Risk Assessment of Bridges Due to Flood and Overloading Events in Manitoba

By

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To all the remarkable individuals who have been a source of unwavering support, inspiration, and love throughout my journey, I extend my heartfelt gratitude .

First and foremost, I would like to pay tribute to my late father, Davoud. His unwavering belief in my abilities and his boundless love have shaped me into the person I am today. Though he is no longer with us, his memory continues to guide and motivate me every step of the way.

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Abstract

The challenges posed by Canada's aging infrastructure and limited economic resources have underscored the need for proactive measures to address the vulnerabilities inherent in its bridge systems. This study seeks to develop a comprehensive framework tailored to the evaluation of risk factors associated with flooding and overweight traffic on typical highway bridges in Manitoba.

The primary objective of this research is to establish a robust methodology for assessing risk values arising from the combined effects of flooding and overweight traffic on bridge structures. To this end, the study engages in a thorough analysis of historical flood data to pinpoint flood-prone zones. Concurrently, historical data pertaining to Average Annual Daily Traffic Volume (AADTT) and Overweight (OW) percentages are examined to ascertain the frequency of overloading risk for bridges due to overweight traffic. The investigation extends to the determination of overtopping levels for individual bridges, complemented by the establishment of vertical clearance thresholds spanning a range from 3 to 12.6 meters. Additionally, the research investigates the interplay between OW (%) and AADTT, revealing a direct relationship wherein heightened truck traffic contributes to an elevated percentage of excessive loading on bridges. Consequently, this heightened loading exacerbates the risk of bridge failures.

The results of the analysis show for five different levels of flooding, a probability of failure ranging between 0.0155 and 0.0081. Bridges close to the Red River are at higher risk due to more water flow. The probability of failure due to overloading ranges from 3.74e-09 to 1.29e-08. The most vulnerable area in Manitoba is along the Trans-Canada highway and the north-south corridors near Winnipeg. This highlights the importance of considering specific locations when designing and maintaining bridges to ensure their safety.

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Chapter One: Introduction

The maintenance and rehabilitation of aging bridges in Canada have become a major challenge as approximately 45% of bridges have reached their life expectancy and the budget only covers 59% of the estimated cost [1]. Moreover, recent natural and man-made disasters have demonstrated the difficulty communities face in re-covering socially and economically from these events. Indeed, floods have been recognized as a significant factor contributing to bridge failures not only in Canada but also worldwide. The destructive force of floodwaters, especially during extreme weather events, can lead to the erosion of bridge foundations, the undermining of support structures, and even structural collapse [2].

1-1 Definitions and Terms

Before discussing the objectives of this research, here several definitions related to the key terms utilized in this research are provided. These definitions aim at establishing a common understanding and terminology for the concepts discussed throughout the study.

1-1-1 Financial Losses

Financial losses refer to the economic impacts and damages incurred as a result of flood events for the community including Commercial and Personal losses [20].

1-1-2 Clearance

In the context of bridges, clearance refers to the vertical distance between the lowest point of a bridge structure (such as the underside of a beam or the bottom of a bridge deck) and a specified reference point, typically the water surface or the road surface underneath the bridge [21].

1-1-3 Vertical Clearance

Vertical clearance specifically refers to the vertical distance between the lowest point of a bridge and the highest point of an object passing beneath it, such as a vehicle, vessel, or floodwater level [21].

1-1-4 Weigh-In-Motion (WIM)

According to the definition provided in ASTM E 1318, vehicle weigh-in-motion (WIM) is the process of determining a moving vehicle's total weight and the distribution of that weight on each wheel, axle, axle group, or combination of these components. This is achieved by measuring and analyzing the dynamic tire forces of the vehicle [8].

1-1-5 Percentage of Overweight Vehicles

The percentage of overweight vehicles refers to the proportion of vehicles that exceed the legal weight limit for a particular road or bridge. This can include vehicles that are overweight in terms of gross vehicle weight (GVW), which is the total weight of a vehicle and its cargo, or axle weight, which is the weight of a specific set of axles with wheels [22]. Overweight vehicles can put excessive stress on bridges and roadways, leading to increased wear and tear and a higher risk of failure. It can also cause damage to the infrastructure and lead to higher maintenance and repair costs. The legal weight limits vary by jurisdiction and are typically set based on the capacity of the infrastructure and the potential impacts of overweight vehicles on safety and the environment [23].

1-2 Objectives of the Research

This research is conducted with the aim of obtaining an estimate of the risk value associated with flood events in Manitoba, Canada. The assessment of risk is a crucial factor in understanding and managing the potential impacts of floods on infrastructure, particularly bridges. The target of this study is to develop a comprehensive framework for evaluating the risk value of typical highway bridges in Manitoba by considering key factors such as the probability of highway traffic overweight, the probability of flood events due to vertical clearance, and the estimation of the financial losses of floods are focused. This framework will contribute to a better understanding of the potential risks and facilitate effective decision-making processes in terms of flood preparedness, infrastructure design, and risk mitigation efforts. In light of these challenges to achieve the goal of this research, three main steps were employed to assess the risk value of bridges in Manitoba. A summary of each step is provided below, and all details of methodology and approaches of them will explain in chapter 3.

1-2-1 Economic Consequences

This section will focus on investigating the impact of financial losses resulting from the flood incident in the regions of major highways in Manitoba province. By analyzing historic records of flood economic consequences collected from the Catastrophe Indices and Quantification Inc. (CatIQ) platform [7], this step will estimate the insurance cost of floods per square kilometre in the vicinity of highway bridges. In addition, as long as estimating the outcomes is logically feasible and allows for comparability, flood financial losses will estimate in two neighbouring states, Minnesota (MN) and North Dakota (ND) in the US. The common point among these three areas is the Red River, which holds significant potential for flood incidents. The Red River originates in the southern parts of North Dakota and Minnesota, and it flows northward, creating the boundary between these two states (Figure 1). Upon entering Canada near Emerson, Manitoba, the Red River undergoes a name change, transitioning from "Red River of the North" (its official name in the United States) to simply "Red River" in Manitoba.

As it flows northward, the Red River is joined by tributaries from both the east and west, forming a trellis pattern at the southern boundary of Winnipeg.

The landscape of the Red River valley plays a significant role in the nature of Red River floods. Firstly, the gentle lateral gradients in the valley allow overbank flows to spread over a much larger area compared to typical floodplains. Secondly, the main channel's very slight down valley gradient, combined with the capacity of the flooded area to store water, results in very slow travel times for floodwaters [3].

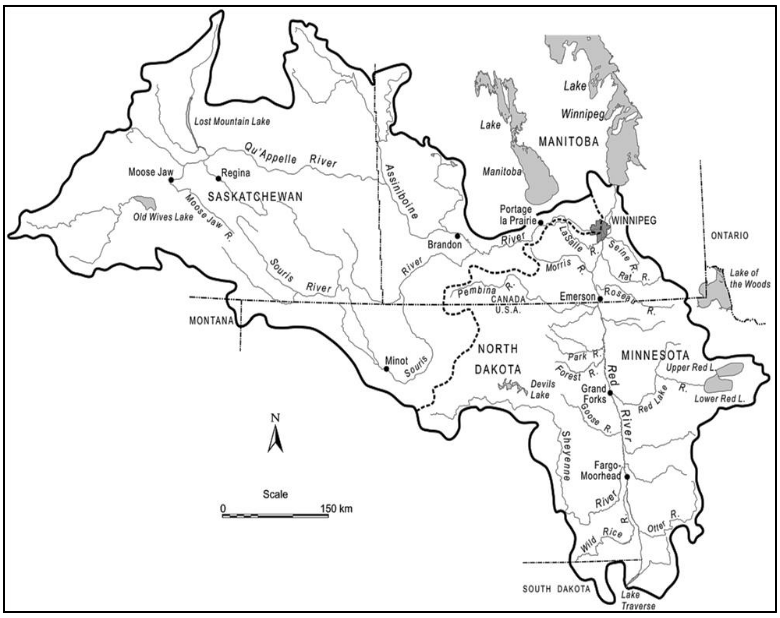

Figure 1. Red River drainage basin [3]

1-2-2 Probability of Bridge Failure due to Floods

Considering vertical clearance as a bridge requirement in flood scenarios will apply to Manitoba's bridges in the context of this step. Using vertical clearance and water level as key parameters, the study seeks to evaluate the probability of bridge failure specifically attributable to floods. By considering these factors, the research aims at developing a quantitative measure of the likelihood of failure in flood-prone areas. During floods and large-scale inundations, adequate vertical clearance is essential to prevent overtopping, structural damage, or even the collapse of bridges during such extreme events. [4]. Floods can lead to increased water levels, river overflow, water turbulence, and high flow velocities. In such situations, vertical bridge clearance must be appropriately designed to allow for the potential volume of water to pass freely, preventing water congestion and interference with the bridge structure [5,6].

1-2-3 Probability of Bridge Failure due to Overweight Traffic

The target of this step is to identify vulnerable areas for Manitoba's bridge failure due to overweight traffic. This information can help prioritize resources for risk-based bridge management. In this part, through statistical analysis of overweight percentage, extracted from

Weigh-In-Motion (WIM) sites, and average annual daily truck traffic (AADTT), the research seeks to quantify the probability of failure associated with excessive weight on bridges. By analyzing WIM data, researchers can identify overweight vehicles and assess the damage they may be causing to the bridge. This information can help inform maintenance and repair strategies, ultimately improving the safety and longevity of the bridge [8].

1-3 Research Relevance

There are several reasons why a risk-based bridge analysis approach is important.

1. Bridge failures can have significant economic impacts: Bridge failures can result in severe economic consequences [31]. The disruption of transportation networks can hinder the movement of goods and services, causing disruptions in supply chains and increased costs for businesses. Local economies may suffer as reduced accessibility and productivity impede economic growth. Industries relying on efficient transportation infrastructure, such as manufacturing and logistics, may experience decreased competitiveness. It is crucial for policymakers and transportation planners to recognize these economic impacts in order to allocate resources effectively, prioritize maintenance and repair efforts, and develop strategies to mitigate the economic consequences of bridge failures [11-12].
2. Bridges are a critical component of transportation infrastructure: Bridges serve as vital links, connecting different parts of a region or country, and enabling the smooth movement of goods, services, and people [9]. Ensuring the safety and reliability of bridges is therefore essential for the economic and social well-being of communities. Research on the economic consequences of bridge failure can help policymakers understand the importance of investing in bridge maintenance and repair and can inform decisions about how to prioritize investments in different types of bridges and transportation projects [10].
3. Cost-Effectiveness: Adequate bridge risk estimates can contribute to cost-effective mitigation strategies [14].
4. Resilience and Adaptation: As climate change leads to more frequent and intense flooding events, it becomes crucial to ensure the resilience of bridges against floods [15]. Bridges with adequate vertical clearance to withstand flood conditions, minimizing damage and facilitating post-flood recovery efforts [16].
5. Fostering Public-Engineering Trust: Building and maintaining trust, confidence, and frankness between the public and the engineering profession is crucial for the long-term

benefit of both parties. When there is open communication and transparency, the public can have faith in the safety and quality of engineering projects, and the engineering profession can gain valuable feedback and insights from the public [17].

6. Perils of Inadequate Structural Design: In many cases, when structures are not designed or built to withstand such extreme loads, there is a risk of failure or collapse. This can have severe consequences, not only in terms of property damage but also the potential loss of life and disruption to communities [18].
7. Safety and Risk Mitigation: Assessing the probability of bridge failure resulting from inadequate vertical bridge clearance helps identify potential hazards and risks. By quantifying this probability, engineers and decision-makers can prioritize corrective actions and allocate resources to mitigate the risk of accidents and structural failures.
8. Optimal Design and Retrofitting: Understanding the probability of failure due to insufficient vertical clearance assists in designing new bridges or retrofitting existing ones. Engineers can optimize designs to ensure that bridges have adequate clearance for various types of vehicles, reducing the likelihood of future failures.
9. Utilizing WIM Data for Bridge Failure Risk Assessment: By analyzing data collected by WIM systems, researchers can identify the percentage of overweight vehicles over a specific time frame on a bridge [19]. This information can then be used to identify bridges that may be at a higher risk of failure due to excessive traffic loads and to inform decisions about weight restrictions and enforcement. Additionally, the relationship between WIM data and the economic consequences of bridge failures can be studied to understand how overweight vehicles contribute to the costs associated with bridge failure, including repair and replacement costs, as well as economic losses due to disruption of traffic flow. Also, WIM data can be used to correlate with the location of bridge failure and the cost of flood and help to identify the areas that are more prone to the weight of the vehicle and flood. This can help decision-makers and transportation engineering to refine probabilistic risk-based models to quantify the risk of failure of highway bridges for design and evaluation purposes.

1-4 Research Questions

The research questions form the backbone of this study as they guide the investigation and provide a clear focus on the key aspects of the financial impact of flood damages, the hazard of floods due to vertical clearance, and the hazard of traffic overweight. By addressing these research questions, gaining a comprehensive understanding of the risks associated with these factors and their implications for flood events has been targeted.

1. How does bridge failure impact local, regional, and national economic activity? This could involve studying the economic impacts of bridge closures on industries such as transportation, tourism, and logistics, as well as the impact on local businesses and workers.
2. Are there specific types of bridges or geographic areas in Manitoba that are more susceptible to damage from overweight vehicles?
3. How does the risk of bridge failure vary across different geographic regions or types of bridges? This could involve studying the factors that contribute to the likelihood of bridge failures, such as climate, traffic volume, and maintenance history, and exploring how these factors vary across different regions or types of bridges.
4. What are the potential risks associated with insufficient vertical clearance of bridges during flood events?
5. How does the variation in water levels during floods pose risks to bridges and their clearance requirements?

1-5 Assumptions

In this study, it is essential to gather and analyze various data sources to address the research objectives effectively. Each section of the research requires specific data related to the financial losses of floods, vertical clearance, water levels, and Weight -in-Motion. The availability and reliability of data play a critical role in ensuring the accuracy and validity of the findings. Therefore, it is important to outline the assumptions regarding the data sources and their limitations to provide a comprehensive understanding of the research process.

1-5-1 Source of Data for Financial Losses of Flood

In this study, various sources were utilized to gather reliable data on the topic of research in Canada. These included correspondence with Manitoba Public Insurance, the National Collision Database, the Hydrologic Forecast Centre of Canada, and Flood Information of Manitoba, among others. However, due to issues such as confidentiality or a lack of sufficient information, the data for this study were ultimately sourced from two valid organizations, CatIQ and FEMA. Canadian data for this study are extracted from the Catastrophe Indices and Quantification Inc. (CatIQ) [7] platform and data related to US states comes from the Federal Emergency Management Agency (FEMA) [25].

1. CatIQ

This research utilized data from the Catastrophe Indices and Quantification Inc. (CatIQ) platform as a source [Appendix A]. CatIQ is a Toronto-based company, CatIQ is a subsidiary of PERILS AG that offers detailed analytical and meteorological data regarding Canadian natural and human-made catastrophes through its subscription-based online platform. This platform combines comprehensive insured loss and exposure indices along with other related information to cater to the needs of the insurance, reinsurance, and insurance-linked securities (ILS) industries, as well as the public sector and other stakeholders. CatIQ was established in 2014 with the support of the majority of the Canadian insurance and reinsurance industry and has earned a strong reputation as a reliable source of catastrophe loss information in Canada [24].

2. FEMA

The Federal Emergency Management Agency (FEMA) is an independent agency of the United States federal government that is responsible for coordinating the response to disasters and emergencies that occur within the United States. It was established in 1979 and is part of the Department of Homeland Security. FEMA provides a wide range of services, including disaster preparedness and response, recovery assistance, and mitigation of the impacts of disasters on communities. In addition to responding to disasters and emergencies, FEMA also works to support and strengthen the preparedness of states, tribes, territories, and local communities to reduce the risk of future disasters. Some of the specific programs and initiatives that FEMA is responsible for include the National Flood Insurance Program, the National Weather Service, the National Earthquake Hazards Reduction Program, and the US Fire Administration [25].

1-5-2 Source of Data for Vertical Clearance

Data related to this section were collected only for the province of Manitoba, Canada, which is the main subject of this research. The information regarding vertical bridge clearance has been obtained from Manitoba Transportation and Infrastructure. In addition, water level data was extracted from the Water Management and Structures-Water Information and Flood Conditions of Manitoba Government Website [26].

This source provides relevant data and information related to water management, including details on water levels, flood conditions, and associated factors that can impact the vertical clearance of bridges.

1-5-3 Source of Data for Overweight Traffic and AADTT

The data of overweight traffic are extracted from Weight -in-Motion (WIM) sites across three regions as follows [27-29]:

- Six LTPP WIM sites in Manitoba, Canada from 2000 to 2013.
- Nineteen WIM sites in Minnesota, USA from 2000 to 2013.
- Fourteen WIM sites in North Dakota, USA from 2000 to 2013.

The WIM sites are shown in Figure 2.

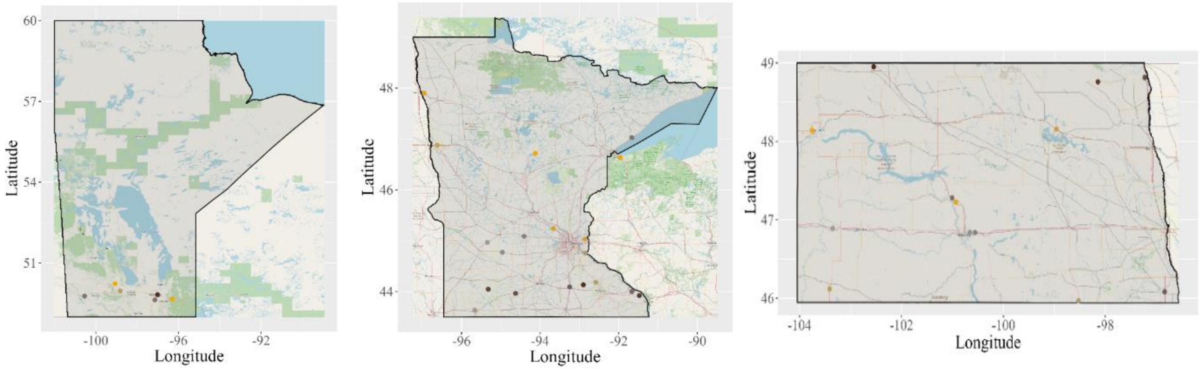

Figure 2. WIM site locations in Manitoba, Minnesota, and North Dakota respectively

To estimate the probability of hazards due to overweight traffic for bridges, the Average Annual Daily Truck Traffic (AADTT) is extracted from Transportation and Infrastructure Organization for each region (MB, MN, and ND) [28,29,30].

1-6 Applications of Proposed Research Results

Overall, the applications of this research extend to various domains, including bridge management, risk assessment, infrastructure planning, policy development, and emergency management which will be explained in Chapter 5. The findings can serve as a valuable resource for decision-makers, engineers, and stakeholders involved in the management and resilience of bridge infrastructure.

1-7 Research Methods

The method of this research is based on Case study and Econometric analysis. In this study, flooding on typical highway bridges in Manitoba, through an examination of Manitoba and two northern states in the US (North Dakota and Minnesota) had been studied.

By combining case study analysis, econometric techniques, and statistical methods, this research aims at providing a comprehensive understanding of the factors contributing to bridge failure risk and the economic consequences of such failures. The findings will support evidence-based decision-making and policy development in managing and mitigating the risks associated with bridge failures in flood-prone areas.

