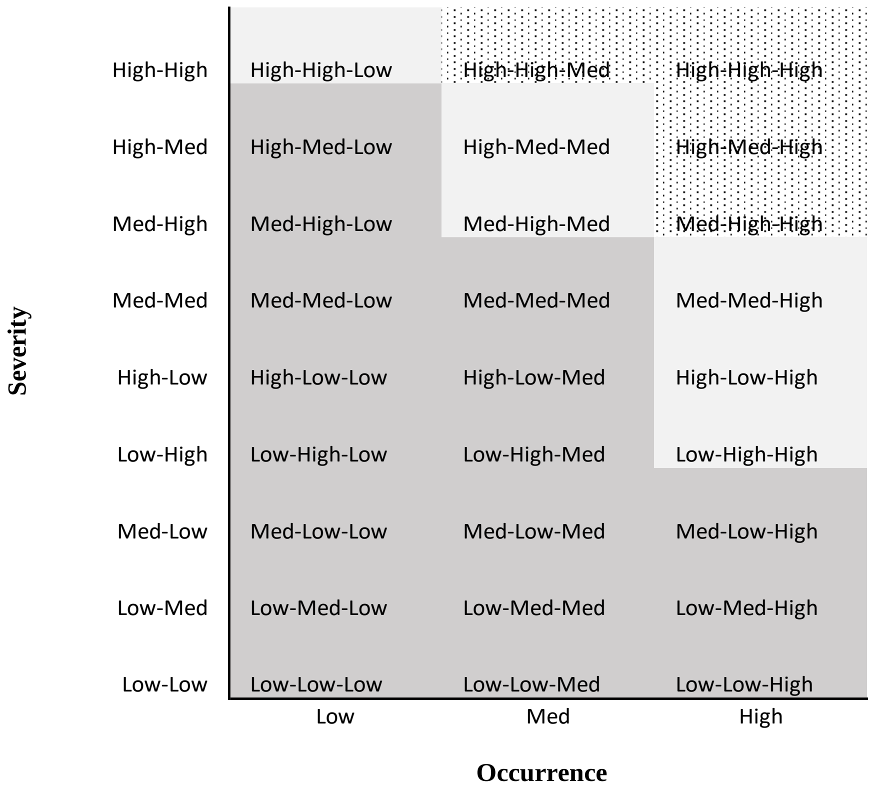

Figure 4. Categorization of overall risk rating.

Table 5. Risk assessment protocol evaluation.

				Occurrence			Overall Rating	
Socioeconomic Factor	**Rating (A)**	**Utilization Factor**	**Rating (B)**	**Definition**	**Probability**	**Rating (C)**	**Definition**	**Rating**
Complete termination of service, time-out-of-service $\geq$ 10 days, significant damage to surroundings with permanent damage, complete re-build of structure is required.	High (3)	Total and permanent damage to the system and fails to satisfy design limit. Utilization Factor $\geq$ 100%	High (3)	Highly likely for the severity to occur.	Probability $\geq$ 65%	High (3)	Critical level of risk due to climate change. Requires immediate intervention and significant resources	18 $\leq$ Rating $\leq$ 27
Major interruption to service with significant cost for work around, time-out-of-service < 10 days, alternative structures are available, non-permanent damage to surrounding, partial re-build of structure is required.	Medium (2)	Significantly reduces the effectiveness of the system such that it would fail to satisfy the design requirements. However, the system would still operate. 90% $\leq$ Utilization Factor < 100%	Medium (2)	Likely/possible for the severity to occur.	35% < Probability $\leq$ 65%	Medium (2)	Moderate level of risk due to climate change. Requires planning for intervention.	9 $\leq$ Rating < 18
Some interruption to service with workaround options available, little damage to surrounding ecosystem that can be cleaned up, no re-build of structure is required, no time out of service.	Low (1)	Reduced effectiveness, design requirements would still be satisfied. Utilization Factor < 90%	Low (1)	Unlikely for the severity to occur.	Probability $\leq$ 35%	Low (1)	Insignificant level of risk, manageable through preventative maintenance programs.	1 $\leq$ Rating < 9

