BEST PRACTICES RESEARCH ON RESILIENCY AND ADAPTATION IN PUBLIC TRANSPORTATION

Prepared by: Rahul Dutta, UBC Sustainability Scholar, 2023
Prepared for: Donna Bartel, Senior Sustainability Advisor, TransLink.

August 2023


Disclaimer

This report was produced as part of the UBC Sustainability Scholars Program, a partnership between the University of British Columbia and various local governments and organizations in support of providing graduate students with opportunities to do applied research on projects that advance sustainability and climate action across the region.

This project was conducted under the mentorship of staff at TransLink. The opinions and recommendations in this report and any errors are those of the author and do not necessarily reflect the views of TransLink or the University of British Columbia.

Acknowledgements

The author acknowledges that the work for this project took place on the unceded ancestral lands of the xwməθkwəy̓əm (Musqueam), Skwxwú7mesh (Squamish), Stó:lō and Səl̓ílwətaʔ/Selilwitulh (Tsleil- Waututh) Nations.

The author would like to thank the following individuals for their contribution, feedback, and support throughout this project:

Donna Bartel, Senior Sustainability Advisor at TransLink

Ralf Nielsen, Director of Enterprise Sustainability at TransLink

Tony Vi, Senior Planner at TransLink

Llewellyn Fonseca, Senior Manager, Corporate Asset Management at TransLink

Dorit Mason, Director, Safety Emergency and Environment Management at TransLink

Internal working resiliency group at TransLink

Cover photo courtesy of TransLink

Contents

.

Executive Summary

Climate change manifests its impact in British Columbia (BC) with warmer temperatures, and more frequent and severe weather events. These impacts are naturally expected to trickle down to the public transportation system in the province, thereby affecting critical transportation infrastructure and services. In the face of BC's changing climate, mass transport organizations such as TransLink proactively seek to identify actions, practices and guidelines that can increase the resiliency of its infrastructure and operations.

The current project investigates the resiliency practices, guidelines, and adaptation strategies prevalent in major transit agencies across North America. In doing so, the project has identified key approaches and methods, which serve as a hallmark for boosting climate resiliency and adaptation efforts in such transit agencies. These key practices provide TransLink the opportunity to design robust resiliency programs, policies, and guiding principles for design and engineering against climate change. Additionally, the current project also designed a survey questionnaire for gaining knowledge on systems and organizational resilience that can benefit TransLink to identify ways to improve its climate adaptation practices.

The current project also sheds light on the role of professional associations in the development of climate adaptation guidelines. Professional associations are indispensable to the development of climate leaders and a well-informed workforce. This is accomplished primarily by the inclusion of climate knowledge, awareness, and experience in the registration process for professional practice in Canada, in addition to, providing a platform for knowledge-sharing among professionals with a wide array of climate resources and expertise.

Finally, the current project recommends a few implementable approaches that can boost systems and organizational resilience at TransLink. These implementable approaches are based on assessments of system criticality and strategies for multi-criteria-decision making for climate adaptation. These approaches have been further demonstrated by the help of case studies at other transit agencies. Outcomes from the current project suggest that resiliency strategies at transit agencies need to be viewed from a professional practice perspective, asset management perspective, and from a decision-making perspective. From a professional practice perspective, organizations such as TransLink must encourage application of a climate adaptation lens to all infrastructure projects by professionals within the organization. From an asset management perspective, TransLink should investigate the potential of asset management approaches for assessing asset criticality with information currently available within the organization. From a

decision-making perspective, TransLink should incorporate multi-criteria decision support systems in scenario-based analysis for selection of climate adaptation options.

.

Chapter 1. Introduction

Resilience can assume various definitions, but its fundamental essence lies in the capacity to be well-prepared for and capable of recovering from adverse occurrences, including events like extreme weather or disasters (Ebinger & Vandycke, 2015). While readiness for emergency scenarios remains crucial for transit agencies, the increasing urgency lies in establishing robust resilience against climate change impacts and extreme weather events. This is imperative to safeguard both present and future investments in transit infrastructure, ensuring the continuity of safe operational capabilities.