1-8 Framework and Structure of the Research

This project has six chapters, which include the following:

Chapter 1: Introduction

- Providing a general overview of the research, highlighting the main objectives and research questions

Chapter 2: Literature Review

- Reviewing relevant literature on bridge failures, flood risks, and economic consequences
- Examining existing research on the factors contributing to bridge failure and the assessment of risk value

Chapter 3: Methods of Analysis

- Research approach and methodology
- Statistical methods employed to analyze the data
- Case study

Chapter 4: Discussion

- Key findings and results of the research
- Highlighting the relationship between flood risks, overweight traffic hazards, bridge failures, and financial looses
- Interpreting the results and discussing their significance

Chapter 5: Conclusions and Future Work

- Summarizing the main findings, contributions, and practical implications of the research
- Restating the research objectives and highlighting the key takeaways
- Suggesting areas for future research and improvement in the methodology

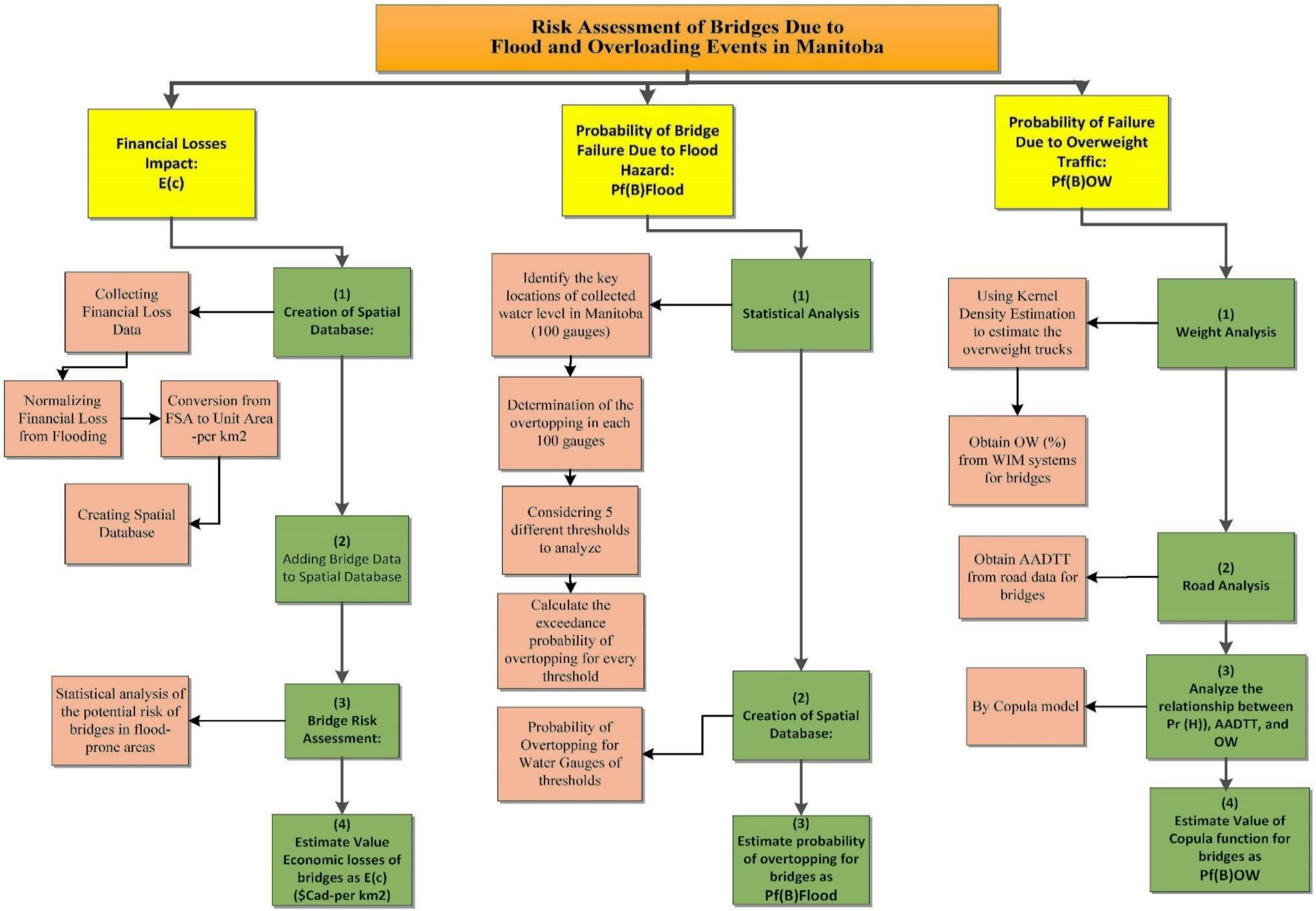

Figure 3. Flowchart of the Methodology

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Chapter Two: Literature Review

Bridge failures are not just about engineering problems in one place. They have widespread effects on how economies work in modern societies [1]. The delicate balance of trade and commerce can be disrupted as transportation networks falter in the face of the bridge collapse, resulting in a domino effect of reduced revenues and heightened operational costs for enterprises. The repercussions, however, are not confined to the immediate economic realm. The ripples of bridge failure cascade outward, touching property values and curtailing tourism, thus impinging on the broader socioeconomic fabric [2]. In this context, this chapter provides a comprehensive overview of the key topics related to risk assessment of bridges from previous research to set the foundation for the subsequent analysis and evaluation of bridge network vulnerabilities, risk mitigation strategies, and resilience-based asset management practices.

2-1 Literature Review

A review of previous studies indicates that a significant portion of research has focused on the failure of bridges and their causes. However, there has been a limited number of studies that have analyzed the risk value base on three main factors of this study integrally: financial impact, probability of bridge failure due to overloading and flood, especially in Canada. After that, the limitations of the existing research are discussed and areas for future study are identified.

Findings from the literature are summarized as follows:

- Simplified methodology for indirect loss–based prioritization in roadway bridge network risk assessment, Abarca, et al., 2022 [3]. The paper focuses on evaluating the relative importance of bridges in terms of network disruption level, considering the potential impact of bridge collapse on the overall functionality of the road network. The method of analysis involves the development of a transportation network model for the case-study region, which is the province of Salerno, Italy. The detailed methodology involves static traffic assignment analysis, while the simplified alternative uses impedance between centroids (Figure 3). These methodologies require preliminary data such as road network configuration, road modelling parameters, origin-destination travel demands, and expected bridge repair times. The outputs of the analysis include economic losses and changes in vehicle hours travelled (VHT).

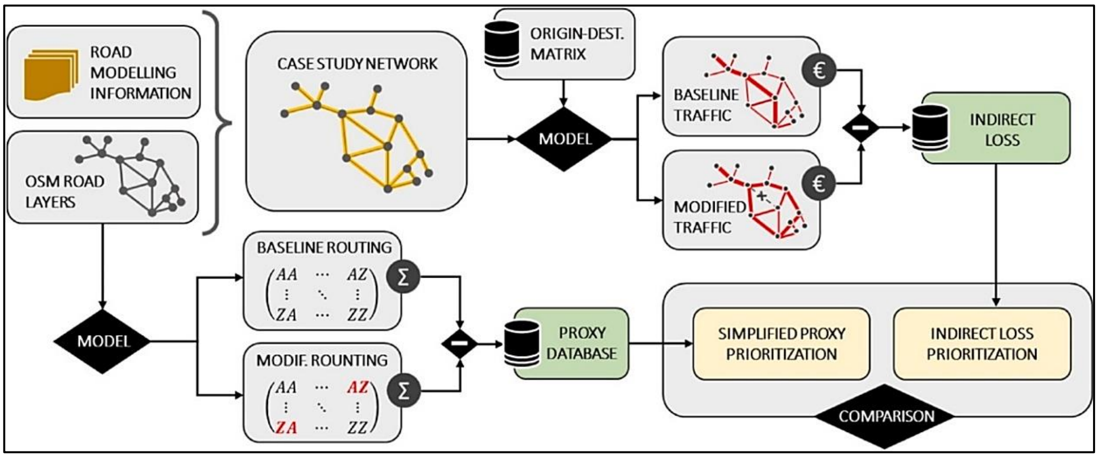


Figure 4. Methodology of estimating indirect losses and a simplified proxy-based alternative [3]

Proxy value:

Eq.2-1 $$\Delta VHT_i = MVHT_i - BVHT$$

Where:

BVHT: the sum of all values from the travel time skim matrix of the fully operational road network

$MVHT_i$: the sum of all values from the travel time skim matrix of the road network after removing bridge i from the model

- "Review Article: Causes and Statistical Characteristics of Bridge Failures" [12]: This paper provides a comprehensive overview of 10 previous investigations focusing on the typical characteristics and causes of bridge failures. The study highlights the close correlation between bridge failures and factors such as regional economy, structural type, type of use, material type, and service age. In this study, the authors noted specific instances of economic loss resulting from bridge failures in case studies. As an example, the authors cited the catastrophic collapse of the Tuojiang Bridge in 2007, which resulted in 64 fatalities, 22 injuries, and a direct economic loss of approximately 39.747 million yuan, as reported by Peng et al. (2019).

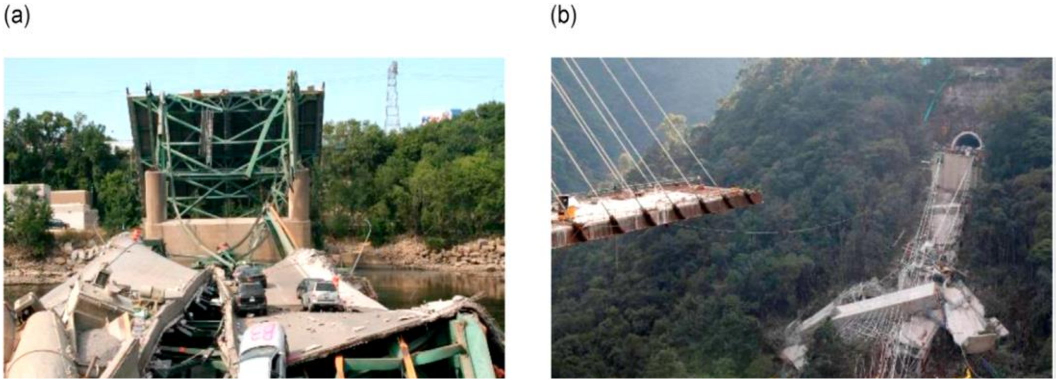


Figure 5. Bridge failures due to design errors.
(a) Defects in design theory. (b) Design mistake [12]

- "Life-cycle cost-based risk assessment of aging bridge networks" [4]. This paper presents a comprehensive framework for the seismic risk assessment of aging bridge networks, focusing on the life-cycle cost perspective. This paper proposes a probabilistic framework that incorporates life-cycle cost considerations to assess the seismic risk of spatially distributed aging bridge networks. In this study, the proposed methodology for life-cycle cost-based risk assessment of aging bridge networks is implemented and tested on a road system located in the Lombardy region of Italy. This road system covers four major cities along with smaller neighboring municipalities within the region. The presented framework provides valuable insights into the seismic risk assessment of aging bridge networks, considering both the structural performance of individual bridges and the economic implications for the overall network.
- The article titled "Development of a Risk Assessment Module for Bridge Management Systems in New Jersey," [5]. This study investigates the application of risk-based methodologies to identify, evaluate, and quantify structural risk factors in bridges, employing probabilistic risk methodologies and data from the National Bridge Inventory database. The authors' objective is to facilitate the seamless integration of risk-based ranking procedures into bridge management system packages, aligning with the MAP-21 vision. They also employed machine learning techniques to aid the implementation of probabilistic risk methods in bridge management systems. The study specifically concentrates on seven hazards that are pertinent to bridges in New Jersey, such as overloading, fatigue, seismic events, flooding, scour, and vehicle and vessel collisions. To ensure a consistent comparison among bridges for various hazards, risk values are quantified in monetary terms. The analysis encompasses a dataset of 5,534 bridges. The findings reveal that seismic events and fatigue caused by truck overloading pose the most significant hazards in New Jersey, affecting approximately 97.0% and 29.0% of bridges, respectively, with some level of risk associated with these hazards.

One of the main limitations of the proposed framework is the difficulty in obtaining precise bridge inventory data, which is essential for conducting a comprehensive structural probabilistic analysis of bridges and reducing the reliance on engineering judgment.

- Risk-based importance factors for bridge networks under highway traffic loads [18]. This article introduces a risk analysis framework that aims to assess the significance of bridges within a highway network when exposed to overweight traffic loads. The study shows that traffic delays are the primary consequence of bridge failure, accounting for 61% of the total risk, followed by the maintenance of bridges (21% of the risk). The analysis also considers the environmental impact, injuries, fatalities, and material construction costs as components of the overall risk. The framework of risk analysis of this study is shown in Figure 6, and the distribution of risk consequences on the network conveys in Figure 7. The pie chart shows how the components that characterize the risk are distributed on the network; the effect of traffic delays (D), environmental impact (E), injuries (I), fatalities (F), construction (C) and maintenance (M).

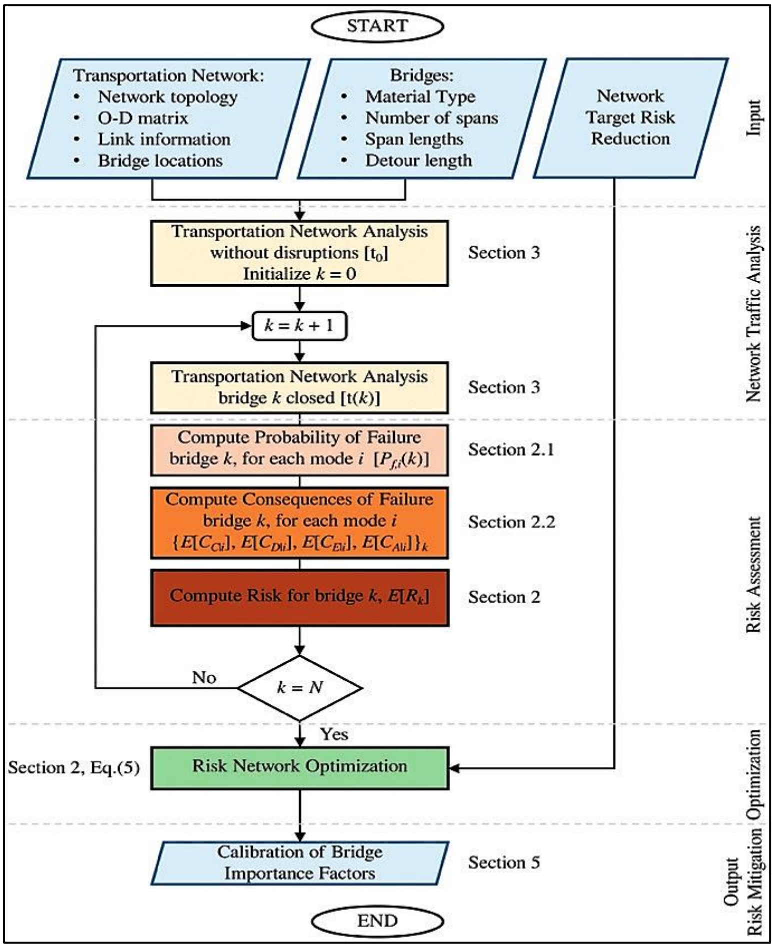


Figure 6. Risk-based framework for the analysis of transportation bridge networks

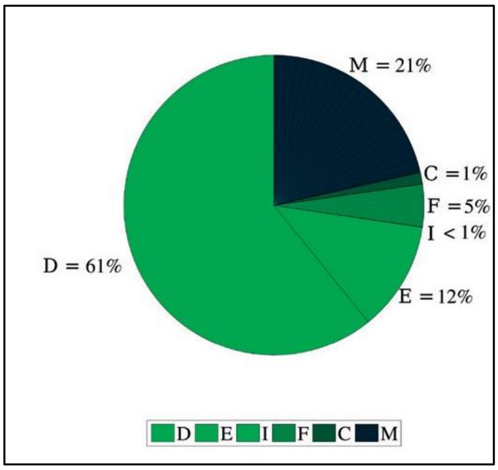


Figure 7. Risk distribution on the network

- System-Level Seismic Risk Assessment of Bridge Transportation Networks Employing Probabilistic Seismic Hazard Analysis [6]. To address the challenges of accurately assessing the seismic risk of such networks and provide valuable insights into estimating their performance (Equation 2-2). The method of analysis presented in this article involves three main steps: 1. Component failure probability calculation of bridges based on probabilistic seismic hazard analysis (PSHA). 2. System-level performance estimation of the transportation network using the matrix-based framework of the Maximum Serviceability Range (MSR) method. 3. Seismic risk assessment based on the total probability theorem.

  The probability of a system is expressed as:

  Eq.2-2 [6] $$P(E_{sys}) = \iint P(E_{sys}|m,l)\, f_{M,L}(m,l) dmdl$$

  Where:
  E_{sys}: the system event of interest
  M : the earthquake magnitude
  L: the earthquake location
  $f_{M,L}(m,l)$: the joint probability density function (PDF) of the earthquake magnitude and location when $M = m$ and $L = l$

- The fragility of transport assets exposed to multiple hazards: State-of-the-art review toward infrastructural resilience [7]. This paper provides a comprehensive state-of-the-art review of natural, geotechnical and weather hazards on transport infrastructure, including the main failure modes, EDPs, and typologies for roads, bridges, tunnels, embankments, retaining walls and backfills. It highlights future opportunities for further developments in the fragility analysis of transport Systems of Assets (SoA) under multiple hazards. This analysis is helpful for decision-making processes regarding adaptation, mitigation, and recovery planning in the face of geotechnical and climatic hazards. The review also discusses engineering advancements in developing numerical fragility functions for individual assets, including considerations for soil-structure interaction, deterioration, and multiple hazard effects.

- "Bridge Collapse Frequencies versus Failure Probabilities" [8]. The book explores the correlation between computed probabilities of failure and the observed frequencies of bridge collapses. Additionally, it identifies accidental loads as the primary causes of bridge failures and delves into the management of these loads through codes of practice. Furthermore, the book highlights that the age of bridges has a relatively minor impact on collapse incidents. Nonetheless, it emphasizes that the significant return periods of accidental loads restrict the conclusions that can be drawn from collapse data with short time periods. Moreover, the book points out that the responsible authority for selecting design loads for accidental impact loads is often the same entity that bears the financial responsibility for strengthening existing structures for new and updated loads, potentially creating a perception of bias. In conclusion, the book emphasizes that the major causes of bridge collapse are technically manageable, and the observed collapse frequencies of bridges affirm the validity of the probabilistic safety concept. Despite the relatively limited risk of human loss associated with most loads and causes, the book advocates for further improvements, particularly concerning impacts, which have historically led to disasters with more than 200 fatalities. This suggests that additional measures and advancements are needed to address this specific risk area effectively.

- Towards a whole-network risk assessment for railway bridge failures caused by scour during flood events [9]. By analyzing historical data from the British railways, it is revealed that there have been 54 recorded events since 1846 in which scour led to the failure of railway bridges. These failures predominantly occurred during periods of extremely high river flow (Equation 2-3,2-4). However, there is uncertainty regarding the precise conditions that result in bridge failures, necessitating a probabilistic analysis of the failure events. In this study, the developed fragility analysis serves as an empirical basis for conducting broader-scale network risk assessments.

Fragility function to describe the probability of failure conditional on a flood event:

Eq.2-3 [9]
$$P_r(failure|y) = F(y) = \phi\left(\frac{ln\left(\frac{y}{\theta}\right)}{\beta}\right)$$

Where:

y is the return period of the flood event associated with a failure.

$\phi(.)$ is the standard normal distribution function.

θ is a location parameter.

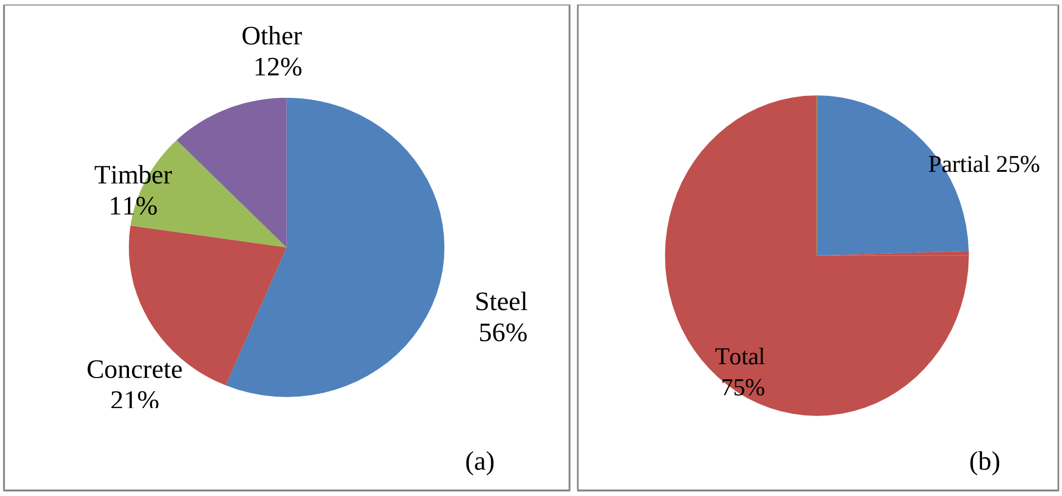
β is a dispersion parameter, and

Eq.2-4 [9]
$$F(y) = \int f(y)dy = \int_y \ \varphi\left(\frac{ln\left(\frac{y}{\theta}\right)}{\beta}\right)$$

- "Bridge Collapses Around the World: Causes and Mechanisms" [10]: This paper provides a review of bridge failures worldwide, focusing on their common causes and mechanisms. Failures are classified into natural factors, such as floods, earthquakes, and landslides, and human factors, including improper design, overloading, and lack of maintenance. The collapse modes of historic bridges are examined, and some recent failures in Bangladesh are discussed. While thousands of bridges are built annually, only a few collapses due to natural and human factors, leading to economic loss and, in some cases, loss of life. Bridge designers learn from past failures and work towards avoiding them by using new materials, efficient construction methods, and advanced technology.