3. Results

An existing highway bridge was used as a simple example to evaluate the potential risk associated with climate change on current infrastructure. The objective was to demonstrate the applicability of the proposed risk assessment protocol in a real-world context. This exercise followed the prescribed steps of the protocol to evaluate the impact of temperature projections aligned with the RCP6.0 model on the selected bridge structure. The mean projected temperature value was used as a static input. The RCP6.0 model was deemed the most relevant projection model for this case study. Adopting the RCP6.0 scenario for quantitative and qualitative climate-related bridge design and assessment is the most likely impact [40].

3.1. Step 1: Bridge Selection

For this study, the Westminster Drive Underpass, which is in London, Ontario, Canada, needed to be replaced due to its age and condition [41]. The original structure of the bridge was a 28.8 m single-span rigid frame bridge, constructed in 1959. The structure carried two lanes of Westminster Drive over four lanes of Highway 401 traffic in Ontario, as shown in Figures 5 and 6 [41]. The Westminster Drive Underpass was chosen for this case study due to the age of the original bridge construction, material composition (reinforced concrete), and its location over a major transportation artery (Highway 401) in Ontario, Canada. This bridge is representative of aging infrastructure in Canada and provided an original construct and replacement bridge to apply the methodology to. The bridge's structural composition and location provided a suitable scenario for evaluating temperature projections, which can highlight the protocol's ability to assess the risk posed to similar bridge types. Bridges over water or timber bridges, for instance, would present different risk profiles, as the effects of moisture and other climate factors (e.g., flooding) would significantly alter the results of the analysis.

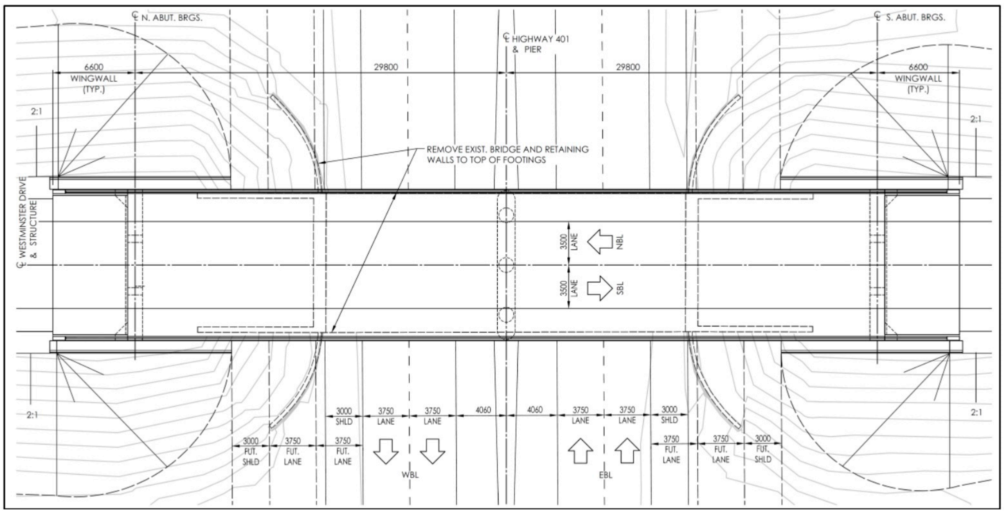

Figure 5. Westminster Drive Underpass—Plan [41].

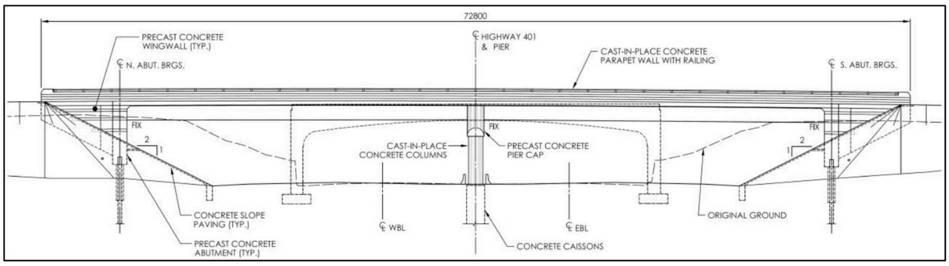

Figure 6. Westminster Drive Underpass—Elevation [41].