While distinct regions of Canada may exhibit variations in terms of projected climate change factors, scientific consensus remains unified in acknowledging that weather events will progressively amplify in terms of their intensity, duration, and frequency (Swanson et al., 2021). Consequently, the heightened occurrence of extreme weather events and natural disasters poses a substantial threat to the operations and infrastructure of transit systems across the nation. In the upcoming years, transit systems in Canada are poised to encounter substantial impacts due to shifting weather patterns. It is both judicious and strategic to undertake an evaluation of the resilience of both operational procedures and capital assets in response to multiple climate change variables. This assessment should account for our geographic location and leverage climate projection data to gain insight into the potential vulnerabilities inherent to Canada's transit system. By engaging in this proactive approach, we can effectively comprehend potential weaknesses and better equip transit systems to mitigate the potential risks stemming from changing climatic conditions.

Over the last century in British Columbia, average temperatures have risen by 1.2 °C and annual precipitation has increased by about 20%. Snowpacks are projected to decrease, and eventually lesser snowmelt would result in lesser runoff during spring and summer. This is expected to impact the public transportation sector within the province. TransLink is the statutory authority responsible for regional transportation network of Metro Vancouver in British Columbia, Canada. In 2022, TransLink's Climate Action Strategy was endorsed by Mayors' Council, committing TransLink to reduce greenhouse gas emissions, adapt to climate impacts, and advance governance and funding. Over the course of the next three years, TransLink aims to complete several actions related to climate adaptation/resilience to mitigate impacts of climate change on infrastructure and operations. As an integral part of initiatives like Transport 2050, the 10-Year Priorities, and the 10-Year Investment Plan, TransLink is embarking on a series of significant expansion projects and renovations that span multiple decades (Translink, 2022). The overarching goal of these projects is to ensure that the transit infrastructure is adequately equipped to meet the growing demand for transit services. While a considerable portion of these projects may not directly interact with customers, they focus on expanding service and enhancing operations and maintenance facilities, as well as supporting infrastructure.

Given the extended lifespan of many of these projects, spanning 50 years or more, it becomes imperative to factor in the projected changes in our region's climate. The anticipated climate alterations include wetter and milder fall and winter months, along with warmer and drier summers. Additionally, an elevated frequency and severity of extreme weather events are expected to occur throughout the year. Given these anticipated shifts, it's essential that TransLink's facilities and infrastructure are designed and constructed to accommodate forthcoming climate conditions. Prioritizing adaptation to future climate norms and fostering resilience against extreme weather occurrences will be integral to the longevity and functionality of TransLink's future endeavors.

This research project stems from TransLink’s quest in integrating climate resiliency standards into the planning, design and construction of new infrastructure, and rehabilitation of existing infrastructure to meet up-to-date climate policies and guidelines. The project leverages TransLink’s unique position to learn from established resiliency practices, policies, and standards in international transit organizations. In doing so, the project initiates a review of best practices for climate change and adaptation in eight transit organizations across North America. Secondly, the current project conducts a survey to gain knowledge on crucial aspects of systems and organizational resilience within transit organizations. Such knowledge will help TransLink develop its own framework and strategy to bolster systems and organization resilience. Following that, the project investigates the role of professional associations in enhancing climate education, awareness, and practice among professionals in Canada. Lastly, the project suggests a few implementable approaches for climate adaptation at TransLink and demonstrates their application through case studies. The objectives of the project can be outlined as follows:

- Reviewing best practices and guidelines for climate adaptation
- Identifying the role of professional associations in developing climate adaptation responses
- Preparing a survey questionnaire for gaining knowledge on adaptation approaches in other transit agencies
- Recommending implementable approaches for climate adaptation in transportation sector

An overview of the project has been presented in Figure 1.1.