- " Bridge Failure Rates, Consequences, and Predictive Trends" [11]: This dissertation investigates the failure rate of bridge collapses in the United States, the causes of these collapses, and the consequences of the collapses. The first investigation analyzed a database of bridge collapses to determine the collapse rate of bridges within one state and the dominant cause of these collapses, which was found to be hydraulic in nature. The second investigation examined the consequences of bridge collapses, such as loss of life and disruption of traffic, and found that the collapse of bridges is random with respect to average daily traffic. The third investigation analyzed the relationship between pre-collapse conditions of bridges, such as age and structural deficiency, and the likelihood of a collapse. The results of this analysis showed that the best predictor of a collapse is a structural deficiency, and the primary recommendation for improving data collection on bridge collapses is to focus on collecting more data.

- A Study of U.S. Bridge Failures (1980-2012) [13]: The objective of this report is to establish data sources for developing load distribution models and bridge damage models for the reliability-based formulation of design limit states. The literature search for this project included various sources such as reports from the American Association of State Highway and Transportation Officials and the Multidisciplinary Center for Earthquake Engineering Research, articles from scientific journals and the American Concrete Institute, books on bridge collapse and failure, articles from newspapers, and web pages. The collected information on bridge damage was used to generate a database and the literature discussed bridge failures and strategies for preventing collapses (Figure 8).



(a) Categories of the material type of the failed bridges due to floods (301 failures)
(b) Categories of the type of failures observed in bridges during floods (301 failures)

Figure 8. Material Types and Failure Types in Bridge Collapses due to Floods [13]

- "Traffic Flow and Road User Impacts of the Collapse of the I-35W Bridge over the Mississippi River" [14]: The study investigates the traffic dynamics following the failure and reopening of the I-35W Mississippi River Bridge. The behavioral reactions of travellers during both unexpected and preplanned disruptions are analyzed. The research collected data through GPS tracking, surveys, and aggregate traffic flow data. After the bridge collapse, an avoidance phenomenon was observed, where drivers initially avoided the disruption site until the perceived risk diminished. The traffic stabilized around the bridge site in about six weeks. The study suggests that quick and well-designed detour plans can help improve traffic conditions and assist travellers in developing alternative travel plans. The new I-35W Bridge proved beneficial in reducing total travel costs for most travellers, and its construction saved travel time worth $49,000 per day. However, some changes in travel demand and route decisions may have affected the overall travel time savings. The study also identified an unusual travel time increase in the morning peak period after adding a faster link with high capacity to the network. It suggests that future bridge maintenance may be more beneficial with full closure, considering the flexibility in travel patterns and network redundancy observed in the study. A transportation planning model with full feedback between travel costs and demand can help weigh potential benefits and costs under partial and full closure scenarios for future decision-making.

- Mohammed Ismail Hersi in his Master's Thesis analyzed bridge failures in the United States from 2000 to 2008 [15]. This thesis focuses on the importance of infrastructure safety in the United States, particularly in regard to bridges. It discusses the various causes of these failures, such as enabling, triggering, and procedural events. The overall safety of bridges and the concepts of structural deficiency and functional obsolescence in the United States are also explored in detail. The purpose of this discussion is to highlight the significance of studying bridge failures in the United States and to identify potential solutions to this problem.

- Comparison of Post-Earthquake Highway Bridge Repair Costs [16]: In this research, the authors attempted to estimate the post-earthquake repair costs, and provide transportation managers with a ratio of these costs to the estimated cost of new construction by statistical analysis. This ratio is intended to be useful for inventory assessment and post-disaster decision support.

- "Reliability-based Failure Cause Assessment of Collapsed Bridge during Construction" [17]: in this article, authors provided an algorithm of automated event tree analysis (ETA) that is proposed and possible to automatically calculate the failure probabilities of the failure events and the occurrence probabilities of failure scenarios. The proposed methodology was applied to the Hang-ju Grand Bridge which collapsed during construction.

2-2 Summary

Despite previous studies on various aspects of risk assessment in bridge failure, there is still a need for further research, particularly in the evaluation of flood-related risks, which are significant contributors to bridge failures worldwide, especially in North America. Previous research has demonstrated that these risks can have devastating consequences, including significant financial losses. However, previous studies have not adequately addressed certain key aspects related to the assessment of flood risks in bridge networks in Canada, such as the consideration of vertical clearance and water levels, the impact of overweight traffic, and the associated financial losses. These factors are crucial in understanding the comprehensive risk profile of bridge infrastructure.

The methodology employed in previous studies primarily focused on qualitative or limited quantitative approaches in specific case studied. In contrast, this research utilizes a combination of statistical methods, risk assessment techniques, and prioritizing. This integrated approach allows for a more robust and comprehensive analysis of the risk factors associated with bridge failures due to flood events. By adopting statistical methods and conducting a thorough risk assessment, this study aims at filling the existing knowledge gaps and provide a deeper understanding of the vulnerabilities and risks faced by bridge networks. The findings of this research will contribute to the development of more effective risk management strategies and decision-making processes.

The significance of this research lies in its emphasis on evaluating the risks associated with flood events, which pose a substantial threat to bridge infrastructure. By addressing the limitations of previous studies and considering the specific factors of interest, such as flood hazards, vertical clearance, overweight traffic, and the impact of flood financial losses, this research aims at enhancing our understanding of the complex dynamics and interactions between these factors.

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Chapter Three: Methods of Analysis

The objective of this chapter is to develop an approach that accounts for the importance of highway bridges in a transportation network and the risk of their failure due to flood events and overloading, on the well-being of the affected community during the bridge design and evaluation processes.

The assessment of risk is a crucial factor in understanding and managing the potential impacts of floods on infrastructure, particularly bridges. In this study, the focus is on evaluating the risk value by considering three key factors, the probability of overweight traffic, the probability of flood events with respect to vertical clearance, and financial losses due to floods. The analysis is performed using the risk analysis framework shown in Figure 9 [1].

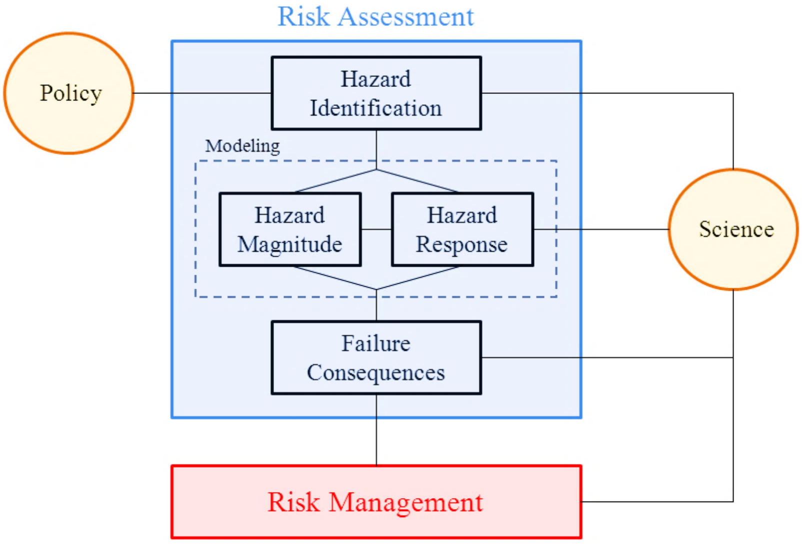


Figure 9. Risk Analysis Framework [1]

As depicted in Figure 9, the risk analysis framework consists of two main components [2]:

Risk assessment and Risk management.

The risk assessment process is divided into four tasks, namely:

1. Hazard identification: This involves identifying and understanding potential hazards that could impact the structure, such as natural disasters or human-induced events. The hazard of interest in this study is characterized by the effect of floods and overweight trucks on highway bridges.
2. Evaluation of hazard magnitude: Once the hazards are identified, their magnitudes are assessed to determine the severity of their potential impact on the structure.
3. Analysis of structural response under the given hazard: This task involves analyzing how the structure will respond and behave when subjected to the identified hazards. It includes evaluating structural vulnerabilities and potential failure modes.

4. Evaluation of failure consequences: The final task is to assess the potential consequences of structural failure, considering factors such as human safety, economic losses, and disruptions to the infrastructure network.

These four tasks collectively form the risk assessment process, which provides valuable insights into the potential risks associated with the structure and aids in developing appropriate risk mitigation strategies.

Risk management is a decision-making process that utilizes the information generated from the risk assessment phase to effectively mitigate and manage the identified risks [2].

3-1 Risk Assessment Model

The typical mathematical framework for risk assessment combines a measure of the consequences of an event with the probability of occurrence of that event which is shown as Equation 3-1. [42-43]

Eq.3-1

$$E(R)_A = E(C)_A \times P_f(A)$$

$E(R)_A$= The expected risk of an event A
$E(C)_A$= The expected consequence of a failure of event A
$P_f(A)$= The probability of failure of event A

This chapter comprises three connected parts which revolve around the risk assessment of Manitoba province's typical highway bridges, as explained as follows:

1. The first part entails an extensive analysis of the financial losses resulting from a flood, with particular attention paid to damages incurred near bridge locations in three distinct regions, Manitoba, North Dakota, and Minnesota.
2. Conversely, the second part of the chapter describes how to estimate the probability of failure due to flood events in Manitoba.
3. The third part focuses on the estimate of the probability of failure stemming from overweight traffic on bridges in three regions (MB, ND, MN).

All three parts convey in the following formula which is the main goal of this research.

Eq.3-2 $$\boldsymbol{Risk = E(C) \times \left[P_f(B)_{Flood} + P_f(B)_{OW} + P_f(B)_{OW} \times P_f(B)_{Flood}\right]}$$

Where:

$Risk$= Risk of bridge failure due to flood disaster and overweight traffic

$E(C)$= Economic consequences of bridge failure due to flood

$P_f(B)_{Flood}$= Probability of failure of bridges due to water level and clearance

$P_f(B)_{OW}$= Probability of failure of bridges due to overweight

$P_f(B)_{OW}$ is computed as follows (Law of Total Probability) [15]:

Eq.3-3 $$P_f(B)_{OW} = P_f(H) \times P_f(B|H)$$

Where:

$P_f(H)$= Probability of the hazard

$P_f(B|H)$= Conditional probability of bridge failure given the hazard H obtained as:

Eq.3-4 [16] $$P_f(B|H) = \phi^{-1}(-4.5) = 3.4 \times e^{-6}$$

Where 4.5 is the reliability index estimated for bridge members in Manitoba. The reliability index (β) is defined as $\beta = -\phi^{-1}(P_f)$, where ϕ is the standard normal cumulative distribution function, and P_f represents the probability of failure for the specific bridge member being analyzed [16]. It should be noted that assuming a conditional probability for a bridge system equal to 4.5 is a conservative approach because the failure of a member does not necessarily mean the failure of the entire superstructure in typical highway bridges.

In addition, in Equation 3-2, 'Probability of failure of bridges due to flooding ' ($\mathrm{P_r(F)_{Flood}}$), and 'Probability of failure of bridges due to overweight loads ' ($\mathrm{P_r(F)_{OW}}$) assumed to be independent variables. This is justified by the fact that flooding and overweight events are physically unrelated.

3-2 Classification of Bridges by Type

The primary objective of this study is to examine highway bridges in Minnesota, North Dakota, and Manitoba. The study focuses on typical highway bridges, for which the estimate of the probability of failure due to overweight described earlier applies. Furthermore, the findings and methodologies employed in this study can be adapted and calibrated for implementation in other geographic locations .The specifications and details about the bridges under consideration are provided in Table 1.

Table 1. Details of the Bridges in Three Regions

Region	Number	Length (m)	Span Length (m)
Manitoba, Canada	1,100	11 to 850	10 to 130
Minnesota, US	3,321	11 to 2,536	10 to 190
North Dakota, US	1,922	11 to 1377	10 to 95

3-3 Data Collection

A summary of data collected in various regions is shown in Table.2. One important point that should be noted is that to create coherence and integrate the data related to Flood economic damages in Manitoba province with neighboring states, only Commercial and Personal Financial Losses are considered to be analyzed.

Table 2. Data Sources for Flood Economic Damages, Bridge Locations, and Water Gauges in Manitoba (MB), Minnesota (MN), and North Dakota (ND)

Location	Type of Data	Source	Quantity
Manitoba (MB)	Flood economic damages: Auto, **Commercial, Personal**, Sewer Backup/Water	CatIQ [10]	424 Records
	Provincial Bridge locations	Manitoba Transportation and Infrastructure (MTI)	1,100 Bridges
	Water Gauges	Water Information and Flood Conditions of Manitoba Government [4]	100 Gauges
	Clearance Measurements for Overpasses	Manitoba Transportation and Infrastructure, Bridges and Highway Structures	79 ID
	WIM data	LTPP WIM sites in Manitoba	6 sites
	Average Annual Daily Traffic Volume (AADTT) of Bridges	Manitoba Transportation and Infrastructure (MTI)	778 Bridges
North Dakota (ND)	Flood economic damages: **Commercial, Personal**	FEMA [5]	45 Records
	Bridge locations	National Bridge Inventory (NBI) [39]	1,922 Bridges
	Average Annual Daily Traffic Volume (AADTT) of Bridges	National Bridge Inventory (NBI) [39]	1,922 Bridges
	WIM data	NDDOT Transportation Platform [40]	14 Stations
Minnesota (MN)	Flood economic damages: **Commercial, Personal**	FEMA [5]	176 Records
	Bridge locations	National Bridge Inventory (NBI) [39]	3,321 Bridges
	Average Annual Daily Traffic Volume (AADTT) of Bridges	National Bridge Inventory (NBI) [39]	3,321 Bridges
	WIM data	Minnesota WIM Data [41]	19 Stations

The subsequent sections will describe each component of the risk, due to flood deterioration and overloading hazards.

3-4 Part 1: Financial Damage Resulting from Floods

As previously mentioned in Chapter 1, this research aims at developing a method for evaluating the flood risk in highway bridges in Manitoba, Canada. To accomplish this, the study examined the effects of flooding on bridges in the Red River region of Manitoba and two northern US states (North Dakota and Minnesota) as a case study. The goal is to identify areas that are particularly vulnerable to flooding and to understand the financial consequences of these events.

The materials in this section were presented at the Canadian Society for Civil Engineering, CSCE Annual Conference - Moncton, NB on May 2023 and are printed here with permission of coauthors Dr. Graziano Fiorillo [7].

3-4-1 Normalizing Economic Losses

Prior to discussing data analysis for this section, it is imperative to consider inflation and fluctuations in the value of currency over time. This is essential to ensure a precise comparison of the economic repercussions of flood events across various years. Data from 2016 to 2022 for three regions were normalized to 2022 CAD. This adjustment allowed us to compare the financial impacts of floods across various years on a consistent and comparable basis. By using a common reference year, the influence of inflation and monetary fluctuations, enabling a more accurate assessment of the relative financial implications of flood events is eliminated.

The process of normalizing economic losses from flooding involved considering the effects of inflation and changes in the value of money over time. To achieve this, the Bank of Canada's inflation calculator [8] is utilized, which employs monthly consumer price index (CPI) data from 1914 to the present. This data reflects variations in the cost of a basket of consumer goods and services, encompassing items such as food, shelter, furniture, clothing, transportation, and recreation. Inflation is defined as the increase in this cost over time. As mentioned before, by utilizing the inflation calculator, all economic loss amounts from flooding to their equivalent values in 2022 Canadian dollars are adjusted.

In addition, to standardize and harmonize the values, the data were aggregated and consolidated based on a specific unit of measurement and grouped according to their respective locations. To ensure comparability, all losses were converted into a value per unit area, specifically per square kilometre (km^2). The following approach was employed to achieve this objective:

1. Calculate the total cost of flood economic consequences from all available years.
2. Compute the average cost of the records.

3. Create a scale factor by dividing each cost of floods from the scattered data by the average cost.
4. Compute the average cost per year per km2 by dividing the total cost at point 1 by the surface area of the region and the number of years on record.
5. Scale the average cost per km2 times the scale factor at each location to describe the distribution of the consequences per unit area.
6. Create a continuous geospatial map of the consequences in the region using the scattered values through a kernel density function [9].

3-4-2 Data Analysis Tools

In this section, various techniques and tools used for data analysis will be delved into, encompassing descriptive statistics, data visualization, and statistical tests.

Descriptive statistics: Descriptive statistics involves summarizing and describing the main characteristics of a dataset. This includes measures such as mean, median, standard deviation, range, and percentiles. Descriptive statistics provide insights into the central tendency, dispersion, and distribution of the data.

Data visualization: Data visualization techniques are employed to visually represent data patterns and relationships. This includes graphs, histograms, scatter plots, and heat maps. Data visualization aids in better understanding the data, identifying trends or patterns, and communicating findings effectively.

Statistical tests: Statistical tests are utilized to analyze data and assess the significance of observed patterns or differences. They help determine whether the observed results are statistically significant or occurred by chance. In this part, the chi-square test is used.

3-4-3 Statistics for Spatial Data

To provide a concise overview of the Spatial data, it is essential to mention that it encompasses information that possesses a spatial or geographical aspect, such as coordinates, location details, or boundaries. In contrast, spatial models are mathematical or statistical techniques employed to analyze and forecast outcomes related to spatial data. These models take into account the spatial relationships and patterns within the data, facilitating the generation of insights and predictions. Spatial models are utilized in diverse fields, including geography, environmental science, urban planning, epidemiology, and others, where understanding spatial relationships and making informed predictions based on spatial data is crucial.

The book "Statistics for Spatial Data" authored by Noel A. Cressie [9] provides an overview of various statistical methods used for the analysis of spatial data. These methods encompass exploratory data analysis, geostatistics, point process models, and spatial regression models.
Exploratory data analysis entails the visualization and summarization of spatial data to detect patterns and trends. Geostatistics comprises a collection of statistical methods employed for analyzing data with spatial correlation, such as weather station or soil sample data. Point process models are utilized to model the spatial distribution of events, such as earthquakes or crime incidents. Spatial regression models are employed to model relationships between spatial data and other variables, such as demographic or environmental factors. Finally, methods for spatial interpolation involve estimating values for unsampled locations based on sampled data, as well as spatial prediction, which involves making predictions about future spatial data based on past data.

In this study, kernel method is employed to estimate spatial density and intensity based on point data. Kernel density estimation is a non-parametric technique used to estimate the probability density function of a random variable in a continuous domain. In spatial analysis, kernel density estimation is commonly utilized to generate heat maps or density maps, illustrating the relative density of events or phenomena across a geographic area.

Kernel density estimation entails the placement of a kernel, or smoothing function, at each point within the dataset, which is then summed to create a continuous surface. The kernel function plays a crucial role in determining the shape and smoothness of the resulting density surface, while the bandwidth parameter governs the level of smoothing. Kernel density estimation is widely employed as a favoured technique for visualizing spatial patterns and identifying regions of high or low density. Moreover, it can be utilized to compare the densities of multiple datasets or to identify spatial clusters or hotspots.

In the subsequent analysis, a geospatial examination of the financial consequences of floods in three locations was conducted using R software [9], as depicted in Figure 10. The maps shown in Figure 10 portray the magnitude and severity of flood events in Manitoba, North Dakota, and Minnesota, represented by the values in Canadian dollars per square kilometre. By visually representing the data in this manner, patterns and trends in the spatial distribution of the financial impact of floods across the three locations can be discerned. Notably, there is a noticeable overlap between the images of Manitoba and North Dakota, particularly in the Red River area, emphasizing the significance of this river in terms of flood risk and its subsequent impact.