Original Bridge

- Age: Originally constructed in 1959.
- Span: A 28.8 m single-span rigid frame bridge.
- Construction: Three variable-depth reinforced concrete box girders; abutments situated adjacent to highway shoulders.
- Operation: Structure carried two lanes of Westminster Drive over four lanes of Highway 401.

Replacement Bridge

- Age: The bridge was replaced after the decision of the Ontario Ministry of Transportation (MTO) in 2014.
- Span: Two-span continuous integral abutment bridge, 29.8 m each.
- Construction: GiGo (get in get out) bridge construction concept, pier situated in the median.

3.2. Step 2: Identifying and Analyzing Each Component for Impact Assessment

This step examines the Westminster underpass to determine each of its components and establish whether they are susceptible to climate change. The components of the Westminster Bridge were disassembled, as shown in Table 6, to identify which components of the bridge are impacted by temperature

Table 6. Parameters to assess the impact of temperature on each component of the Westminster Underpass.

Structure	Components	Is It Pivotal to Integrity of Structure?	Is It Impacted by Temperature?
Substructure	Abutment	No	No
	Piers	Yes	Yes
Superstructure	Girders	Yes	Yes
	Cast-in-place Deck	Yes	Yes
Adjoining	Joints	Yes	Yes
	Drainage System	No	Indirectly

3.3. Step 3: Calculation of Utilization Factor for Design Temperature and Projected Temperature

This step involves the calculation of the utilization factor for each component of the Westminster Drive Underpass. It should be noted that within the context of a bridge featuring piers, the piles assume a foundational role. Consequently, the pile component was chosen for determining the utilization factor. This deliberate choice emphasizes the pile element's critical influence within the substructure's broader structural context. The utilization factor was determined for design temperature and projected temperature scenarios i.e., based on the selected RCP6.0 model. The capacity of each component of the bridge is outlined in Table 7. Based on load combination (factored deadload and live load), the utilization factor was calculated at the component factor. In Table 7, the "Utilization Factor" is based on current performance of the bridge, and the "Utilization Factor design temperature" is the design (per code) utilization factor. The utilization ratios were then calculated for each component to determine the governing utilization ratio, as demonstrated in Table 7. The relevant utilization factor for the purpose of risk assessment was for the year 2100. This factor was used to evaluate the impact of climate change (increase in temperature) on the bridge infrastructure. Following the determination of the utilization factor for each component, as demonstrated in Table 7, the subsequent step involved the determination of the component that exhibits the highest utilization factor. This becomes the governing utilization factor, as demonstrated in Table 8.

Table 7. Utilization ratios at design and projected temperature for the Westminster Bridge.

Component	Capacity	Load Combination			
		Utilization Factor	Utilization Factor [1]	Utilization Factor [2]	Utilization Factor [3]
Girder Moment (Positive)	13,740 kN·M	0.77	0.84	0.85	0.86
Girder Shear	4933 kN	0.29	0.29	0.29	0.29
Pile Moment [4]	502 kN·m	0.72	0.97	0.99	1.00
Pile Shear	4800 kN	0.08	0.10	0.11	0.12

[1] Utilization factor calculated based on design temperature. [2] Utilization factor calculated based on projected temperature for year 2050. [3] Utilization factor calculated based on projected temperature for year 2100. [4] The initial utilization factor was calculated as: [Dead Load + 1.7(Live Load)]/Capacity. The utilization factors were then re-calculated for design temperature and projected temperature: [Dead load + 1.6(Live load) + 1.15(design temperature + gradient)]/Capacity.