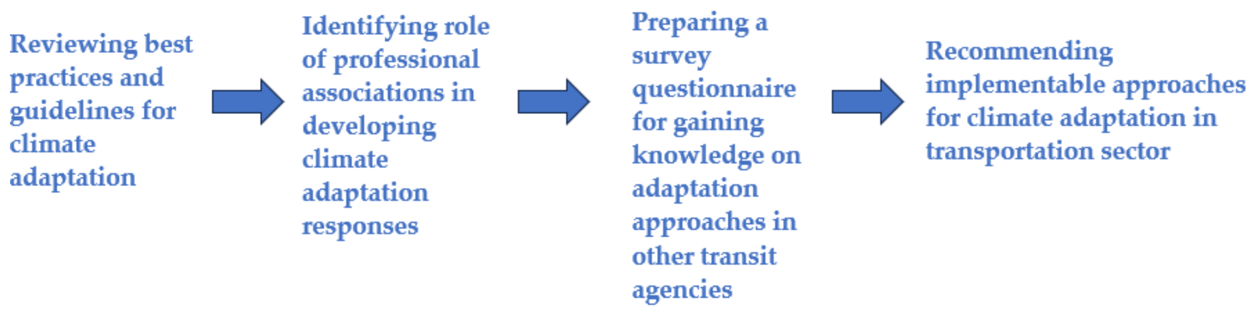

Figure 1. 1 Project overview

.

Chapter 2. Best practices for climate change and adaptation in the transportation sector: A review

For organizations to ensure their survival, growth, and effective provision of public services, they must be capable of adjusting to evolving conditions and requirements. One such imperative demand is posed by the challenges of climate change. A risk-based systematic approach is indispensable now because of the long lifetimes of urban infrastructure, long-term planning horizons, and the significant socio-economic risks posed by climate change in today's world.

This chapter reviews the systematic approaches being adopted towards climate adaptation in transit organizations/agencies across North America. These systematic approaches are becoming a hallmark for best practice in climate adaptation in the transportation sector. In this chapter, best practices for climate adaptation in two transit agencies across North America have been discussed. A total of eight transit agencies were reviewed but for brevity only two have been discussed in this section. Information from other transit agencies has been compiled into Table 2.1 at the end of the chapter.

2.1 Metrolinx

Metrolinx is a governmental agency under the jurisdiction of the Government of Ontario. Its primary responsibility involves coordinating and seamlessly integrating transportation services across the Greater Toronto and Hamilton Area (GTHA) in Canada. The agency oversees various operational components, including GO Transit's regional bus and rail services, as well as UP Express. Metrolinx boasts a wide-ranging portfolio of assets, encompassing bus and train fleets, rail lines, stations, parking facilities, maintenance centers, and the electronic payment system known as PRESTO (Chiotti, 2016).

In 2014, the Metrolinx Five-Year Strategy (2015-2020) committed to the establishment of a Corporate Climate Adaptation Plan which would encompass facilities, practices, and protocols within the organization (Chiotti, 2016). The following key themes reflect the best practices for climate adaptation currently being implemented at Metrolinx. These key themes range from awareness and education programs currently in-place at Metrolinx to identifying opportunities for action and the barriers associated with them.

Awareness, Education and Communication: In 2015, Metrolinx established a Resiliency Working Group, which includes members from various business units within the organization, such as those responsible for bus, rail, stations, and planning. This group collaborated with a consulting team to undertake a test application of Engineers Canada's Public Infrastructure Engineering Vulnerability Committee (PIEVC) Protocol. This protocol was employed on six chosen infrastructure assets that are representative of Metrolinx's operations.

This exercise yielded valuable insights for Metrolinx, enhancing its comprehension of how vulnerable its assets are to extreme weather events and the impacts of climate change. While certain areas exhibit significant adaptive capacity and resilience, there are apprehensions regarding other areas where critical thresholds might be surpassed by the middle of the century. This could have significant implications for operational efficiency and safety within the organization.