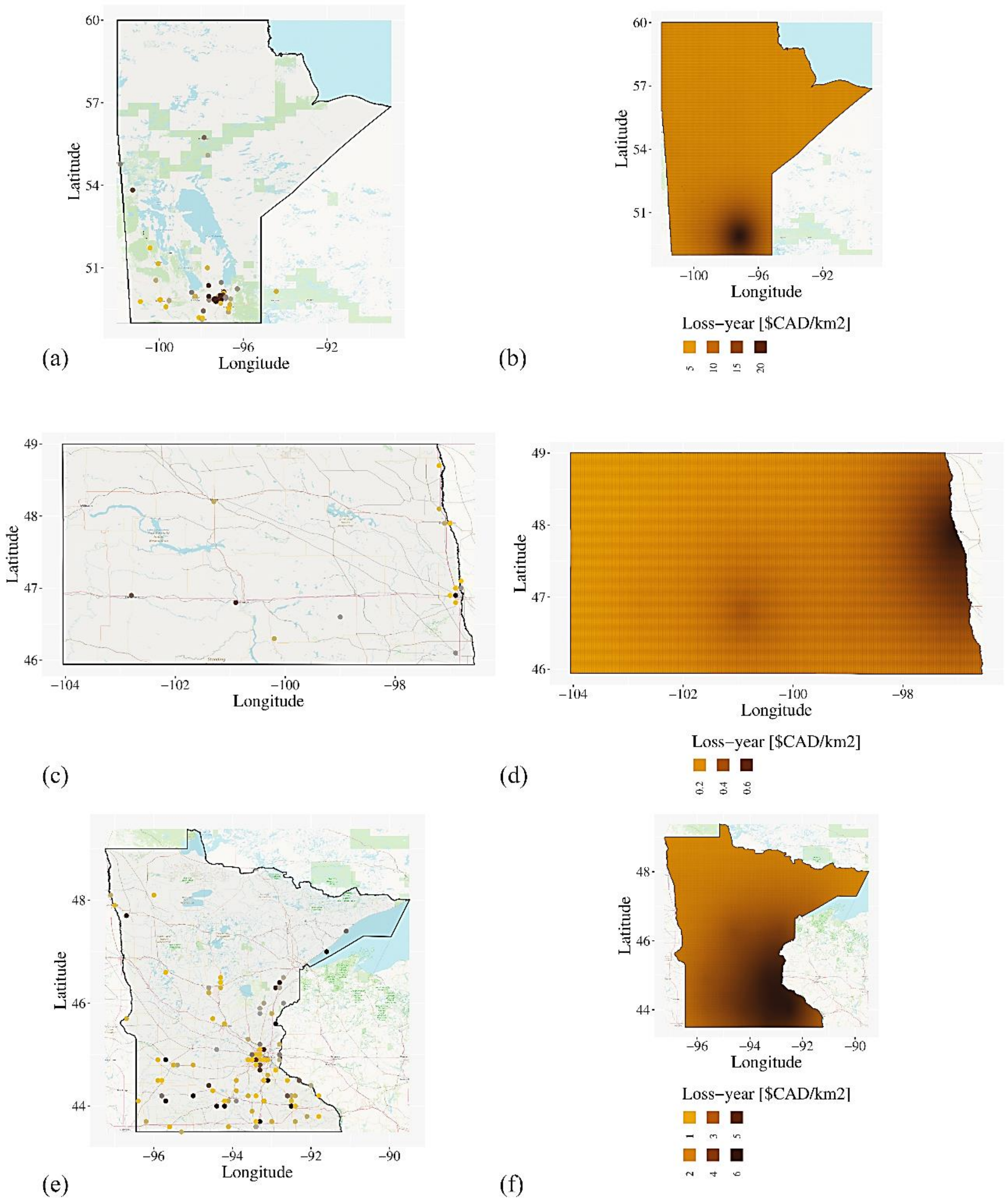


Figure 10. Financial Impact of Floods.
Source data in Manitoba (a), North Dakota (b), and Minnesota (c).
Kernel model in Manitoba (d), North Dakota (e), and Minnesota (f).

Table 3 presents a summary of the cost of flood damage for three specific locations, including relevant statistical measures.

Table 3. Summary statistics of the cost of flood damage for three locations in $CAD/km2-year.

Manitoba	North Dakota	Minnesota
Min: 2.2	Min: 0.1	Min: 0.1
Max: 98.5	Max: 6.7	Max: 201.0
Median: 41.5	Median: 0.6	Median: 6.6
Mean: 41.5	Mean: 1.3	Mean: 15.9

It should be mentioned that unit costs per square kilometre result low because the total losses per year in each region have been divided by the total area of the region, which is much larger than the affected areas. This measure is deemed necessary because data are not homogeneous. In Manitoba, losses were provided in lumped values per postal code, while in the US, losses are available per unit. As a result, the unit costs per km2 represent a nominal value of the losses rather than the actual one.

By performing statistical analyses on the financial loss data from the three regions, the parameters of a statistical distribution were determined by fitting the data [11]. The analysis revealed that the data from Manitoba exhibited the best fit with a normal distribution, whereas the data from North Dakota and Minnesota followed a log-normal distribution, as depicted in Figure 11.

The available data was thoroughly analyzed, taking into consideration the topography, hydrology, and land use characteristics of the three regions, to identify potential factors that could explain the observed distribution patterns. The examination revealed significant differences among the regions. For example, the Red River basin in Manitoba displayed a more uniform topography, suggesting a more evenly distributed pattern of flood damages. Furthermore, variations in land use practices and flood mitigation strategies across the regions may also contribute to the observed differences in the distribution of losses. These findings emphasize the importance of critically evaluating assumptions underlying statistical analyses and carefully interpreting unexpected results.

Table 4. Parameters of distributions for flood consequences

Manitoba	North Dakota	Minnesota
norm-mean 41.5	lognorm-mean -0.51	lognorm -mean 1.89
norm-sd 11.35	lognorm -sd 1.34	lognorm -sd 1.39

The adequacy of the normal and log-normal distributions as models for the flood damage data in Manitoba, Minnesota, and North Dakota was assessed using Pearson's chi-squared test. The test was performed with a specific number of degrees of freedom (dof), which in this case was set to 97[12]. The reference chi-square statistic at the 95th percentile for 97 dof is 75.3. A chi-square goodness of fit value below 75.3 indicates a very good fit to the data. The results of the test, presented in Table 5, demonstrate that all fitted models accurately capture the distribution of losses in Manitoba, North Dakota, and Minnesota, respectively.

Table 5. Chi-square values with number dof = 97

Manitoba	North Dakota	Minnesota
Chi-2 = 6.78	Chi-2 = 2.17	Chi-2 = 13.47

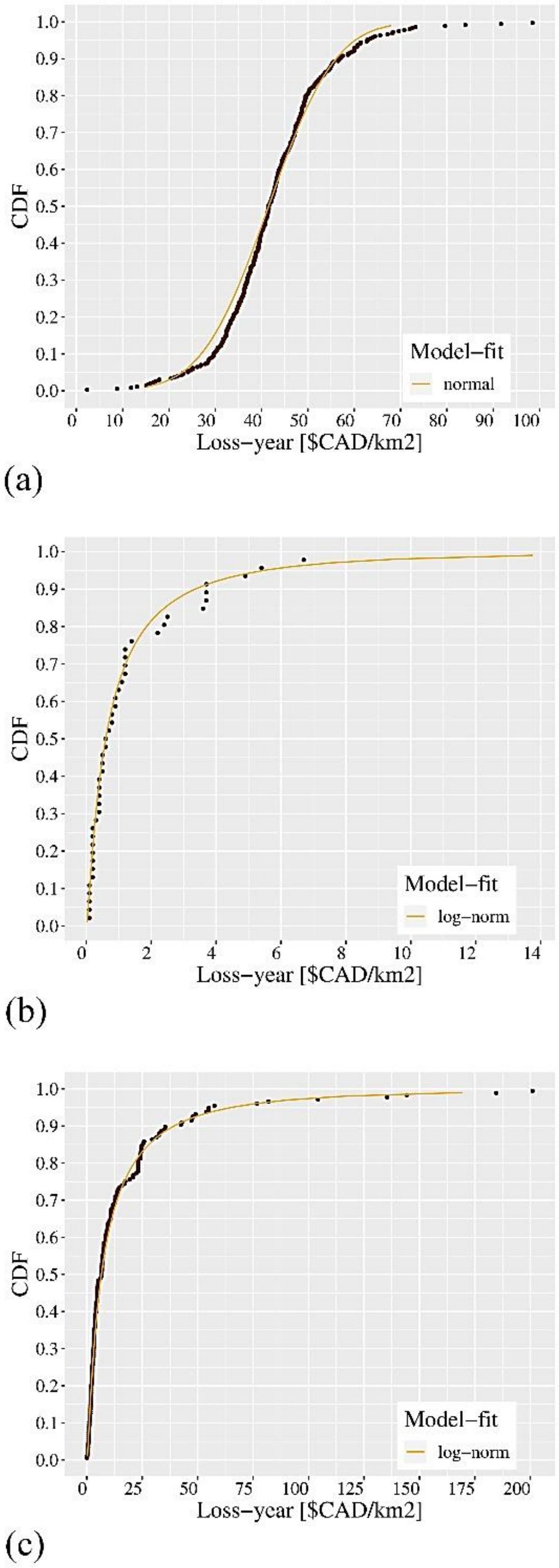


Figure 11. Statistical distributions of Flood damage costs in Manitoba (a), North Dakota (b), and Minnesota (c)

3-4-4 Summary

The main results and stages of this part regarding the financial damages originating from floods can be summarized as follows:

1. The primary objective of this part is to develop a method for analyzing economic consequences in each flood-prone region. This analysis consists in extracting and associating the value of consequences at each bridge location, enabling us to quantify the potential impacts of future flood events on highway bridges in Manitoba and two northern US states (North Dakota and Minnesota).
2. Utilizing historical records of flood economic consequences to identify flood-prone areas and understanding the financial consequences of these events.
3. For a homogeneous comparison of the financial impacts of floods in different years, based on considering inflation, data from the years 2016 to 2022 were normalized to the 2022 Canadian Dollar value.
4. Considering the varying number of years available for each region, economic loss values from floods were converted into a unit area measure, specifically per square kilometre. The representation of losses per square kilometre helps harmonize costs collected in different areas and risk estimates for bridges.
5. Various statistical and spatial methods were employed for data analysis in this research, including descriptive statistics, data visualization, and statistical tests.
6. The results of the tests indicated that the economic loss data from Manitoba align well with a normal distribution, while the data from the northern US states (North Dakota and Minnesota) follow a log-normal distribution. The obtained statistical results can be used as statistical models in future research on action criteria.
7. Heat maps and local density representations were used to illustrate the extent of financial damages caused by floods in different study areas.

3-5 Part Two: Probability of Bridge Failure Due to Flood Hazard

In this section, the Probability of Bridge Failure Due to Flood Hazards ($\mathrm{P_f(B)_{Flood}}$) is discussed. This analysis complements the earlier discussion on the financial damage resulting from floods. By considering both the financial damage resulting from floods (E(C)) and the probability of failure due to flood hazard $\mathrm{P_f(B)_{Flood}}$, a comprehensive understanding of the potential risks and impacts of floods on the identified bridges can be reached. This holistic approach enables us to prioritize mitigation strategies, allocate resources effectively, and develop resilient infrastructure systems to withstand flood events.

3-5-1 Vertical Clearance

In the context of floods, vertical clearance refers to the minimum distance required between structures and the flowing water during a flood event [13]. It is a critical consideration in the design and construction of structures in flood-prone areas. Therefore, in the design of structures in flood-prone areas, the vertical clearance needs to be carefully calculated based on hydrological and hydraulic analyses [14]. It should ensure that the structure is not exceeded by the volume of water flowing underneath the bridge. By providing appropriate vertical clearance, structures can effectively mitigate the risks associated with floods, allowing floodwater to flow unobstructed and reducing the potential for damage to the structures.

Flood studies typically consider the historic performance of vertical clearance to assess the adequacy of structures in flood-prone areas. This involves analyzing past flood events and their impact on structures, including the clearance provided between the structures and the floodwater. Historical data on flood events, such as water levels, flow rates, and damage reports, are collected and analyzed to understand how existing structures have performed during past events. In this part, the focus is only on Manitoba, to reduce the data analysis on water gauge levels. So, the data measuring the vertical clearance of the waterway from Manitoba Transportation and Infrastructure, Bridges and Highway Structures have been calculated. In addition, historical water level data were processed at several locations in Manitoba.

The term "bridge failure due to flooding " in this study refers to the bridge water level surpassing the overtopping threshold. To provide a clearer explanation, Figure 12 illustrates the concept of "overtopping" with respect to the bridge height. The model assesses the probability of exceeding the overtopping threshold in a given time range.

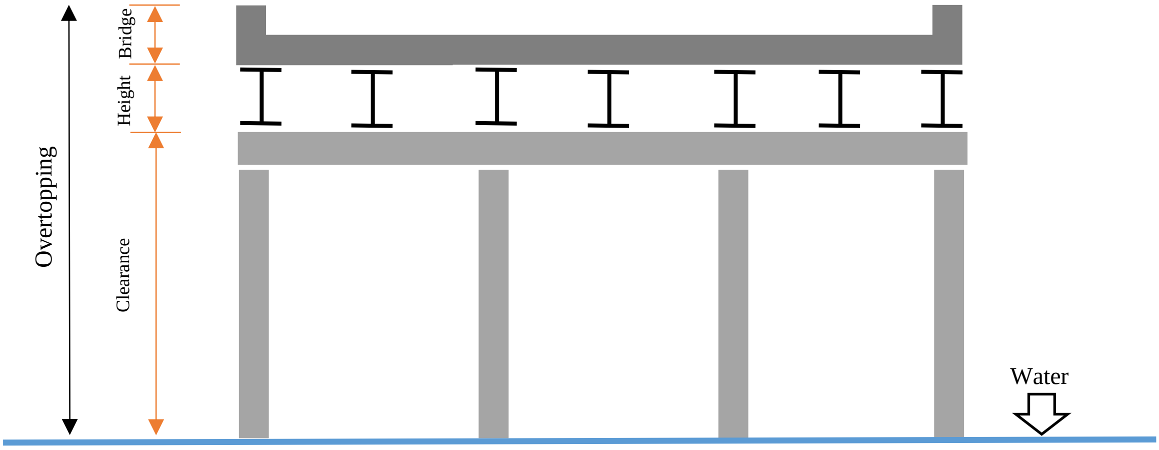


Figure 12. Schematic Representation of Overtopping and Bridge Failure Due to Flooding

3-5-2 Vertical Clearance Data Analysis

First, the historical Monthly Mean Water Level (m) from 2013 to 2022 at 100 stations, located in Manitoba have been extracted. For a given month in a given year, the monthly mean water level or discharge value is calculated by averaging all the historical daily water level or discharge values for the month. The monthly mean is not calculated when one or more daily mean values are missing [4]. This information is extracted from Hydrologic Forecast Centre (HFC). The Hydrologic Forecast Centre's (HFC) [4] mission is to produce accurate timely hydrologic forecasts and information to the public and all levels of government using the best available scientific principles to integrate and model water, weather, and climatic information such as Produce hydrologic information and forecasts used in the operation of provincial water control structures. The map of these stations is shown in Figure 13. Each green point conveys the location where the water level is recorded in Manitoba.

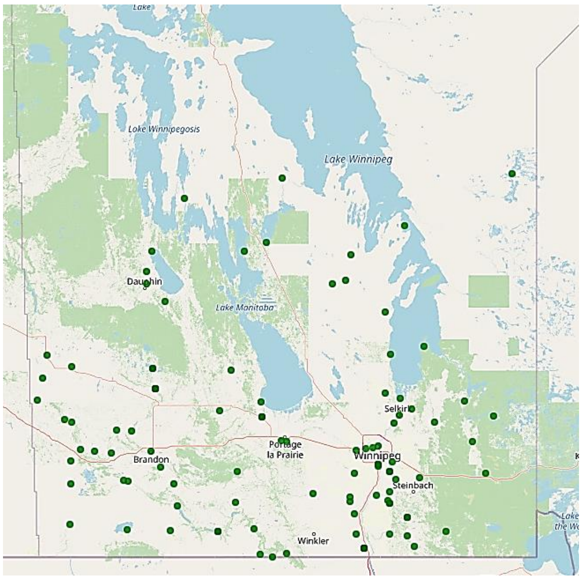


Figure 13. Water stations in Manitoba [4]

Steps of data analysis for the key locations:

1- Calculation of the annual average of Monthly Mean Water Level (m) for each year within the period of 2013 to 2022, for ten years.

2- Determination of the overtopping, which involves subtracting the average value of the Monthly Mean Water Level (m) from each data point for every month.

As an example, the graph of Figure 14 shows the distribution of the differential water level at the Birch River station. The red dashed line is the average of the water height and the distance between the water height and the average, overtopping, is shown by the blue arrow line. In this part of data analysis, looking for the exceed of overtopping is the target.

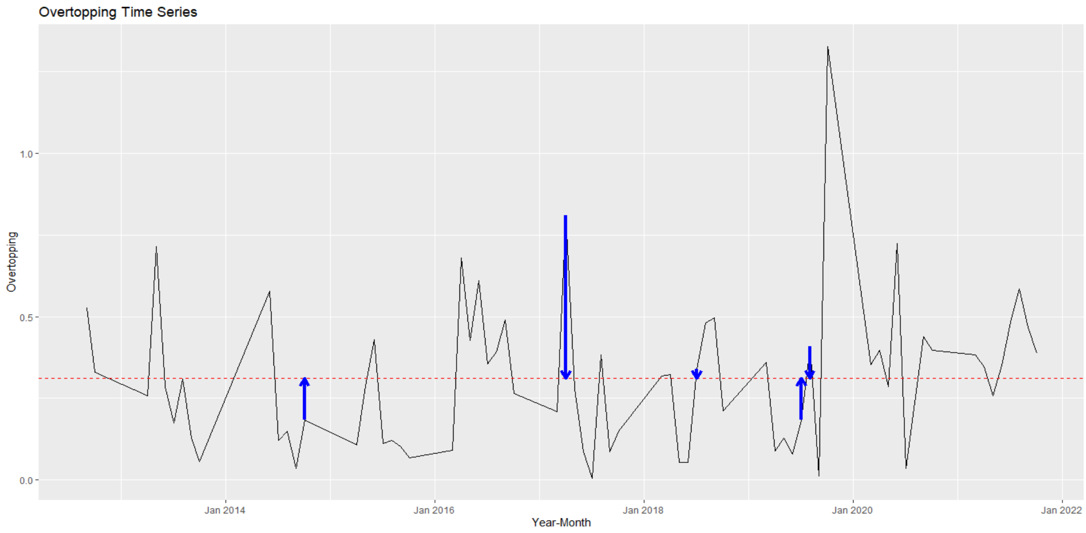


Figure 14. Example of a Time Series of Overtopping with Mean Highlighted for One Station

3- Analyzing the Probability Density Function (PDF) of the obtained overtopping values. In this step, the probability of overtopping based on the distribution is computed.

4- The dataset for vertical clearance comprises a total of 79 observations, while our studies have encompassed 1,100 bridges. To explore the possibility of different clearances, five thresholds were investigated, including maximum, minimum, average, and the first (25th percentile) and third (75th percentile) quartile of the available data. The respective values for these thresholds are 3, 4.6, 5.4, 5.6, and 12.6 meters, respectively.

5- Calculate the exceedance probability of overtopping for all stations from all five thresholds. Exceedance refers to the occurrence of a value or event surpassing a specified threshold. In this context, the threshold corresponds to the specific values mentioned. For instance, if the exceedance probability is 0.05, it indicates that approximately 5% of the data will exceed the threshold.

For a clearer explanation, a general schematic of the overtopping PDF plot, which represents the difference between the water levels and their mean, is displayed with 5 different water level thresholds in Figure 15. In this graph the region where the probability of overtopping exceeding the threshold (4.6 as an example) is shown in grey color.

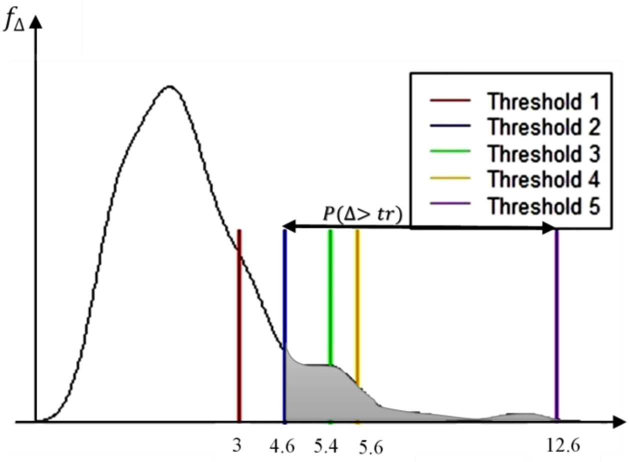


Figure 15. Probability of Overtopping

3-5-3 Statistics for Spatial Data

Using statistics for spatial data to the generation of a kernel map based on the locations of the stations and the calculations made in the steps mentioned above. In this step, same as part one, Kernel methods are used to estimate spatial density and intensity from point data. Unlike histograms, the kernel density estimation (KDE) technique provides a smooth and continuous density estimate, even with a small number of samples [37].

In this section, KDE as a smoothing method is used to take individual observations at point locations or events, xi, i = 1, ..., n, and extends them to cover the entire area, giving us observations, at any location within the study region.

Imagine it like a three-dimensional sliding function that moves across every location (Figure 16). To calculate the density, estimate at a specific location x, we measure the distances to each observed event (xi) that falls within a specified distance (bi), called the bandwidth or smoothing parameter. The closer they are to x, the more they contribute to the density estimate at x [37].

The result is a smoother estimate of the observations as the contributions from all the kernels centred at each observation are added up.