Table 8. Assessment of utilization ratios at design and projected temperature for the Westminster Bridge.

Structure	Components	Is It Pivotal to Integrity of Structure?	Is It Impacted by Temperature?	Utilization Factor
Substructure	Abutment Piers	No Yes	No Yes	NA 1.00
Superstructure	Girders Cast-in-place Slab	Yes Yes	Yes Yes	0.86 NA
Adjoining	Joints Drainage System	Yes No	Yes Indirectly	NA NA

3.4. Step 4: Severity Evaluation

Step 4a: Calculating the governing U/R. To evaluate the severity of the risk associated with the Westminster Bridge, the governing ratio for each individual component was calculated as detailed in Table 7. The maximum utilization factor at each component is considered the governing utilization factor, enclosed in Table 8. The next undertaking involved assigning the appropriate level of risk by correlating the level of risk of the utilization ratio outlined in Table 5. For example, in the case of the Westminster Bridge, considering the U/R of the girder moment based on the projected temperature was 0.86, Table 5 reveals that this value falls below 90%, therefore signifying a risk level of 1. This evaluation step was repeated for all components, as demonstrated in Table 9, with the overall risk score when U/R becomes the highest value; in this example, the U/R of 100% for the pile component resulted in a risk score of 3.

Table 9. Calculation of governing U/R for the Westminster Bridge.

Structure	Utilization Ratio U/R	Governing Utilization Ratio	Assigned Level of Risk
Substructure	Pile Moment: 1 Pile Shear: 0.12	1.00	3
Superstructure	Girder Moment: 0.86 Girder Shear: 0.29	0.86	1
Non-structure	NA	-	
Risk score of governing utilization factor			3

Step 4b: Evaluating the socioeconomic impact. The next step in the severity evaluation is to consider the socioeconomic impact of the risk. The process of evaluating the socioeconomic risk requires a multifaceted approach, including factors such as the impact on traffic flow, the cost of repair or replacement, and ecological impact. The careful quantification of ratings for each factor was executed and is summarized in Table 10.

Table 10. Calculation of socioeconomic impact for the Westminster Bridge.

Socioeconomic Factors	Assigned Level of Risk as per Table 5
Out of commission for $\geq$ 10 days.	3
Major interruption to service with high cost of work required.	2
Alternatives available.	1
Little or reversible damage to surrounding eco-system.	1
Partial rebuild of structure required.	2
Risk score of the socioeconomic factor.	2

3.5. Step 5: Determination of Overall Risk Rating

The overall risk rating for the Westminster Bridge was determined by combining three essential rating components: the utilization factor risk rating, the socioeconomic factor risk rating, and the occurrence rating. The occurrence rating, an essential dimension, depends on the probability of failure, which is assumed to be more than 65% due to the decision by the MTO to replace the bridge. According to Table 5, a probability of more than 65% corresponds to a high occurrence rating of 3. Therefore, the overall risk rating was determined with the following factors:

- Utilization factor risk rating = 3 (High). As demonstrated in Table 9, the risk rating was determined to be 3.
- Socioeconomic factor risk rating = 2 (Medium). As demonstrated in Table 10, the risk rating was evaluated to be 2.
- Occurrence rating = 3 (High). As demonstrated in Table 5, and inputting other factors into Table 5, the occurrence rating was determined to be 3.

According to Table 5, the overall risk rating for the Westminster Bridge is 18, which is categorized as "High Risk" according to the risk assessment protocol. Receiving a categorization of "High Risk" indicates that the bridge is in critical condition and requires immediate intervention to ensure the safety of the public and the integrity of the structure. All these assessments were carried out based on projected temperature, which means that climate change has a high impact on the infrastructure of existing bridges.

4. Discussion

This case study demonstrated that the original bridge was categorized as "High Risk" based on the input of projected temperature values from the RCP6.0. This conclusion was validated by the action taken by the MTO. The protocol was applied again to the improved bridge design, which resulted in a "Medium Risk" score, demonstrating an improved overall risk rating. The model prediction was validated by the actual results of the improved risk rating of the Westminster Bridge.