By establishing the Resiliency Working Group, Metrolinx has a strong base for involving a diverse array of partners, stakeholders, and audiences in discussions concerning the attainment of resiliency. Past endeavors and ongoing projects stand as positive examples and chances for learning, both for Metrolinx itself and for other transit organizations within North America (Chiotti, 2016).

Incorporating education to raise awareness internally and externally stands as a crucial facet of an effective adaptation action plan for Metrolinx. This approach ensures that the organization remains well-informed about leading practices and also highlights its role as a leader in climate resiliency efforts. Establishing collaborative relationships with external partners and agencies is imperative, given that addressing resiliency needs might surpass Metrolinx's individual capabilities. This engagement strategy, encompassing heightened awareness, education for key personnel, and strategic partnerships both within and outside Metrolinx, plays a pivotal role in proficiently managing the risks presented by extreme weather events and the impacts of climate change. With its firm footing, Metrolinx is well-positioned to foster discussions among various stakeholders, partners, and audiences to collectively work towards achieving greater resiliency.

Assessment of vulnerabilities and risk of climate change within the agency: Comprehending the susceptibility and potential dangers posed by infrastructure assets, individuals, and services to different climate factors is paramount for adeptly handling climate-related risks and leveraging potential benefits. This task necessitates access to pertinent and dependable data concerning the evolving climate, encompassing both historical patterns and future forecasts. Additionally, the capability to decipher and employ this information within the context of distinct climate parameters, types of assets, and geographic locations will be indispensable.

Following its establishment in 2015, Metrolinx's Resiliency Working Group undertook an initial review of optimal practices in vulnerability assessment. Based on the outcomes of this review, the group was assigned the task of collaborating with a consulting team to implement Engineers Canada's Public Infrastructure Engineering Vulnerability Committee (PIEVC) Protocol on six selected assets that serve as broad representations of infrastructure within the regional transit network. This endeavor marked the first application of the PIEVC Protocol for evaluating transit infrastructure assets in Canada. The project significantly contributed to enhancing the comprehension of Metrolinx's assets' vulnerability and risk to extreme weather occurrences and the impacts of climate change. The project team comprised internal staff, engineering consultants knowledgeable about Metrolinx's assets (AECOM), climate experts (Risk Sciences International), and flood specialists (Toronto Region Conservation Authority, TRCA). Among the six assets examined, the selection process considered factors such as ridership, strategic importance, historical vulnerability, and system-wide significance. These assets encompassed a bus maintenance facility, a rail maintenance facility, two GO stations, and segments of two rail corridors. A key initial step involved the identification of climate parameters, thresholds and projected probabilities and their potential interactions with asset components. Projected probabilities were estimated from historical data provided by Toronto Pearson International Airport and a group of more than 40 climate models released by IPCC AR5 in 2013 (Chiotti, 2016).

The study enabled Metrolinx to better address its resiliency needs by establishing a central database for asset conditions and weather-related incidents, assessing vulnerabilities and risk across the entire transit network, and adding resiliency measures for future projects.

Identifying opportunities of action: The first step towards identifying opportunities of action involves gaining evidence to make informed decisions on costs of today's action vs the future costs of inaction. This requires and in-depth knowledge on climate modelling and hazard mapping, to conduct in-depth vulnerability assessments.

Secondly, a strategic approach of identifying priority action areas and targets for climate resiliency of assets is needed. Asset management employs a methodical process of deploying, operating, maintaining, upgrading, and eventually disposing of assets. This is executed in a way that maximizes their cost-effectiveness and performance throughout their lifespan, all while ensuring the delivery of safe and reliable services. Implementing robust asset management practices leads to well-informed decisions that strategically optimize investments, enhance risk management (including the risk of infrastructure failures), and factor in the potential consequences of extreme weather events and climate change. Through the integration of considerations such as lifecycle costs, risk assessment, and performance trade-offs, asset management encompasses the allocation of limited resources in a manner that optimally addresses capital expenses, operational costs, and maintenance needs.