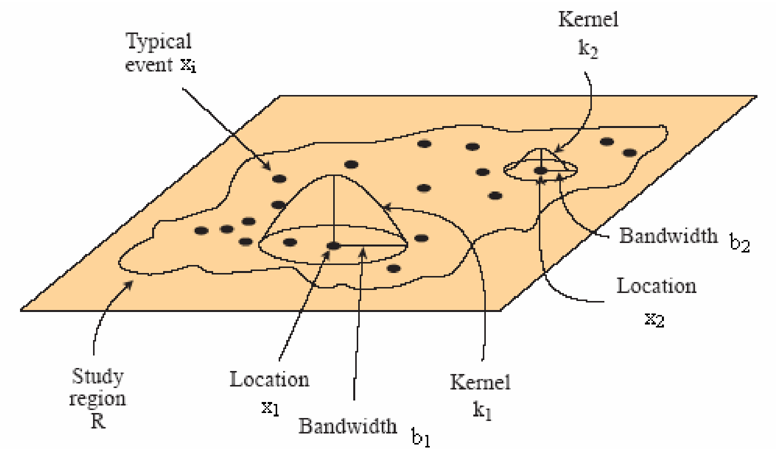
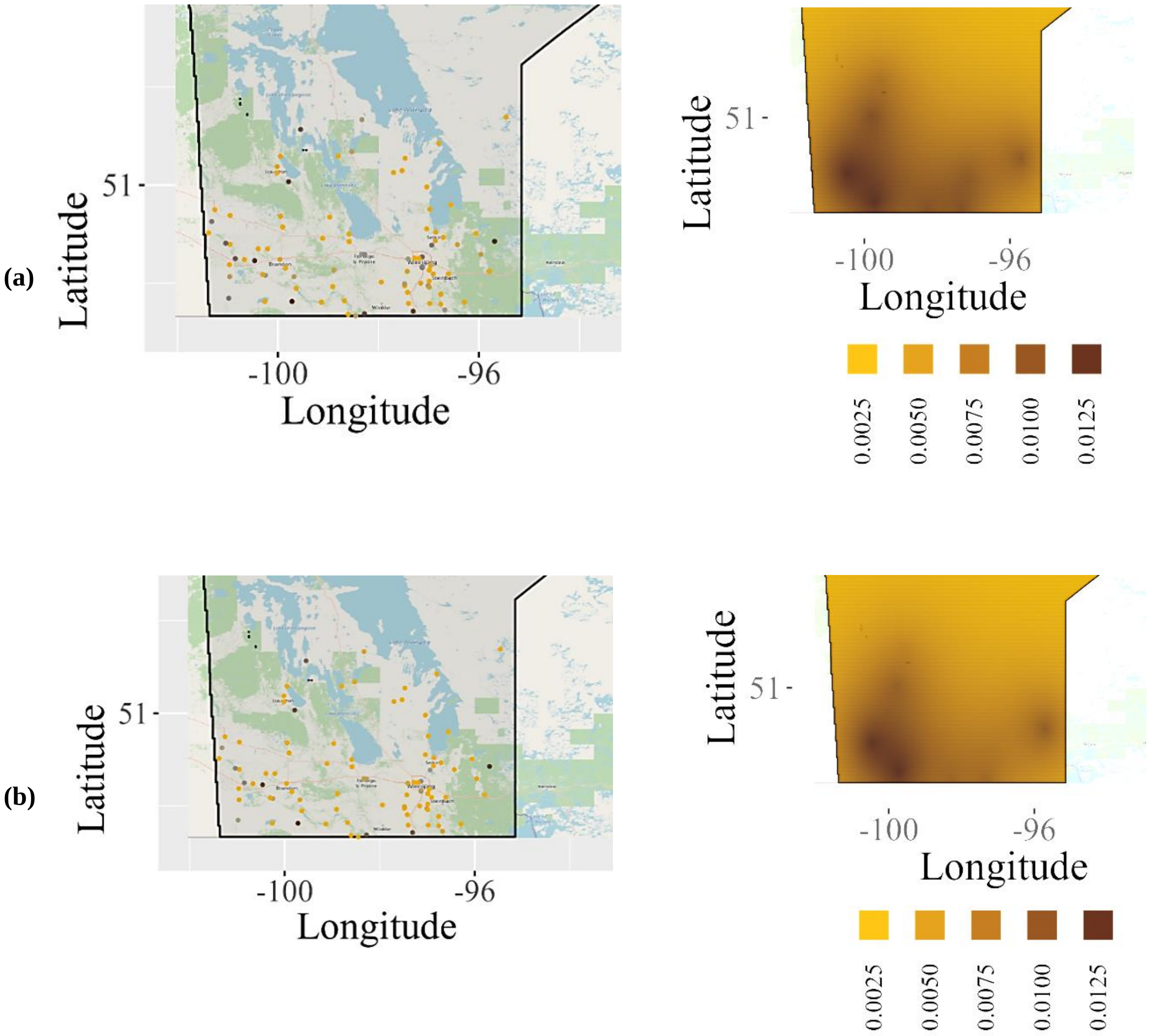


Figure 16. Kernel density estimation of a spatial point process

The results obtained using a Kernel density estimator are depicted in Figure 17, showing colour variations based on the increasing probability of overtopping. The estimation of smooth and continuous density is shown on the right side of the figure.



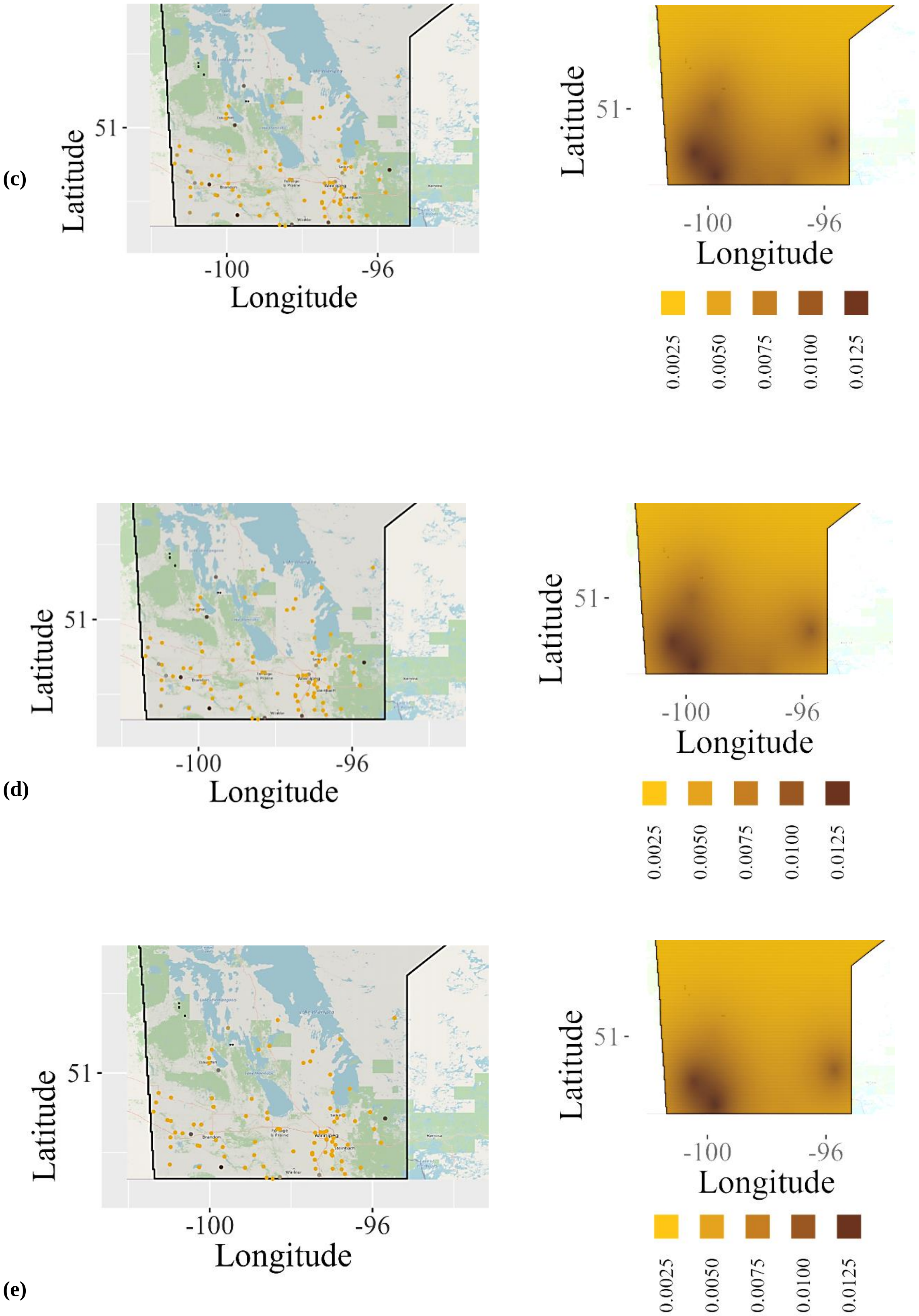


Figure 17. Probability of Overtopping for Water Gauges
Of 3(a), 4.6(b), 5.4 (c), 5.6 (d),12.6 (e) threshold (m)

Based on the kernel function derived from the probability of overtopping data, the information is available in the form of ".tif" files. Subsequently, using the R software, the tif file along with the locations of 1,100 bridges is coded. The probability of overtopping for each bridge output provided is extracted from the generated kernel density maps for each threshold as shown in Figure 18.

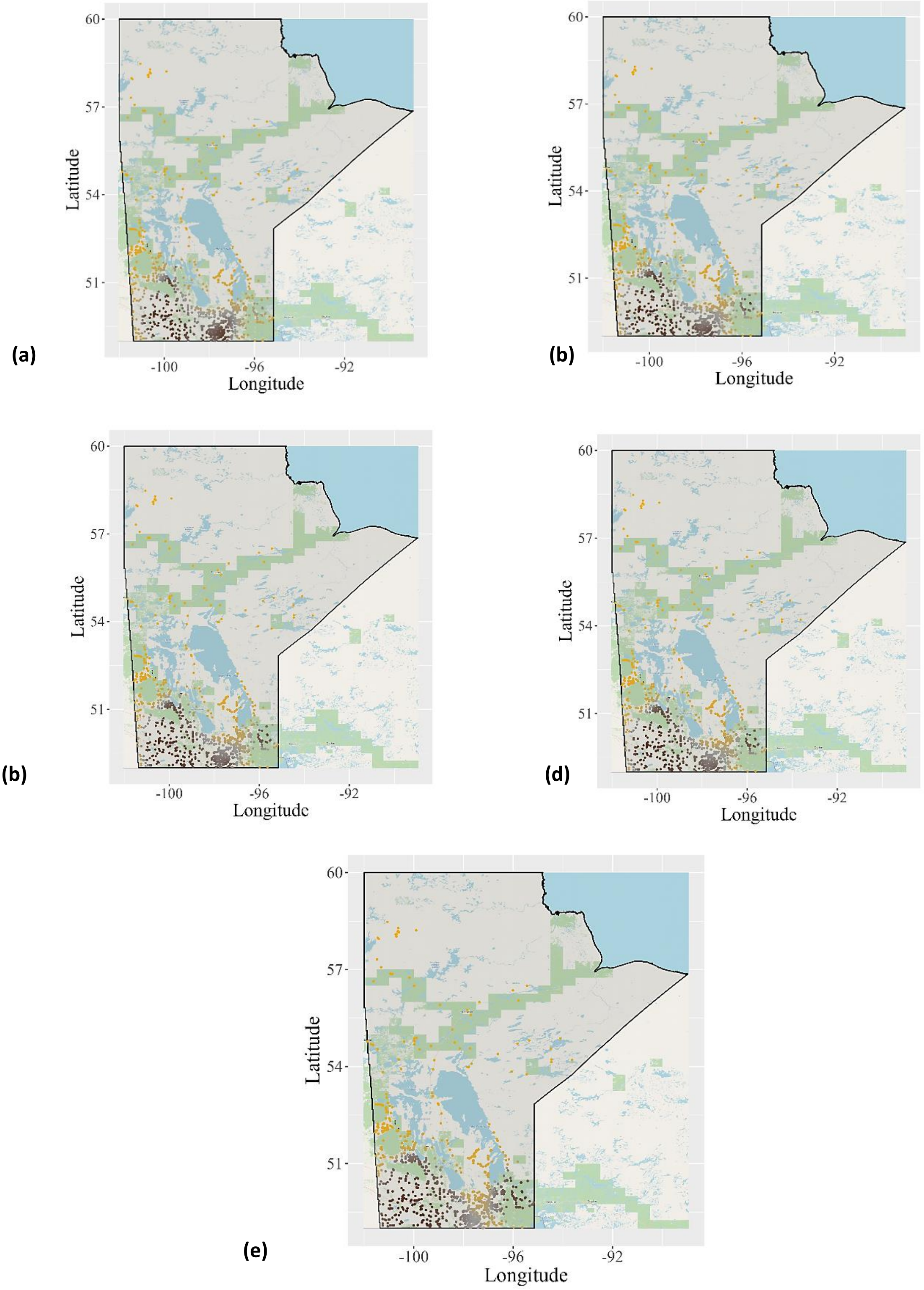


Figure 18. Probability of Overtopping at scattered locations- Threshold [m] Of 3 (a), 4.6(b), 5.4 (c), 5.6 (d),12.6 (e)

Based on the scatter plots drawn in this section, it was observed that different locations show a different probability of failure to flood events based on hydrologic data. These maps also indicate that bridges located near the Red River or its branches have a higher level of overtopping. This may be due to the higher water flow in these areas, indicating greater risks for these bridges. Generally, these intensity variations on the maps can signify the spatial distribution of overtopping on the bridge surfaces and highlight the potential importance of risk assessment and maintenance actions on the bridges.

A summary of the results for the overtopping probability with different clearance levels is presented in the table below.

Table 6. Summary of Probability of Overtopping for Bridges in Manitoba

Threshold of Clearance		Min	Max
Minimum	3 m	0.0000109	0.015515785
The first quartile (25th percentile)	4.6m	0.00000731	0.012833093
Average	5.4 m	0.00000631	0.012119718
Third quartile (75th percentile)	5.6 m	0.00000603	0.011915418
Maximum	12.6 m	0.00000241	0.008069047

3-5-4 Summary

Based on the findings from the conducted analysis:

1. This section of the study discussed the Probability of Bridge Failure Due to Flood Hazards ($P_f(B)_{Flood}$) and complemented the previous section on the financial damages caused by floods.
2. In the first part of this section, Vertical Clearance was defined as a critical factor during flood events, referring to the minimum required distance between structures and flowing water. Ensuring adequate vertical clearance allows structures to effectively reduce the risks associated with floods, enabling floodwater to flow unobstructed and minimizing potential damage to structures.
3. To examine the vertical performance during floods, the historical water levels were studied to assess how existing structures would have responded to flood levels in the past.
4. Historical data on water levels at 100 stations in Manitoba were collected and analyzed.
5. A probability Density Function (PDF) was utilized to assess the probability of exceeding certain thresholds based on the distribution of overtopping.
6. The Kernel method was used to create density maps based on the locations of stations and the calculations performed.

7. Observations indicated that different bridges had varying probabilities of failure due to flood based on hydrological data. The maps also showed that bridges situated near the Red River or its branches had a higher probability of being flooded, likely due to higher water flow in those areas.

While estimating the probability of failure due to flooding based on historical hydrologic data and a kernel density estimator is a valuable method, it is crucial to acknowledge its limitations and the underlying assumptions. Interpretation of the results should be done with caution, and efforts should be made to address uncertainties and biases arising from data limitations and assumptions. For example, the method assumes that the underlying hydrological processes and flood characteristics remain stationary over time. However, climate change and other external factors can influence flood patterns, potentially challenging the assumption of stationarity. In addition, the model used to calculate the exceedance is computed assuming the average water level as the actual level of streams, while this may not be accurate. Deviations from these assumptions can affect the validity of the probability estimates.

3-6 Part Three: Probability of Failure Due to Overweight Traffic

The focus of this part is estimating the probability of failure due to overweight trucks. It is based on the collection of traffic loads on the transportation network. To perform an analysis of this section, it is necessary to examine the structural reliability.

The objective of structural reliability theory is to consider the uncertainties that arise when assessing the safety of structural systems or when calibrating load and resistance factors for structural design and evaluation codes. Structural safety can be defined as a condition where the structural capacity surpasses the applied load demand. In this context, the reserve margin of safety for a bridge component is denoted as Z.

Eq.3-5 $$Z = R - S$$

Where:

R is the resistance or member capacity

S is the total load effect.

An alternate formulation has also been used, where the safety margin is obtained using the following ratio, in which case the probability of failure is the probability that Z is smaller than 1.

Eq.3-6 $$Z = \frac{R}{S}$$

Probability of failure, $\boldsymbol{P_f}$, is the probability that the resistance R is less than or equal to the total applied load effect S or the probability that Z is less or equal to zero [20], which means:

Eq.3-7 $$P_f = P_r[R \leq S]$$

where P_r is used to symbolize the term probability.

3-6-1 Determining the Reliability of Bridge Superstructures

The order of magnitude of the probability of failure for structural components and systems is in general very low. For this reason, instead of using P_f, many researchers have used the reliability index β to quantify the safety level of structural members and systems. β is defined as the minimum number of standard deviations that separate between the point of failure when Z=R-S=0 and the mean of the variable Z. For normal distributions, β can be presented as shown graphically in Figure 18 and mathematically by Equation 3-8 [27,28].

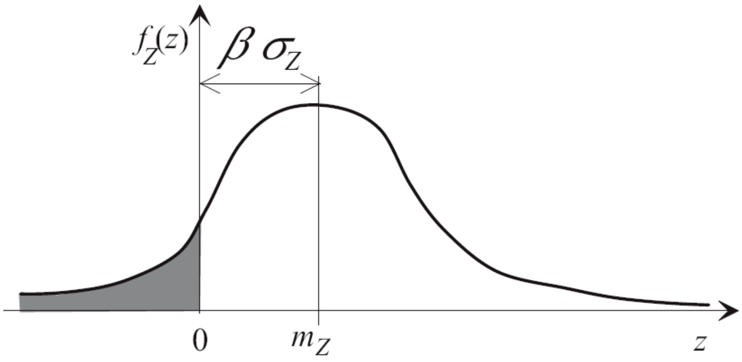


Figure 19. Representation of β in the univariate Z space

Eq.3-8

$$\beta = \frac{\bar{Z}}{\sigma_Z}$$

The relationship between the reliability index β and the probability of failure P_f is also often estimated using Equation 3-9, where Φ $(*)$ is the cumulative distribution of the Gaussian Normal univariate N (0,1).

Eq.3-9

$$\beta = \phi^{-1}(1 - P_f)$$

The estimation of the probability of failure, as indicated by Equation 3-7, involves an initial step of characterizing the distributions of the variables that define the resistance (R) and the applied load (S). Additionally, it is necessary to develop efficient techniques for determining the reliability index of the probability of failure. This becomes particularly challenging when the safety margin (Z) is a nonlinear function of numerous independent and correlated random variables. These variables cannot be expressed using closed-form expressions [22].

This study is concerned with evaluating the safety of bridges by utilizing reliability analyses to determine the likelihood of failure under a specific hazard, namely, the impact of overweight (OW) vehicles travelling across highway bridges. Assessing the structural reliability of bridges has been the subject of research for several decades, and various techniques have been explored in the literature to achieve this objective. These techniques include methods developed by Moses [23] and Moses et al. [24], Nowak [25], Ghosn and Moses [26], Estes and Frangopol [27], Miao and Ghosn [28], and Wang et al. [29].

Bridge reliability is related to both the number of trucks passing over them and the percentage of those trucks that exceed the weight limit. Specifically, in cases of overstress, the probability of a bridge failure can be described as the conditional probability of the bridge's failure, given the hazard ($P_f(B|H)$) multiplied by the likelihood of the hazard ($P_r(H)$) [30]. The hazard is defined as the portion of overweight (OW) in the truck population that is extremely heavy.

Eq.3-10 [3] $$P_f(B,H) = P_f(B|H) \times P_r(H)$$

Where:

$P_f(B|H)$= the conditional probability of failure of the bridge B

$P_r(H)$= the probability of occurrence of the hazard

In this research, the likelihood of the hazard $P_f(H)$ is evaluated based on the analysis of the data gathered from Weigh-In-Motion (WIM) sites which will be explained in the following parts.

It should be noted that $P_r(H)$ represents the probability of overloading, considering factors such as truck size, configuration, and weight which data comes from two research papers [3,15]. Additionally, $P_f(B|H)$ denotes the probability of mechanical failure in the presence of the overloading hazard which is considered in this research study.

3-6-2 Analysis of the Hazard Due to Overweight Trucks

The probability of exceedance, in general increases with high Average Annual Daily Traffic Volume and Overweight truck percentages [11]. In this study, the probability of bridge failure ($P_r(H)$) is estimated as a function of independent variables two parameters, the Average Annual Daily Traffic Volume (AADTT) and the percentage of Overweight (OW) trucks. The AADTT values for the bridges considered in this research are already available in our dataset (Table 2). Now, considering that both the OW percentage and AADTT values for the bridges are known, the extent of their influence on $P_r(H)$can be examined [3].