Further evaluation of the model is possible through the application of various RCP models. The RCP6.0 emission scenario was selected based on the recommendations of the IPCC as the most likely scenario. Selecting a lower emission scenario is not reflective of the conditions a bridge will experience this century. It is possible to apply the model with RCP8.5; however, given that the bridge in this case study received a risk rating of "High Risk", it is reasonable to conclude that a more aggressive emission scenario will yield the same outcome.

While the proposed risk assessment protocol effectively evaluates the impact of temperature variations on bridge infrastructure, it is important to note the limitations in its current application. The protocol is specifically designed to incorporate the impact of projected temperature on structural risks, but does not currently account for other climate-related impacts such as flooding, hurricanes, or storm surges. These factors, which also pose significant risks to bridge infrastructure, can be incorporated into future iterations of the methodology. The current focus on temperature reflects the primary concern for bridges in regions such as Canada, but the protocol is adaptable to include additional climate effects as data and modeling capabilities evolve. To further improve the protocol, additional factors that can influence risk assessment can be included. Such parameters that can be assessed for input factors can include other climatic factors, maintenance practices, material properties, and construction quality.

5. Conclusions and Future Work

This paper presented a protocol to assess the risk to existing bridge infrastructure in the face of climate change, specifically, projected temperature values. By integrating projected temperature values into determining structural integrity and values for socioeconomic factors, the developed risk assessment protocol provides decision-makers, practitioners, and engineers with a tool to strengthen bridge infrastructure management and resilience for the future.

The case study conducted on the Westminster Drive Underpass in London, Ontario, Canada, highlighted the potential risk and challenges that bridge infrastructure may face due to the IPCC RCP6.0 temperature values. Further, this case study provided an illustration of the usability of the protocol and application in practice. The model was validated by concluding the reduction in risk between the original bridge and the improved bridge.

The risk assessment protocol outlined five steps that provide a clear and systematic approach to evaluating the risk of an existing bridge. By selecting a bridge, breaking down the overall bridge system into components, then calculating the utilizing factors, evaluating severity factors, and determining an overall risk rating, this protocol provides a comprehensive evaluation that encompasses both the structural response and socioeconomic implications of failure.

The protocol emphasizes the importance of considering socioeconomic factors in the risk assessment process. By incorporating the potential impact of bridge failures on society, such as disruptions to transportation networks, economic losses, and public safety concerns, the protocol ensures that decision-makers take a holistic approach to evaluating risk.

This protocol addresses the gap in research on creating a risk assessment method for bridges that evaluates structural integrity based on projected models and incorporates socioeconomic considerations. It proposes that current practices, including design code values and risk evaluation of structural integrity on its own, are not sufficient for future climate change considerations.

There is a need for ongoing adaptation strategies for managing the risk to bridge infrastructure due to our rapidly changing climate. As climate change continues to evolve, it is crucial that the risks and vulnerabilities of existing bridges are regularly reassessed and that appropriate programs are implemented. The protocol presented is a tool for decision-makers to assess the level of projected risk effectively and efficiently.

The protocol's potential impact extends beyond assessing existing infrastructure, as it can guide the design of future bridges and influence design codes. Future studies could include additional factors such as the impact of extreme weather events, changing precipitation patterns, and their combined effect. Additionally, the applicability of the protocol to different bridge types of geographical regions could be explored to ensure its effectiveness in various contexts. Future work and models can also be designed to allow for input of dynamic climatic projection values to assess the impact on bridge structure. Furthermore, ongoing research and collaboration with other disciplines, such as climate science and social sciences, could enhance the understanding of the complex interactions between climate change and bridge infrastructure.

In conclusion, this paper provides an approach to assessing the risk of existing bridge infrastructure in the face of climate change. By integrating temperature projections, structural integrity and socioeconomic factors, the developed risk assessment protocol offers a valuable tool for decision-making to strengthen bridge infrastructure resilience.

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