Thirdly, reviewing emergency response plans, standards of practice, and standard protocols increasingly to minimize the impacts of climate change. Metrolinx has consolidated over 60 individual emergency response plans, each corresponding to a major asset, into a comprehensive and coordinated single plan. This unified plan encompasses various protocols tailored to different types of assets and emergency situations, with specific provisions for handling extreme weather events.

Lastly, collaboration and involvement with professional associations in Canada that support knowledge building and sharing. Currently, Metrolinx shares information with regional and local governments, many of which have similar climate challenges. Furthermore, results from vulnerability assessments are shared with industry associations such as Engineers Canada, which developed the PIEVC protocol used by Metrolinx.

Implementation of strategies for climate adaptation: Characterizing feasible options for adaptation is crucial towards climate risk mitigation. In Canada, mostly standards and codes for design consider historical climate data as a good indicator of the future. However, with increasing uncertainties in climate, it is essential to ensure that upcoming infrastructure conforms to updated climate resilient standards. Recently, the Standards Council of Canada and the National Research Council have received over $55 million in funding for the development of new standards in response to climate change. However, still a lot remains to be done. Currently, transit organizations such as Metrolinx are relying on stakeholder engagement through workshops for characterizing the feasibility of adaptation options.

Moreover, with climate adaptation for infrastructure assets comes the challenge of monitoring the performance of the adaptation strategies. Such monitoring programs are not only centred around the asset in question but also climate hazards against which the asset was designed. Reliable and precise short-term forecasts for localized heat waves and storm warnings are of utmost importance for ensuring uninterrupted service. While the accuracy of current forecasts for rapid and isolated rainstorms that could result in flooding or washouts, as well as for freezing rain, is among the most advanced, there are instances where the exact timing and intensity of certain events cannot be precisely predicted. Enhancing resiliency efforts would greatly benefit from the establishment of a standardized reporting protocol and a central repository for information. Additionally, ongoing monitoring of advancements in scientific knowledge, policy changes, technological innovations, best practices, and the endeavors of Metrolinx's counterparts and collaborators is essential. This process requires the utilization of appropriate tools and methodologies for assessing the effectiveness of resiliency measures, encompassing approaches like cost-benefit analysis and the triple bottom line concept. As a result, TransLink's Corporate Climate Adaptation Plan should be viewed as a dynamic and evolving document. Regular reviews and updates should be conducted to ensure its relevance and alignment with the changing landscape. Effective monitoring and adaptive management will facilitate continuous enhancements by implementing resiliency measures that span from incremental improvements to transformative changes.

Acknowledgement of challenges, gaps, and barriers: Acknowledgement of knowledge gaps and challenges that can act as barriers to action is important for climate adaptation. Uncertainty around climate change parameters, lack of localized data, reliance of data on external agencies, and uncertainties about cost estimates are all part of the challenges which exist when dealing with an uncertain phenomenon such as climate change. Consequently, adaptation plans should be treated as a living document, continuously reviewed, and updated in an ongoing basis.

2.2 New York City Metropolitan Transportation Authority (MTA)

In order to neutralize the impacts of climate change on its assets MTA has made significant efforts to integrate climate adaptation into its programs. This section outlines the steps undertaken at MTA in a bit more detail.

Identifying MTA facilities and programs vulnerable to climate risk*:* This step involved the development of an appropriate inventory of MTA assets and operations in relation to climate risk. Creating an inventory serves as a fundamental initial step in pinpointing MTA assets and operations, susceptible to climate risks (Jacob et al., 2008). It's crucial to consider the potential for synergistic interactions between different climate risks. For instance, flooding in low-lying regions might result from the combined impact of heavy rainfall and storm surges.