To analyze the relationship between $P_r(H)$, AADTT, and OW percentages, the joint cumulative density function using a statistical tool called Copula is constructed. Copula is well-suited for modelling the dependence structure between variables.

3-6-3 Copula Models and Fragility Curve

Fragility curves are statistical representations that depict the probability of structural failure or damage for a given range of stress or load levels. In the case of bridges, fragility curves provide valuable insights into the vulnerability and resilience of bridge structures under different stress conditions [34]. When it comes to modelling the fragility curves of bridges in relation to overstress, a copula-based approach offers several advantages. Copulas provide a flexible and robust framework for capturing the dependency structure between multiple variables. By utilizing copulas, it becomes possible to model the joint behavior of different factors influencing the bridge's response to overstress, such as material properties, loading conditions, and structural design [35].

The copula-based modelling approach allows the inclusion of various marginal distributions that best represent the individual factors affecting the bridge's performance. This flexibility enables a more accurate representation of the complex interactions between stress levels and structural failure probabilities [36]. Furthermore, copulas facilitate the estimation of joint probabilities and enable the construction of fragility curves that provide comprehensive information about the probability of bridge failure across a range of overstress levels.

Copula models come in several variants for modelling and analyzing multivariate distributions [33]. Archimedean Copulas are of particular interest in engineering applications due to their simple mathematical representation. These Copulas rely on a single parameter, θ (Equation 3-12), with the exception of the Independent Archimedean Copula, which does not require any parameters. The Independent Copula, denoted as C (q, v), is obtained by taking the product of the variables q and v. Equation 3-11 gives the expression of a Copula for two independent variables q and v [32].

Eq.3-11

$$\mathrm{C}\,(\mathrm{q},\mathrm{v}) = \mathrm{P_r}(\mathrm{Q} \leq \mathrm{q}, \mathrm{V} \leq \mathrm{v})$$

Both variables q and v are distributed in the interval [0, 1]. These variables are the transforms of the independent variables AADTT and OW through their corresponding Cumulative Distribution Function (CDF) . In this case, AADTT and OW percentages act as the independent variables, while the empirical observations of $\mathrm{P_r}(\mathrm{H})$ serve as the dependent variable.

The parameter θ for the remaining Archimedean Copulas is estimated using the Maximum Likelihood Estimator (MLE) from a sample of independent variables, as described by Nelsen [32]. Among the variables considered in this study, only the Frank Copula, which is a type of Archimedean Copula, and the Independent Copula are investigated due to their minimal distortions. It is worth noting that the parameter θ can take any real value except zero, as the function is not defined at zero. In the dataset analyzed in this study, the MLE for θ is calculated to be -2.88 [3]. The expression of the Frank Copula is provided in Equation 3-12.

Eq.3-12

$$C(q,v,\theta) = -\frac{1}{\theta}\left\{1 + \frac{[e^{(-\theta.q)}-1]\times[e^{(-\theta.v)}-1]}{e^{(-\theta)}-1}\right\} \qquad \theta\epsilon\mathbb{R} - \{0\}$$

Based on previous research from Fiorillo and Ghosn (2018), a normal distribution for both parameters, AADTT and overweight percentage is assumed to compute the value of the probability of occurrence of overweight vehicles for the reliability analysis [3]. The parameters of the reference normal distribution for AADTT are mean 5.63e + 3 and standard deviation

4.52e + 3, while those of the overweight percentage are 0.48 and 0.09, respectively. Employing Copula, the joint cumulative distribution of $P_r(H)$ based on the given AADTT and OW percentage data will be captured.

In the following section, it is shown how the AADTT and OW percentages for the Manitoba bridges are obtained.

3-6-4 Analysis of AADTT in Manitoba

Based on the primary dataset (Table 2), an examination of 1,100 highway bridges situated in the region of Manitoba has been undertaken. However, a refinement process has been executed utilizing the transportation data available in the Manitoba roads database. This refinement involves filtering the bridges based on their alignment with REGION Number, ROAD Number, and SECTION Number of roads. Consequently, bridges located within segments that accommodate Average Annual Daily Traffic Volume (AADTT) have been singled out for further analysis.

In instances where AADTT information could not be ascertained for the particular segment housing a bridge, the bridge in question has been excluded from the initial count of 1,100 bridges. Subsequent to this iterative procedure, the selection has been narrowed down to 778 bridges, each of which possesses an AADTT value greater than zero. Hence, it is important to note that the ensuing analysis exclusively pertains to bridges with an AADTT value exceeding zero.

3-6-5 Collection of Truck Data with Weigh-In-Motion Systems

Weigh-In-Motion (WIM) is used in this part to estimate the probability of failure due to overweight trucks. It is based on the collection of traffic loads on the transportation network. This enables a more precise evaluation of critical bridge safety and the potential consequences of failures for the communities involved [11].

During the 1980s, due to the lack of extensive Weigh-in-Motion (WIM) data, the establishment of live load factors was based on limited truck samples. However, with advancements in WIM technology, millions of vehicles have been recorded and are publicly available at diverse locations [12]. Although WIM data have been mostly used for pavement design and transportation planning purposes [13] they have also been used to develop live load models for application in bridge design codes, for evaluating the safety of existing bridges and for permit checking [14-17].

WIM systems are in place at several locations in Manitoba. In this study data collected under the Long Term Pavement Program (LTPP) at six locations in Manitoba were analyzed [21].

The locations of these sites are shown in Figure 20. The most common type, the piezoelectric WIM system, consists of a capacitive strip sensor and two inductive loops linked to a roadside processing unit. The capacitive sensor of a piezoelectric system is commonly made of ceramic material. The sensor extends across the lane and, when compressed, during the passage of a vehicle, the capacitance between the extrusion and the electrode changes proportional to the load. An axle load is computed by integrating the signal from the sensor with the speed information. When a vehicle approaches, the upstream inductive loop is used to alert the system and the downstream loop is used to detect the length of the vehicle to determine gross vehicle weight and overall length [6].

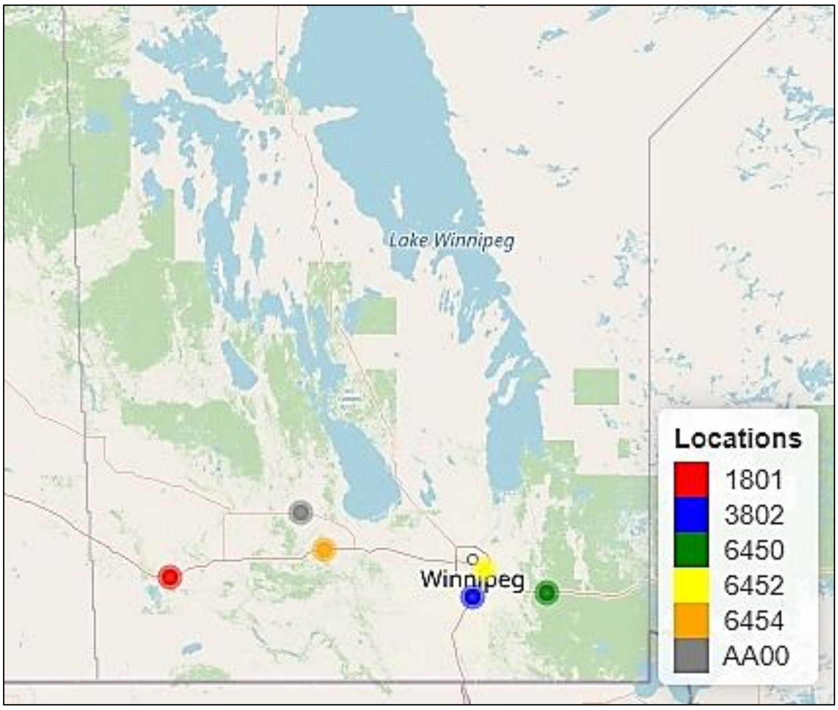


Figure 20. Locations of WIM sites in Manitoba, Canada

Weigh-In-Motion systems are currently installed at several locations in North America providing a considerable amount of truck data [6]. In North America, bridge failures related to overloading are ranked as the third leading cause following hydraulic events and collisions [3].

3-6-6 Legal Load Limits

The impact of trucks on highway bridges is closely tied to their weights, especially those that exceed the legal limits, as well as the distribution of these weights. Therefore, the characterization of trucks takes into account their compliance with truck weight limit regulations and their axle configurations. These factors play a crucial role in understanding the potential effects of trucks on bridge structures and form the basis for assessing their impact and developing appropriate measures for bridge safety. Based on Vehicle Weights and Dimensions Limits in Manitoba, the Maximum Gross Vehicle Weight (GVW) Limits are shown in Table.7 [17].

Table 7. Annual GVW weight allowances [17]

Province of Manitoba and the City of Brandon	Max. GVW 60,000 kg
City of Winnipeg	Max. GVW 56,500 kg

Table 8. Annual axle weight allowances [17]

Steering axles (truck tractors)	**Legal weight**
Single steering axle (straight trucks)	9100 kg
Tandem steering axle (straight trucks)	16,000 kg
Tandem axle	21,960 kg
Tridem axle	27,500 kg

Truck size and weight regulation modifications in Canada have influenced the interprovincial freight operating environment over the last five decades, which in turn has impacted the truck fleet mix, trucking costs and rates, shipment sizes and truck gross vehicle weights [18-20]. Trucks often exceed legal limits. By leveraging the WIM data, trucks can be grouped into clusters based on their weight characteristics, allowing the derivation of weight distributions essential for comprehensive structural reliability analysis of bridge superstructures [31].

The aim of this part is to assess the safety of bridges by employing reliability analyses to quantify the probability of failure when subjected to a particular hazard, specifically the impact of overweight (OW) vehicles traversing highway bridges. By analyzing the data of WIM systems and incorporating it into our reliability analysis, the probability of failure associated with the passage of OW vehicles can be estimated [18].

The methodology for assessing the probability of bridge failure due to overloads is described in the following subsections.

3-6-7 Analysis of Trucks Weight Data

In this section, relevant data about the weight of vehicles passing over bridges are described. For data collection, all relevant data from the Weight-in-Motion (WIM) stations located in Manitoba, were collected and aggregated (Appendix). These data included information on ID and locations of WIM stations, number of trucks, and percentage of overweight trucks. For example, more than 22,140,000 truck records were analyzed in MB. The data were extracted from six LTPP WIM sites in Manitoba, Canada from 2000 to 2013. These data are a very good representative picture of the truck population in Manitoba. Weigh-in-Motion (WIM) systems are designed to gather data on vehicles and classify them according to their axle configuration [19]. The analysis of Weigh-in-Motion (WIM) data in Manitoba showed that three categories account for over 97% of trucks, as illustrated in Figure 21.

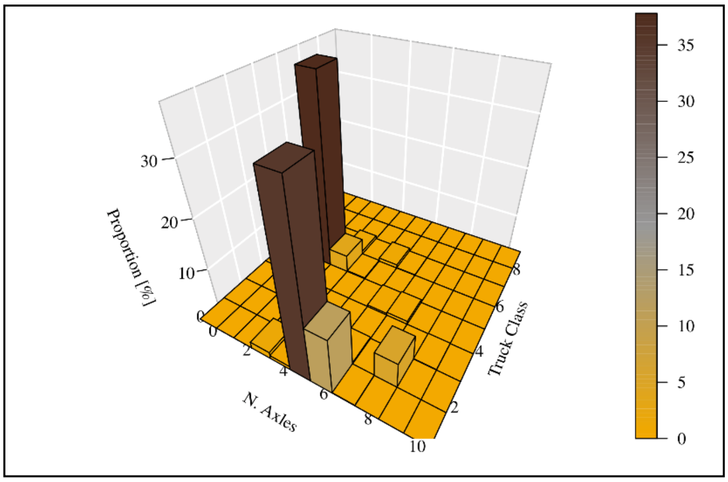


Figure 21. Trucks proportion based on the axle configuration

After gathering the relevant data, an analytical approach is utilized to estimate the overweight percentage of vehicles at a certain location. This information is at specific WIM locations and then interpolated to different positions in a region. For this task, once again, a Kernel Density Estimation is used. In this case, it allows us to estimate the density of OW (%) of trucks in the study regions. By considering the locations of the WIM stations and their associated weights, a density estimation that reflects the spatial distribution of OW percentage trucks are constructed.

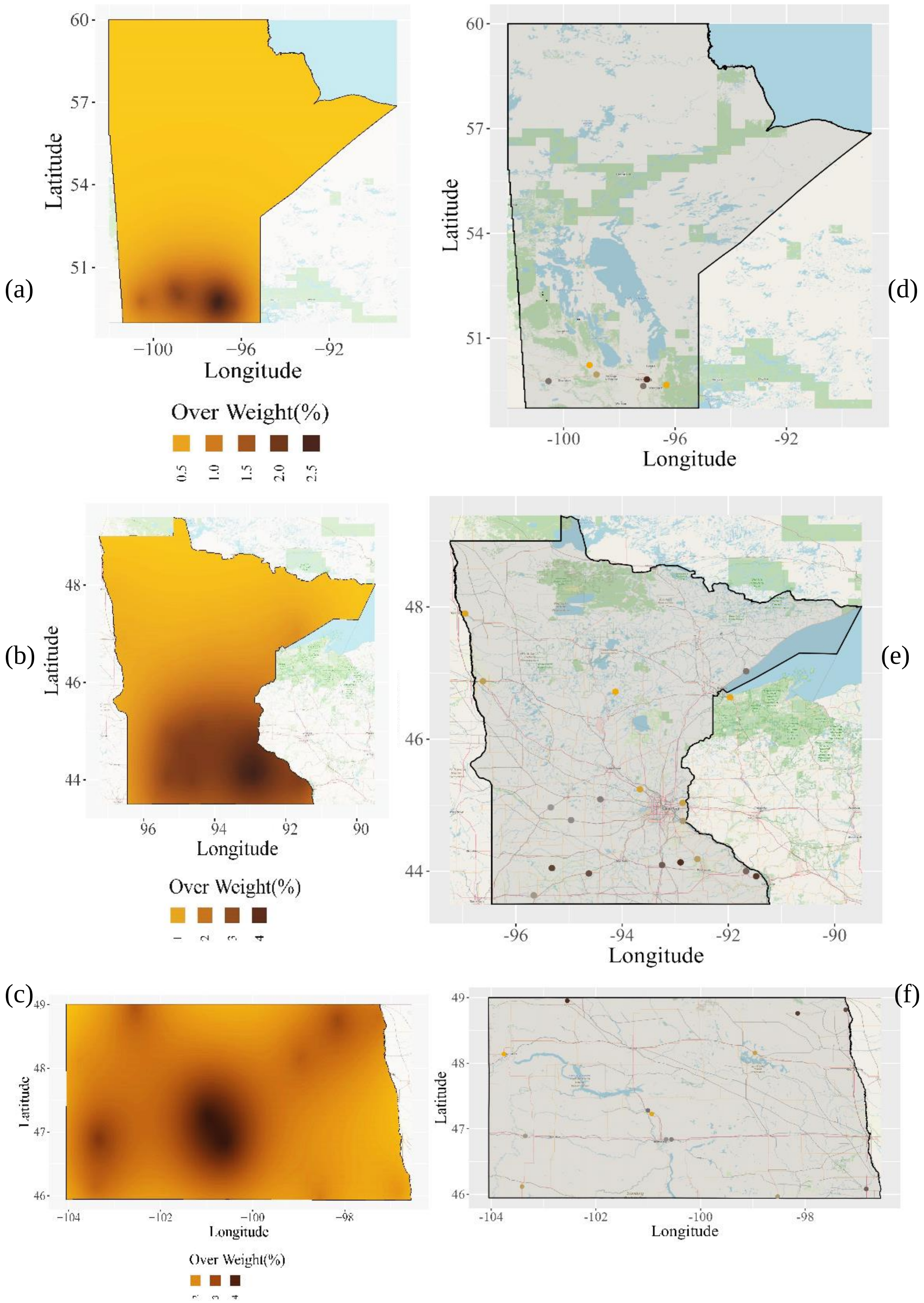


Figure 22. WIM Locations
Right side: Source maps showing locations of WIM systems across three locations
Left Side: kernel density map showing concentrations of overweight across three locations

As a comparative term, overweight maps were generated for the near states of North Dakota and Minnesota in the US using traffic data and federal weight regulations in these regions.

Figures 22(a), (b) and (c) show Kernel Maps, while Figures 22(d) (e), and (f) show the locations of each Weigh-in-Motion (WIM) system. In Manitoba, the percentage range of overweight (OW) is between 0.5% and 2.5%. For the region of North Dakota, it spans from 2% to 4%, whereas in Minnesota, it varies from 1% to 4%.

In addition, the Kernel Maps display distinct variations in overweight intensity, with darker regions indicating a higher prevalence of OW (%). These darkened areas show higher percentages of overweight truck occurrences compared to the dispersed regions. The Kernel Maps offer a comprehensive visual depiction of the spatial distribution patterns of OW percentages across the examined regions.

Finally, overweight percentages for each bridge in Manitoba, where the AADTT is more than zero, are extracted from the generated maps, similar to those obtained for the probability of flooding discussed in the previous section (Figure 23).

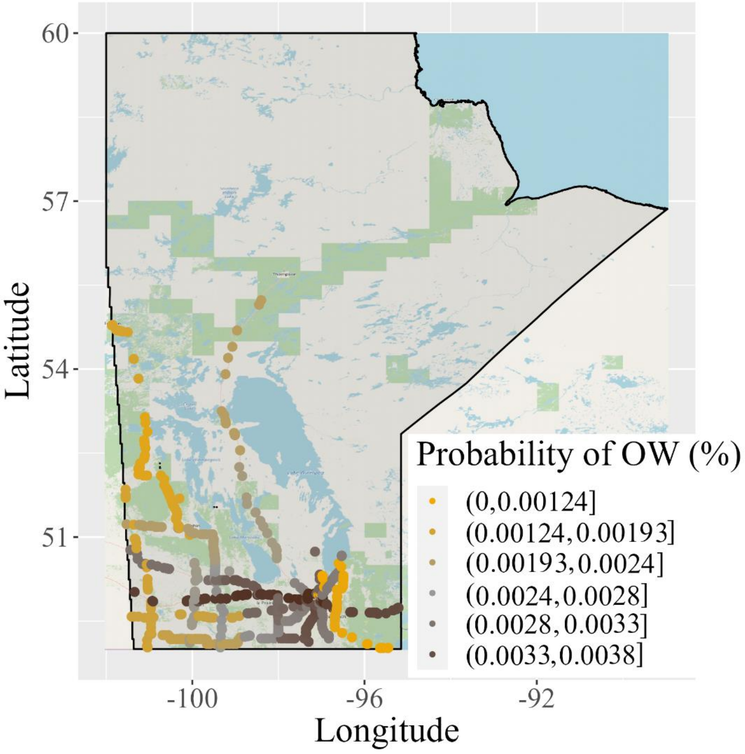


Figure 23. Probability of Overweight percentages for 778 bridges in Manitoba

3-6-8 Comparing Manitoba Overweight Truck Data with Neighbor Regions

As previously mentioned, data from the neighboring province of Manitoba have been employed to facilitate a comparative examination of the results. As depicted in the kernel maps (Figure 21), the outcomes obtained within the province of Manitoba are logically consistent, given that the same data analysis framework across both Manitoba and the states of North Dakota and

Minnesota have been applied. The range of values obtained aligns sensibly with the expected range for these two states.

Furthermore, a pointwise comparison can be established by examining the corridors extending from the two states into Manitoba and scrutinizing the numerical values associated with them. Thus, this comparative approach may serve as empirical evidence supporting the comprehensibility of the derived numerical results.

3-6-9 Quantitative Measure of the Overweight Hazard

Based on Equation 13, the essential parameters required for computing the copula value encompass the variables q and v. Both variables, q and v, are distributed within the interval [0, 1]. These variables serve as transformations of the independent variables AADTT and OW through their corresponding Cumulative Distribution Function (CDF).

In the preceding two sections, the analysis involving the calculation of OW (%) and AADTT of Manitoba bridges was elucidated. In addition, as mentioned in section 4-7-3, the parameter θ is computed as -2.88. Consequently, by substituting the derived values of bridges into Formula 13, the copula values for each bridge are determined. These values effectively denote the level of probability associated with bridge failure due to overweighting $P_f(B)_{OW}$.