Identifying primary climate hazards to MTA assets, facilities and programs: The subsequent step investigated the primary climate hazards to MTA assets, facilities and programs in the region. The MTA relied on the plethora of literature evidence demonstrating the present and future climate change threats to the region. Changes in precipitation patterns, inclusion of extreme events such as heat waves and sea-level rise, and saltwater intrusion were some of the primary hazards identified in the region. The potential interaction of each of these risks with MTA's assets were evaluated and recorded. Climate projections were also derived from global climate model simulations provided by IPCC. MTA considers up-to-date information being generated through suite of models.

Characterizing adaptation options and conducting an initial screening: Adaptations can include management and operations adaptations, options for infrastructure investments, and policy adaptations. While investigating a range of adaptation options, planners and engineers review a range of options relating to specific facilities in order to choose those measures which appear to be feasible and sustainable in technical, financial, policy terms, and by timing. An example of an adaptation measure that might be overlooked is flood protection work if it proves to be excessively costly when compared to alternatives such as elevating facilities, relocating assets, or implementing operational adjustments. However, during this assessment, it is vital to adopt a comprehensive approach, providing a broad array of alternative options (Jacob et al., 2008). This inclusivity is crucial as the feasibility criteria can evolve over the course of adaptation planning.

The feasibility evaluation must incorporate decision pathways that are time-sensitive and consider not just the initial capital expenditure, but also the long-term expenses associated with maintenance and upgrades throughout the proposed solution's lifecycle. Moreover, the chosen solution(s) should be designed to be adaptable in response to the evolving demands driven by the escalating impacts of climate change. What might initially appear as a highly cost-effective solution can, as time goes on or during particularly severe events, potentially lead to significantly detrimental outcomes.

Cost/benefit analysis and environmental impacts: The assessment of potential climate change adaptations involves evaluating their alignment with various factors such as the climate change timeframe (immediate, medium, and long-term), the capital cycle, associated costs, and other related impacts. This evaluation should consider not only changes that result directly from climate change but also changes that occur over time, regardless of climate change effects. These could include factors like population growth and shifts in per capita public transportation usage. The purpose of evaluating potential adaptations is to devise strategies that effectively manage the risks posed by climate change to the agency's infrastructure. These strategies provide a comprehensive approach for coping with the challenges presented by climate change, enhancing the overall resilience of the agency's operations and assets. One significant innovation in evaluating climate change adaptations is the concept of optimal scheduling. This entails determining whether implementing adaptations during an earlier timeframe, such as during rehabilitation activities, is more efficient compared to delaying these measures. While there might be increased risks associated with early implementation, there could also be considerable savings in terms of discounted capital expenditures over time. This approach involves weighing the trade-offs between potential risks and financial benefits to make strategic decisions about the timing of adaptation actions.

Monitoring and re-assessment of adaptation strategies: In the realm of adaptation efforts, continuous monitoring of climate change parameters is essential. This involves considering updated climate projections, re-evaluating the effectiveness of adaptation strategies, and integrating new insights into future initiatives. An integral component of this process involves employing indicators (Jacob et al., 2008). These indicators serve as measurable markers that can be tracked to both assess and monitor the necessity for specific adaptations, as well as the performance of those adaptations. Indicators can encompass a range of sources, including direct climate model outputs, data derived from model analyses, or data series obtained from various other sources. Crafting an appropriate set of indicators becomes a critical component of the MTA's climate adaptation endeavors, enabling informed decision-making and facilitating effective tracking of progress and outcomes.

2.3 Summary of best practices for climate adaptation in the transportation sector

The review yielded best practices and guidelines for climate adaptation at various transit organizations in North America, which has been summarized in Table 2.1. The current practices for climate adaptation at TransLink were compared against the practices being followed at eight other transit organizations (Amtrak, 2022; B.C. Ministry of Transportation and Infrastructure et al., 2014; Chiotti, 2016; Jacob et al., 2008; SF Environment, 2021; Société de transport de Montréal, 2017; Translink, 2022; U.S. Department of Transportation, 2021). The review demonstrated that TransLink is taking significant strides in the positive direction. The implementation of adaptation strategies is ongoing at TransLink. To aid this implementation, the upcoming chapters focus on implementable approaches of adaptation options, and case studies which demonstrate their application.

Table 2. 1 A summary of best practices for climate adaptation at nine transit organizations across North America

Best practices for climate change adaptation	Metrolinx	NYC MTA[1]	City of San Francisco	BC MoTI[2]	SEPTA[3]	US DoT[4]	Amtrak	STM Montréal	TransLink
Awareness, education and communication									
Development of internal working groups, collaborations with external partners and agencies	x	x					x		x
Increasing climate literacy among personnel and other stakeholders	x		x		x	x	x	x	x
Assessment of vulnerability and risk of climate change within the agency									
Identifying and tracking vulnerability among existing assets	x	x	x	x	x	x	x		x
Using up-to-date climate parameters and applying extreme climate change projected scenarios to assess risks on existing assets	x	x	x	x	x	x	x		x
Categorizing assets by type of primary hazard most critical		x			x	x	x		x
Conduct vulnerability assessments	x			x					x

Access to sufficient climate change educational resources	x		x			x	x	x	x
Identifying opportunities of action									
Evidence-based decision making to inform the cost of today's action versus the future costs of inaction	x	x			x	x	x		
Identifying priority action areas and targets for climate resiliency of assets from data gathered on climate stressors.	x	x	x		x	x	x		x
Developing a resiliency working group to spearhead resilience efforts.	x	x					x		x
Reviewing of emergency response planning and preparedness	x	x			x	x	x		x
Collaborating with professional associations (such as EGBC) which promote climate education and knowledge sharing	x					x			x
Implementation of strategies for climate change adaptation									
Characterize feasible adaptation options	x	x	x	x	x	x	x		

.

Development of implementation plans, scheduling of timeframes and categorizing solutions by time-horizons.		X				x	x		
Performing a cost/benefit analysis to evaluate the option/strategy most suitable to an asset by considering the severity of the hazard at present and in the future.	X	x				x	x		
Monitoring performance and reassessment of adaptation options/strategies	x	x	x	x	x	x	x	x	
Acknowledgement of gaps, challenges and barriers in an implemented strategy	x	x			x	x	x		

[1]New York City Metropolitan Transportation Authority

[2]British Columbia Ministry of Transportation and Infrastructure

[3]Southeastern Pennsylvania Transportation Authority

[4]United States Department of Transportation

.

Chapter 3. Development of a survey questionnaire to gain knowledge on systems and organizational resilience in transit organizations

Based on the review in chapter 2 and the inputs gathered from the Resiliency Working Group at TransLink, a survey questionnaire was developed to help gain knowledge on hazard identification, systems and organizational resilience in transit organizations across North America. The questionnaire consisted of three components – primary hazard determination, system and asset identification, decision-making on investments for climate adaptation.

3.1 Components of the survey

Hazard Identification/Resilience to what: The hazard identification component of the survey aimed at gaining knowledge on the type of primary climate hazards to existing assets within the transit organization. Additionally, the method and criteria for determining the primary hazards to the existing assets were also included as a part of the survey. This component of the survey also inquired about action plans to climate hazards, the frequency at which these plans are reviewed, emergency response plans for a climate disaster, and plans for climate preparedness before a forecasted event.

System and asset identification/Resilience of what: The system and asset identification component of the survey aimed at gaining knowledge on system interdependencies, service functions, or infrastructure assets deemed critical for preservation and restoration in the occurrence of a climate hazard. Questions involved knowledge about the steps involved in the determination of asset criticality within the organization, the criteria for prioritizing asset upgrades and functional capacity, and metrics to monitor resiliency adaptations. Additionally, this component of the survey also added questions on pre-set functional targets for an asset and if these targets were achieved, following the implementation of climate adaptation strategy.