3-6-10 Summary

In part three of this chapter Weigh-In-Motion (WIM) data is used to estimate the probability of failure due to overweight trucks on highway bridges ($P_f(B)_{OW}$). The summary of this process is included:

1. Reliability Analysis: The study employed structural reliability theory to assess the safety of bridges. The reliability index (β) was used to quantify the safety level of structural members and systems.
2. Hazard Analysis: The probability of bridge failure ($P_r(H)$) due to overweight trucks was estimated based on two parameters: the Average Annual Daily Traffic Volume (AADTT) and the percentage of overweight (OW) trucks.
3. AADTT analysis: Filtering Bridges with AADTT more than zero from road data of Manitoba was obtained.
4. Weigh-In-Motion (WIM) Technology: Utilizing Weigh-In-Motion (WIM) data, which collects information from six WIM sites in Manitoba, from 2000 to 2013, on vehicle weights, to perform the analysis of $P_f(B)_{OW}$.
5. Weight Analysis: The study used Kernel Density Estimation to estimate the probability density function of overweight trucks' distribution in the study regions.

6. Overloading on bridges: Identification of overweight percentage on bride network on three regions. It represents the probability of bridge failure across various regions. By this identification, prioritization of bridges can be implemented to enhance bridge safety against the entry of overweight vehicles.
7. Comparative Analysis: The consistent outcomes in Manitoba, analyzed using the same data framework applied to North Dakota and Minnesota, fall within the expected range for these states.
8. Copula Models: Regarding the effect of AADTT on bridge failure due to overloading, values of the Copula function were calculated based on the Archimedean Copulas model to estimate the joint cumulative distribution of $P_f(H)$.

3-7 Quantitative Measures of the Risk for Bridges in Manitoba

As indicated at the beginning of this chapter, the aim of this research is to analyze and estimate three significant parameters for Equation 3-2.

Eq.3-2 $$\mathbf{Risk} = \mathbf{E(C)} \times [\mathbf{P_f(B)_{Flood}} + \mathbf{P_f(B)_{OW}} + \mathbf{P_f(B)_{OW}} \times \mathbf{P_f(B)_{Flood}}]$$

$E(C)$= Economic consequences of bridge failure due to flood

$P_f(B)_{Flood}$= Probability of bridge failure due to water level and clearance

$P_f(B)_{OW}$= Probability of bridge failure due to overweight

As the value of Risk is small considering the low probability of occurrence of joint events, a non-dimensional risk index (RI) is computed by normalizing the risk value through the following formula (Min-max feature scaling) [38]:

Eq.3-13 $$RI = \frac{\mathrm{Risk} - 0.5 \times \mathrm{Risk_{min}}}{\mathrm{Risk_{max}} - 0.5 \times \mathrm{Risk_{min}}}$$

This allows us to quantify and characterize the relative risks associated with the identified factors and their interplay.

The only factor that differentiates the results of the above formula calculations is the variation in the clearance levels of different bridges.

In the table below, a summary of the minimum and maximum risk index (RI) in each threshold of clearance is given.

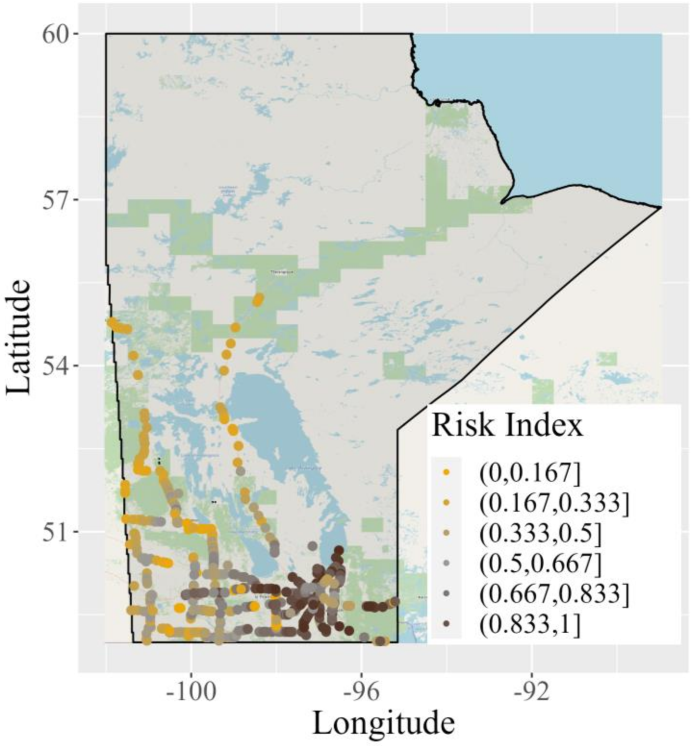
Table 9. Summary of RI for different overtopping thresholds in Manitoba

Threshold of Clearance		RI **(Min)**	RI **(Max)**
Minimum	3 m	2.63E-04	1
The first quartile (25th percentile)	4.6m	2.16E-04	1
Average	5.4 m	1.94E-04	1
Third quartile (75th percentile)	5.6 m	1.99E-04	1
Maximum	12.6 m	1.23E-04	1

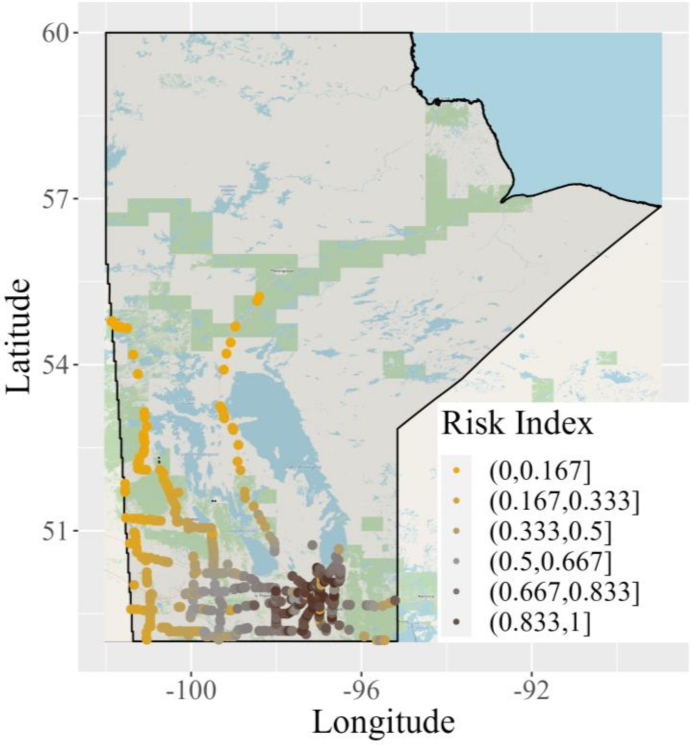
In Table 9, it is clear that with an increase in the RI index, the risk of bridge failure increases as well. In other words, as the value of the RI increases so does the value of the risk. This implies that in regions where the risk index is low, bridges are less exposed to the hazards of flooding and heavy loading. Consequently, utilizing the risk index allows decision-makers to better define mitigation strategies and management operations.

3-7-1 Statistics for Spatial Data

Scatter maps of the risk index are shown in Figure 24 for five thresholds. Each map displays a risk index as a function of the clearance threshold selected. Figure 24 is providing a comprehensive view of how the risk index is distributed across the province. By examining these scatter maps, one can gain insights into the patterns, trends, and potential relationships between the risk index and the variables being compared.



(a)



(b)

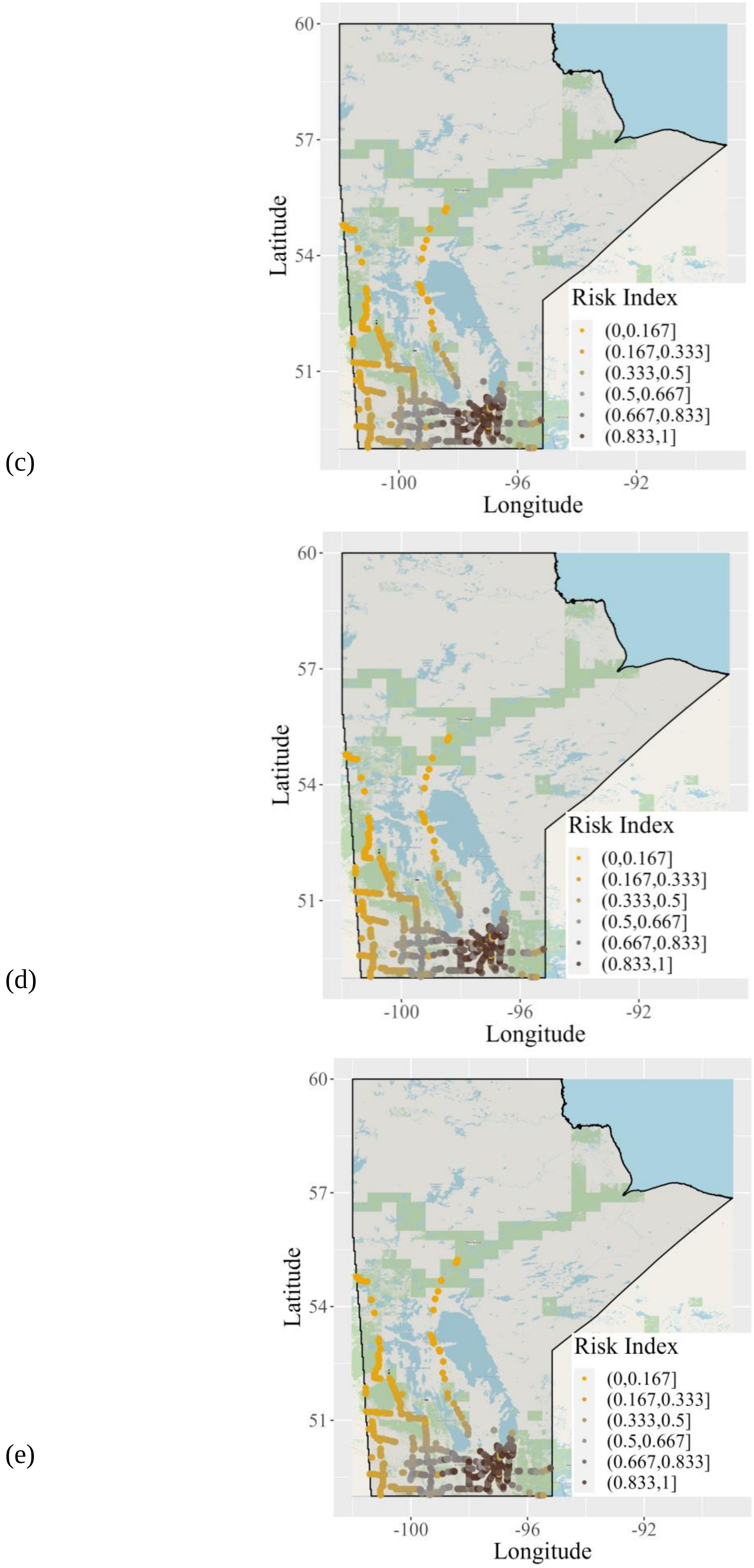


Figure 24. Risk Index for Highway Bridges in Manitoba for Five Threshold of Vertical Clearance (m) 3(a), 4.6(b), 5.4 (c), 5.6 (d),12.6 (e)

3-8 Analysis of Results

In this section, a comprehensive analysis of the results obtained from this research is presented. Through this analysis, a well-rounded perspective on bridge risk analysis in Manitoba can be developed.

This chapter evaluated the risk of bridge failures due to flood disasters and overloading in Manitoba, Canada. It also highlighted the importance of analyzing the relevant characteristics of the bridges and their surrounding environment to make better decisions for improving the performance and safety of the bridges. First, the methodology used to assess the economic impacts of floods and the risk of bridge failure, which includes examining financial losses between 2016 and 2021 and using geographical maps to identify areas that experienced significantly greater losses was discussed. Then, insights on how to assess the performance and safety of bridges, including the introduction of quantitative risk assessment into the bridge design process were provided by risk assessment of bridge failure through vertical clearance in flood-prone areas. The findings of the data analysis were discussed in detail and it can help decision-makers to design structures to better withstand flood impacts by enabling the unobstructed flow of floodwater, thereby reducing potential damage. Additionally, the section discussed the spatial distribution of exceedance probabilities on bridge surfaces, as illustrated by the density maps, and how bridges situated near the Red River or its branches face higher risks due to the higher water flow in these areas during flood events. The section emphasized the need for risk assessment and targeted maintenance actions to mitigate potential damage to these bridges. Finally, the risk index for typical highway bridges in Manitoba was defined to compare bridges within a region of interest. A higher index value indicates a greater risk for the community. Therefore, prioritizing bridge preconception based on this risk index holds significant importance. This underscores the need for ongoing research in this domain, aimed at aiding decision-makers and code developers in refining precise probabilistic risk-based models. These models play a crucial role in evaluating the susceptibility of highway bridges to failure induced by flood events.

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Chapter Four: Discussion

In this chapter, the results of data analysis from chapter three are discussed. The goal of this study is to develop a methodology for evaluating the risk of bridge failure due to flood disasters and overloading in Manitoba, Canada (as a case study) and develop an approach to introduce the concept of quantitative risk assessment into the bridge design process. By examining these differences and analyzing the relevant characteristics of the bridges and their surrounding environment, better decisions for improving the performance and safety of the bridges can be made.

In the following sections, the findings of each data analysis section in Chapter 3 are discussed, and ultimately, a general conclusion is presented.

4-1 Financial Damage Resulting from Flood Disasters

The study introduced a methodology for assessing the economic impacts of floods and the risk of bridge failure in Manitoba. First, the financial losses between 2016 and 2021, in which the losses for each year were measured in square kilometres, were examined. Then, using geographical maps was shown that the Red River area experienced significantly greater losses than other regions in Manitoba. On the other hand, expressing the losses per square kilometer helped in standardizing the collected costs across different areas and estimating the risks associated with bridges.

Moreover, the statistical analysis conducted in this part demonstrated that the log-normal distribution was a more suitable fit for the flood damage data in North Dakota and Minnesota, whereas the data from Manitoba follows a normal distribution. The statistical models of the three regions offer valuable information that can aid decision-makers in modelling future events.

4-2 Probability of Bridge Failure Due to Flood Hazard

During flood events and high-water flows, increased water volume and velocity can lead to the scouring of bridge foundations, structural integrity reduction, base and column erosion, and even the destruction of certain bridge components. Therefore, careful examination and planning for the prevention of scouring and bridge deterioration are of utmost importance.

After estimating the impact of financial losses, $(P_f(B)_{Flood})$, valuable insights into the Probability of Bridge Failure Due to Flood Hazards and shed light on the importance of Vertical Clearance as a critical factor during flood events were provided in the second part of the analysis. By assessing historical performance and using the Probability Density Function

(PDF) and Kernel method, the study identified varying probabilities of bridge failure due to floods based on hydrological data.

The significance of Vertical Clearance in flood-prone areas was highlighted in the study to assess the possibility of bridge flooding and related closure. Adequate vertical clearance allows structures to better withstand flood impacts by enabling unobstructed flow of floodwater, thereby reducing potential damage. The findings underscore the importance of considering this factor during the design and construction of structures, especially in regions prone to flooding. The spatial distribution of exceedance probabilities on bridge surfaces, as illustrated by the density maps, indicated that bridges situated near the Red River or its branches face higher risks. This observation aligned with the higher water flow in these areas during flood events. It emphasized the need for heightened risk assessment and targeted maintenance actions to mitigate potential damage to these bridges. However, while the method for estimating the probability of failure due to flooding based on historical hydrologic data and a kernel density estimator is deemed acceptable, the study also acknowledged certain limitations and assumptions that need to be considered when interpreting the results.

One significant limitation was the assumption of stationarity in flood patterns over time. The model assumed that hydrological processes and flood characteristics remained consistent, which may not hold true in the context of climate change and other external factors. Changing precipitation patterns, land use, or river dynamics can impact flood events, potentially leading to deviations from historical data and affecting the validity of probability estimates.

In addition, the omission of considering the spatial correlation of bridge failures caused by flood events stands as a limitation in this study.

The reference water level of each stream was assumed to equal to the average value in the time history. If the water level is higher than the assumed values, the predictions would underestimate the true probability of flooding. Also, the vertical clearance thresholds used to estimate the probability of overtopping are based on a very limited set of data. Further information is required to better estimate this parameter.

To enhance the reliability of the study's findings, future research should focus on addressing these limitations. Incorporating climate change scenarios and considering non-stationarity in flood patterns could lead to more robust probability estimates. Additionally, sensitivity analyses can be conducted to evaluate the impact of different distribution assumptions and threshold values on the results.

4-3 Probability of Failure Due to Overweight Traffic

In the third part of the chapter, the study utilized Weigh-In-Motion (WIM) data to estimate the Probability of Failure due to Overweight Trucks on highway bridges ($P_f(B)_{OW}$). The process involved several steps, including data collection, reliability analysis, hazard analysis, overloading identification, and the use of Copula models.

The fragility of bridges for overstress depended on two factors, the overweight percentage and the number of daily trucks in the traffic flow. To model the fragility curve for overstress, a copula was employed, utilizing normal distributions for both the overweight percentages and Average Annual Daily Traffic (ADTT).

By characterizing the reliability of bridges within a network using fragility equations, maintenance operations for existing bridges can be prioritized based on the actual traffic conditions. This approach also offers the potential to quantify the risk for large bridge networks with minimal computational effort.

In that process, Weigh-In-Motion (WIM) Technology was employed to collect data on vehicle weights from six WIM sites in Manitoba spanning from 2000 to 2013. This data formed the basis for the analysis of $P_f(B)_{OW}$, enabling researchers to understand the impact of overweight trucks on bridge safety. The study employed a Kernel Density Estimation to estimate the probability density function of overweight trucks' distribution in the study regions. This statistical technique allowed the researchers to understand the frequency and distribution of overweight trucks on highway bridges. To assess the safety of bridges, the study employed structural reliability theory. The reliability index (β) was used to quantify the safety level of structural systems. Hazard analysis was performed to estimate the probability of bridge failure ($P_f(H)$) due to overweight trucks. This estimation was based on two key parameters: the Average Annual Daily Traffic Volume (AADTT) and the percentage of overweight (OW) trucks.

To understand the effect of AADTT on bridge failure due to overloading, the study employed Copula models. These models calculated the values of the Copula function based on the Archimedean Copulas model, estimating the joint cumulative distribution of $P_f(H)$. The Copula models utilized transformed independent variables AADTT and OW (%) through their corresponding cumulative distribution functions based on a normal distribution. The Copula model values provided insights into the probability of failure due to an overweight percentage for bridge superstructures.

These findings are crucial for bridge safety management and can aid in the development of targeted strategies to mitigate the risks associated with overweight trucks on highway bridges.

However, it is essential to acknowledge the limitations of the methods and assumptions involved in the analysis to ensure the robustness of the results. Future research could focus on refining the models and expanding data sources to further enhance the accuracy of the probability estimates.

4-4 Risk Assessment Model for Bridges in Manitoba

The aim of the research was to analyze and estimate three significant parameters ($\mathrm{E(C)}, \mathrm{P_f(B)_{Flood}},$ and $\mathrm{P_f(B)_{OW}}$) to estimate risk values for typical highway bridges in Manitoba.

To compute a quantitative measure of the risk (Risk) and risk index (RI) for Manitoba's bridges five different vertical clearance thresholds were selected. The risk index (RI) is a normalized risk value (Risk), indicating that higher values of RI correspond to higher risks of bridge failure due to flooding and overloading. In simpler terms, as the value of RI increases, while one location anticipates marginally lower probabilities, the potential outcomes hold greater significance; however, both risk and RI would remain elevated. This is because risk encompasses more than just probability, and more attention should be paid to the affected bridges.

To facilitate a better comparison, scatter maps for each of the five thresholds, displaying the value of risk index representation of highway bridges risk levels across Manitoba, were provided. In conclusion, the risk assessment model and the use of the risk index (RI) provided valuable insights into the potential risks associated with bridge failures due to flooding and overloading. The findings can aid in optimizing preventive and mitigation measures to enhance bridge safety in flood-affected regions.

One of the limitations of this research about the analysis of financial damages resulting from floods is the disparity in insurance coverage between the United States and Canada. This discrepancy arises from the fact that insurance mechanisms differ between the two countries. While FEMA operates as a federal agency in the United States, CatIQ functions as a private insurance institution. The divergence between these two insurance frameworks can potentially pose a challenge when attempting to analyze financial damages caused by floods in the research. The different roles of FEMA and CATIQ, as federal and private entities respectively, may lead to variations in data availability, coverage extent, and the overall landscape of flood-related financial assessments. The constraint arising from the availability of data between the United States (represented by FEMA) and Canada (represented by CATIQ) may affect the way flood-related financial damages are evaluated and compared in this research.

4-5 Additional Remarks:

The research findings underscore the importance of proactive measures to enhance bridge safety, especially in regions susceptible to floods and overloading. The information gained from this study can guide decision-makers in implementing targeted strategies to mitigate risks and improve infrastructure resilience. Future research endeavors should address uncertainties associated with climate change impacts and explore alternative techniques for robust risk assessment.

Chapter Five: Conclusion and Future Work

The research presented in this study was motivated by the condition of Canada's aging infrastructure, limited economic resources, and the consequences of bridge failures on local communities and highway networks. The main objective of this study was to develop a methodology for quantifying the risk of bridge failure due to flooding and overloading events for the significance of bridges within the broader highway network. The procedure is accomplished by implementing a control mechanism that regulates the necessary safety level of the bridge under analysis.

The study aims at enhancing the overall resilience of bridges and their impact on the highway network considering the probability of failure attributed to flood disasters and overweight conditions, along with their associated consequences.

In the first step, this research identified the financial impact of flood events in three regions, Manitoba, Minnesota, and North Dakota. In this part, the estimated financial damages to the surrounding community were quantified per square kilometer. The analysis was conducted statistically, considering the geographical locations.

In the second part of Chapter 3, vertical clearance data from the Manitoba province (as the case study for this research) were utilized. Then the key locations of flood-prone zones in Manitoba were identified (100 locations), and the historical flood data were extracted for analysis. Based on the average water level over the past 10 years (from 2013 to 2022) at these locations and the vertical clearance data of Manitoba's bridges, another statistical analysis was performed. First, the deviations from the obtained averages were estimated. Subsequently, a sensitivity analysis was conducted to explore the effects of different vertical clearance thresholds (5 thresholds) including maximum, minimum, average, and the first quartile (25th percentile) and third quartile (75th percentile) of vertical clearance have been established, on the analysis. The respective values for these thresholds are 3, 4.6, 5.4, 5.6, and 12.6 meters. Finally, in this section, the overtopping levels for each bridge in the province were calculated, and bridge prioritization based on higher overtopping was provided.

In the third part of Chapter 3, another factor influencing the risk assessment of bridges, overweight traffic, was examined. The relationship between the percentage of overweight vehicles and the Average Annual Daily Truck Traffic (AADTT) was modelled. It was observed that an increase in truck traffic leads to a higher percentage of excessive loading on the bridges and, consequently, an increased risk of bridge failures.

5-1 Applications of Proposed Research Results

There are several potential applications of this research. Some possible applications include:

1. Bridge Management and Maintenance: The findings of this study can be applied to bridge management and maintenance practices. By quantifying the risk value of bridges and identifying high-risk bridges, authorities and bridge managers can prioritize their resources and efforts toward the maintenance, inspection, and rehabilitation of bridges most susceptible to failures caused by floods or overweight traffic. This can contribute to enhancing the safety and reliability of bridge infrastructure.
2. Risk Assessment and Mitigation Strategies: By understanding the probability of failure due to floods or overweight traffic, decision-makers can devise appropriate measures to reduce the risks associated with these factors. This may include implementing improved flood management plans, upgrading bridge designs and structural elements, implementing weight restrictions or monitoring systems for heavy traffic, and enhancing emergency response plans.
3. Infrastructure Planning and Design: The insights gained from this research can inform infrastructure planning and design processes. Engineers and designers can utilize risk values to make informed decisions during the planning and design phases of bridge projects. This can lead to the incorporation of appropriate clearance requirements, flood-resistant designs, and weight-bearing capacities to ensure the longevity and resilience of bridges in flood-prone areas.
4. Policy Development: Authorities and policymakers can utilize the risk assessment outcomes to establish regulations, standards, and guidelines aimed at ensuring the safety and sustainability of bridges in the face of flood events and overweight traffic hazards. This can help in setting comprehensive frameworks for bridge infrastructure management and ensuring compliance with safety standards.
5. Emergency Preparedness and Response: The research outcomes can enhance emergency preparedness and response strategies. By understanding hotspots of economic consequences of bridge failures caused by floods and overweight traffic, emergency management agencies can allocate resources and develop contingency plans to mitigate the impact of such events. This can involve establishing early warning systems, evacuation plans, and measures to ensure effective emergency response and recovery.

Overall, the applications of this research extend to various domains, including bridge management, risk assessment, infrastructure planning, policy development, and emergency management. The findings can serve as a valuable resource for decision-makers, engineers, and stakeholders involved in the management and resilience of bridge infrastructure.

5-2 Future Work

The research on the risk assessment of bridge failure has highlighted the significant costs and issues associated with these failures, as well as the ways in which policy responses can mitigate these costs. However, there are still many questions that need to be addressed in order to better understand the economic impacts of bridge failure and develop more effective policy responses. In this section, a number of directions are proposed for future research that could help improve our understanding of this important issue.

1. Developing advanced modelling techniques for assessing the combined effects of multiple hazards on bridge failures: While this study focuses on flood-related risks, it is important to recognize that bridges can be exposed to multiple hazards simultaneously. Future research should explore the development of advanced modelling techniques that integrate the effects of floods, earthquakes, and other potential hazards to provide a more comprehensive assessment of bridge network resilience.

2. Exploring innovative monitoring and maintenance strategies for bridge networks: Continuous monitoring and effective maintenance play a crucial role in ensuring the longevity and safety of bridge infrastructure. Future research can focus on advanced monitoring techniques, such as remote sensing technologies and structural health monitoring systems, to detect early signs of vulnerability and deterioration. Additionally, investigating innovative maintenance strategies, including predictive maintenance and condition-based assessments, can help optimize resource allocation and extend the lifespan of bridges.

3. Conducting comparative studies across different regions and bridge typologies: While this study focuses on a specific region or bridge typology, conducting comparative studies across different regions or bridge types can provide valuable insights into the variations in vulnerability, risk factors, and resilience strategies. Comparative studies can help identify best practices, transfer knowledge, and foster collaboration in addressing bridge failures due to floods.

4. Regarding the economic consequences of bridge failure, it would be valuable to conduct further research on the impact of bridge failure on local and regional economic activity. Previous studies have demonstrated that bridge closures can have significant negative impacts on local businesses and workers, particularly in communities with a reliance on transportation infrastructure. There is also a need to explore the economic impacts of bridge failures on industries such as tourism and logistics, as well as the ways in which bridge closures can disrupt supply chains and reduce demand for goods and services.

5. Another area of research should focus on the costs and benefits of different approaches to bridge maintenance and repair. Some studies have compared the costs of different materials and technologies for bridge repairs, while others have analyzed the trade-offs between preventive maintenance and more expensive repairs or replacements which is still debatable.

6. Another area for future research could be investigating the importance of other factors that contribute to the risk of bridge failure. This could include the role of climate, and maintenance history, as well as other factors such as the age and design of the bridge. By studying these factors, researchers could identify the characteristics of bridges that are most at risk of failure and the specific contexts in which the economic consequences of bridge failure are likely to be most severe. Such research could help policymakers prioritize bridge maintenance and repair efforts and develop more effective strategies for mitigating the economic impacts of bridge failure.

Appendix A – CatIQ Records and WIM Data

- **Sample of CatIQ Records for financial losses for Manitoba- 2018**

Province	FSA*	Latitude	Longitude	LoB**	Buildings Value / Vehicle Value, C$	Loss Limit
MB	XYZ	Y.YY	X.XX	P	37,008,006	57,957,672
MB	ABC	Y.YY	X.XX	C	2,176,556,399	2,616,701,085

*Postal Code
**Line of Business (P: Personal and C: Commercial)

- **Weigh-In-Motion (WIM) data at stations located in Manitoba**

WIM ID	Latitude	Longitude	Number of trucks	Number of OW trucks	OW Trucks (%)
1801	49.76956	-100.541	2655448	153180	5.8
3802	49.6275	-97.1382	2653594	152833	5.8
6450	49.66152	-96.3066	6884327	256839	3.7
6452	49.82259	-97.0115	3416710	277653	8.1
6454	49.96156	-98.8235	3912337	182820	4.7
AA00	50.22567	-99.0713	6884327	256839	3.7

- **Weigh-In-Motion (WIM) data at stations located in Minnesota**

WIM ID	Latitude	Longitude	Number of trucks	Number of OW trucks	OW Trucks (%)
#26	44.09514	-93.2474	1047056	182239	17.4
#27	43.96686	-94.6251	360484	64875	18.0
#30	47.02696	-91.6629	138881	22015	15.9
#31	47.9019	-96.9556	120566	8919	7.4
#32	44.18613	-92.5821	864283	84558	9.8
#33	44.77474	-94.9603	273301	36264	13.3
#34	44.96731	-95.3424	184159	22065	12.0
#37	45.24128	-93.6633	1554012	115102	7.4
#38	46.63374	-91.9657	655945	32346	4.9
#39	44.00194	-91.6662	190277	31858	16.7
#42	44.76225	-92.8543	559577	56917	10.2
#43	46.87699	-96.6196	365424	31466	8.6
#44	46.71726	-94.1254	24207	525	2.2
#45	45.08851	-94.4083	136378	21070	15.4
#46	44.13549	-92.8995	11206	4073	36.3
#47	45.03561	-92.8598	264486	22164	8.4
#48	44.04864	-95.3209	20359	4733	23.2
#49	43.63785	-95.6639	594879	61530	10.3
#59	43.92565	-91.4748	373767	92002	24.6

- **Weigh-In-Motion (WIM) data at stations located in North Dakota**

WIM ID	Latitude	Longitude	Number of trucks	Number of OW trucks	OW Trucks (%)
Belfield	46.8893	-103.3492	137269	17423	12.69%
Bowman	46.117	-103.411	32660	5092	15.59%
Ellendale	45.9649	-98.5274	108725	18508	17.02%
Wahpeton	46.0812	-96.8354	228630	43736	19.13%
Williston	48.1399	-103.7573	579592	45722	7.89%
Joliette	48.815582	-97.22883	191839	36918	19.24%
Portal	48.9528	-102.546	33375	9420	28.22%
Washburn	47.2251	-100.9339	126809	15800	12.46%
Devils Lake	48.1578	-98.9596	36190	5088	14.06%
Langdon	48.7612	-98.1459	21431	5294	24.70%
Apple Creek EB	46.8384	-100.6581	375895	66717	17.75%
Apple Creek WB	46.8371	-100.5564	269123	49234	18.29%
Panger	46.8893	-103.3492	16177	2801	17.31%
Sykeston	47.278287	-101.005784	95770	18087	18.89%

Appendix B - R code

```
## PERFORM SPATIAL PREDICTION OF OVERWEIGHT TRUCK STATS BASED ON SCATTER WIM INFO


# Libraries

library(gstat)
library(gridExtra)
library(RColorBrewer)
library(MASS)
library(ggplot2)
library(ggpolypath)
library(OpenStreetMap)
library(osmdata)
library(maps)
library(mapdata)
library(raster)
library(rgdal)
library(factoextra)
library(class)
library(reshape2)
library(latex2exp)
library(foreach)
library(iterators)
library(doParallel)
library(openxlsx)
library(writexl)


# Path to the folder
machine_path <- "File Location"

# Load functions from external files
source(file = paste(machine_path, "/Master_Plot_Functions.R", sep = ""))

# INVERSE DISTANCE WEIGHTED INTERPOLATION METHOD (IDW) OR EXPONENTIAL WEIGHT (EXP)
idwE <- function(Q, xi, yi, zi, idp = 1.0, smoothing = "exp") {
  Dx <- xi - Q[1]
  Dy <- yi - Q[2]

  if (smoothing == "idw") {
    Wg <- (Dx^2 + Dy^2)^(-idp) # Power distance weight
    zQ <- (Wg %*% zi) / sum(Wg)
  } else if (smoothing == "exp") {
    Wg <- (exp(-sqrt(Dx^2 + Dy^2)))^idp # Exponential weight
    zQ <- (Wg %*% zi) / length(zi)
  }
  return(zQ)
}
# Create raster layer from OpenStreetMap objects
map_rast <- function(bbx, zm = 20) {
```

```r
  map <- openmap(upperLeft = bbx[1:2], lowerRight = bbx[3:4], type = "osm", minNumTiles = zm)
  map_bbox <- c(map$bbox$p1[1], map$bbox$p2[1], map$bbox$p2[2], map$bbox$p1[2]) # left, right, bottom, top
  map_proj <- map$tiles[[1]]$projection # get current geoRaster coordinate system
  .extent <- extent(as.numeric(map_bbox))
  my_map <- raster(.extent, nrow = map$tiles[[1]]$yres, ncol = map$tiles[[1]]$xres, crs = map_proj)
  rgb_cols <- setNames(as.data.frame(t(col2rgb(map$tiles[[1]]$colorData))), c('red', 'green', 'blue'))
  red <- my_map
  values(red) <- rgb_cols[['red']]
  green <- my_map
  values(green) <- rgb_cols[['green']]
  blue <- my_map
  values(blue) <- rgb_cols[['blue']]
  Lyr <- stack(red, green, blue)
  Rst <- raster::merge(Lyr)
  Rst <- projectRaster(Rst, crs = CRS('+proj=longlat +datum=WGS84')) # Change projections to Long-Lat format
}

# COLOR PALETTE EXAMPLE
mypal <- colorRampPalette(c(rgb(0.0, 0.9, 0.0), rgb(0.0, 0.5, 0.0), rgb(0.0, 0.2, 0.8)))
CLRpl <- mypal(20)

# MULTIPLE DATA
# MB, ND, MN
CNTls <- c("Canada", "USA", "USA")
RGNls <- c("Manitoba", "North Dakota", "Minnesota")
BBls <- list(
  c(60.0, -102.03, 48.99, -88.94),
  c(49.0005, -104.0489, 45.9350, -96.5545),
  c(49.3843, -97.2392, 43.4993, -89.4917)
)
DBls <- c(
  "File name.csv",
  "Data_2016-2021_ND_unitarea.csv",
  "Data_2016-2021_MN_unitarea.csv"
)
nmFGls <- c("MB", "ND", "MN")
nMP <- 1

pltNMrst <- vector(mode = "list", length = nMP)
pltNMsct <- vector(mode = "list", length = nMP)

cores <- detectCores()
cl <- makeCluster(min(nMP, floor(0.8 * cores[1])), outfile = "")
registerDoParallel(cl)

foreach(i1 = 1:nMP, .packages = c("OpenStreetMap", "raster", "osmdata", "ggplot2")) %dopar% {
  BB <- BBls[[i1]]
```

```
 OSmap <- openmap(upperLeft = BB[1:2], lowerRight = BB[3:4], type = "osm", minNumTiles = 20)
 mymap <- openproj(OSmap)

 # CREATE A RASTER TO BE FILLED WITH DATA
 BBrst <- map_rast(BB)

 # GADM POLYGONS
 MapSp <- getData(country = CNTls[i1], level = 1)
 NMpv <- data.frame(NAME_1 = MapSp@data$NAME_1, id = rownames(MapSp@data), clr =
sample(1:(2 * length(MapSp@data$NAME_1)), size = length(MapSp@data$NAME_1)))
 ALLmap <- fortify(MapSp)

 STmap <- ALLmap[which(ALLmap$id == as.numeric(NMpv$id[NMpv$NAME_1 == RGNls[i1]])),] #
Select region

 # EXTRACT THE PERIMETER OF THE REGION
 STmap$group <- as.numeric(STmap$group)
 STmap <- STmap[STmap$group == STmap$group[1],]

 polyR <- SpatialPolygons(list(Polygons(list(Polygon(STmap[, c("long", "lat")])), 1)))

 # CREATE A POLYGON MASK WITH AREA BORDER
 BBrstm <- mask(BBrst, polyR)
 BBcrp <- c(BB[2], BB[4], BB[3], BB[1]) # xmin, xmax, ymin, ymax
 BBrstm <- crop(BBrstm, BBcrp)

 # SCATTER DATA POINTS TO CREATE A FIELD MAP WITH INTERPOLATION (OR KERNEL DENSITY
FUNCTIONS)
 NMdb <- paste(machine_path, "/", DBls[i1], sep = "")
 DataDB <- read.csv(file = NMdb, stringsAsFactors = FALSE)
 names(DataDB) <- c("Lat", "Lon", "OW(%)")

 # DEVELOP MAPS
DBmap <- BBrstm
Nx <- dim(BBrstm)[2]
Ny <- dim(BBrstm)[1]
Dy <- res(BBrstm)[2]
Dx <- res(BBrstm)[1]
X0 <- extent(BBrstm)[1]
Y0 <- extent(BBrstm)[3]
GRD <- as.matrix(BBrstm) # GRID OF POINTS TO BE POPULATED

# POPULATE THE GRID
for (i3 in seq(1, Nx)) {
 for (i2 in seq(1, Ny)) {
  # (Note: MATRIX Y INDEX GOES TOP DOWN, WHILE THE RASTER GOES BOTTOM UP)
  Qi <- c(X0 + i3 * Dx, Y0 + i2 * Dy)
  GRD[Ny - i2 + 1, i3] <- ifelse(is.na(GRD[Ny - i2 + 1, i3]), NA, idwE(xi = DataDB$Lon, yi = DataDB$Lat,
zi = DataDB$Field, Q = Qi))
```

```
 }
}
# ASSIGN THE VALUES TO THE GEORASTER
values(DBmap) <- GRD

NMtif <- paste(nmFGls[i1], "-raster.tif", sep = "")
writeRaster(DBmap, filename = paste(machine_path, "/", NMtif, sep = ""), bylayer = TRUE, overwrite = TRUE)
DBmap <- raster(paste(machine_path, "/", NMtif, sep = ""))

# PLOT RASTER
pltNMrst[[i1]] <- plotRasterMap(Rast = DBmap,
 figNM = paste(nmFGls[i1], "-raster", sep = ""),
 PTHo = machine_path,
 top = BB[1],
 left = BB[2],
 bottom = BB[3],
 right = BB[4],
 GADM_Country = CNTls[i1],
 GADM_NAME_1 = RGNls[i1],
 GADM_Level = 1,
 nClr = 5,
 lgnName = "Loss-year [$CAD/km2]",
 lgnPos = "bottom",
 alphaVal = 1
)

# PLOT SCATTER DOTS
names(DataDB) <- c("yDB", "xDB", "grpDB")
pltNMsct[[i1]] <- plotDBmap(DB = DataDB,
 figNM = paste(nmFGls[i1], "-scource", sep = ""),
 PTHo = machine_path,
 top = BB[1],
 left = BB[2],
 bottom = BB[3],
 right = BB[4],
 GADM_Country = CNTls[i1],
 GADM_NAME_1 = RGNls[i1],
 GADM_Level = 1,
 sizeDots = 2,
 lgnName = "Loss-year [$CAD/km2]",
 lgnPos = "none"
)
}
stopCluster(cl)

# Plot distribution of data
mdlFT <- c("normal", "log-norm", "log-norm")
for (i1 in seq(1, nMP)) {
```

```
  NMdb <- paste(machine_path, "/", DBls[i1], sep = "")
  DataDB <- read.csv(file = NMdb, stringsAsFactors = FALSE)
   MDL <- ProbPlot(DataDB[, 3], dist = mdlFT[i1], nSmp = 100, Ltail = 0.05)
    DBsct <- data.frame(x = sort(DataDB[, 3]), y = seq(1:length(sort(DataDB[, 3])))/(length(DataDB[, 3]) + 1))
    DBfit <- MDL$cdfSample
  DBfit$grp <- mdlFT[i1]
    plotDBscatFit(DBsct = DBsct, DBfit = DBfit,
                figNM = paste(nmFGls[i1], "-dist", sep = ""),
                PTHo = machine_path,
                lgnNM = "Model-fit",
                xLab = "Loss-year [$CAD/km2]",
                yLab = "CDF",
                lgnPOS = c(0.8, 0.1))
  print(summary(DataDB$Loss_km2))
  print(paste("Distribution: ", mdlFT[i1], sep = ""))
  print(paste("Parameter 1: ", MDL$p1, sep = ""))
  print(paste("Parameter 2: ", MDL$p2, sep = ""))
  print(paste("Chi2 Val: ", MDL$chisqVal, sep = ""))
  print(paste("Chi2 Ref: ", MDL$chisqRef, sep = ""))
  print(paste("Chi2 DoF: ", MDL$DoF, sep = ""))
}

# Extract field points at a specific location x, y
DBmap <- raster(paste(machine_path, "/MB-raster.tif", sep = ""))
DF <- read.csv("location of bridges.csv")
names(DF)[1:2] <- c("x", "y")
DF$field <- rep(0, times = nrow(DF)) # Data frame of scattered points (like bridges)
for (i1 in seq(1, nrow(DF))) {
  # Create a bounding box
  xMin <- DF$x[i1] - 0.1
  xMax <- DF$x[i1] + 0.1
  yMin <- DF$y[i1] - 0.1
  yMax <- DF$y[i1] + 0.1
  Bx <- extent(xMin, xMax, yMin, yMax)
  DF$field[i1] <- mean(extract(DBmap, y = Bx), na.rm = TRUE)
}

write.csv(DF, " File Location /mydata.csv")
```