Investment decisions/Organizational resilience: The investment decisions component of the survey aimed at gaining knowledge on any investment decisions, actions, or initiatives currently being considered for climate resilience. The process involved in making these decisions was inquired. Additionally, this component of the survey aimed at gaining knowledge on short-term, mid-to-long term, and long-term solutions on climate change being pursued at the transit organizations. Questions also entailed collaboration with stakeholders, professional associations, and academia, as well as challenges and gaps encountered for climate adaptation.

3.2 Responses

The survey questionnaire was sent to climate specialists, asset managers, and sustainability professionals from 10 transit organizations within North America. Communication was done primarily via email and LinkedIn. A deadline for the response was set at two weeks from the date at which the survey was communicated.

Unfortunately, only one positive response was received from a climate adaptation specialist at the City of Calgary (COC). Four other responses were received from professionals at Metrolinx, STM Montreal, King County, and Amtrak, who declined to participate in the survey due to being out of the office for vacation. No responses were received from five other transit agencies. While conducting the survey, it was realized that summer is not a great time to conduct such surveys as most of the staff are on vacation.

3.2.1 City of Calgary – A chat with climate adaptation specialist

A video-conferencing interview was conducted with a climate adaptation specialist at the COC. The total duration of the interview was 45 minutes. During this interview, Pippa Cookson-Hills, the climate adaptation specialist answered questions primarily focused on the current approaches to climate adaptation being investigated at the COC, the methods involved in implementing the approaches, monitoring strategies for the approaches, and recommendations for large infrastructure owners such as TransLink in climate adaptation.

The primary approaches for climate adaptation being investigated at the COC involves:

- Asset criticality assessment for present and future scenarios against the primary climate hazards in the region
- Decision making approaches for selection of climate adaptation options by considering multiple criteria

During this video-conferencing interview, Pippa also provided access to a case study conducted by the COC on asset criticality assessment for their transit electrification fleet. This case study demonstrated the use of PIEVC protocol in doing a preliminary assessment with an endogenous approach, where an organization does not have to rely too much on data provided by external agencies. The case study has been discussed in detail in Chapter 5.

Both of the primary approaches for climate adaptation at COC involve stakeholder engagement. Stakeholder engagement occurs in the form of workshops and surveys conducted by COC. Annually, 1-3 workshops have been conducted in the past for criticality assessment of assets. Additionally, the approaches also incorporate opinions of subject matter experts within the organization for investigating the consequences of occurrence of a climate hazard on any particular asset. Such opinions are considered indispensable to the adaptation of cost-effective and robust approaches in the COC.

The timeline for monitoring the performance of adaptation strategies in the COC is currently reliant on external funding. Presently, the COC is looking into the possibility of establishing a 10–15-year monitoring timeline for climate adaptation strategies. The implementation of such a timeline would require additional funding from the Council Strategic Initiative Fund (CSIF) and the COC is currently in its early stages of securing this funding.

The challenges and barriers involved in the adoption of climate adaptation options were mostly related to the costs of supporting the implemented option over the upcoming years. As the uncertainty of climate events remains, it can be difficult to ascertain if an implemented option today is not rendered useless in the future. Therefore, a lot of complexity prevails for asset managers and climate adaptation specialists in the COC to select an adaptation option that is going to be resilient in current and future climate scenarios. Additionally, there exists challenges in engaging the design team in the development of retrofits to existing infrastructure and incorporate climate resilient design to upcoming infrastructure that would help secure funding from CSIF.

Recommendations to large infrastructure owners such as TransLink from the interview yielded:

- The need for regular engagement with professionals of various disciplines within the organization to combine design, engineering, and policy-making principles regarding climate adaptation.
- The need for viewing resilience development from an internal systems resiliency perspective, where an organization can consider adaptation options resulting from preliminary assessments that require less reliance on data from external sources.

Chapter 4. Role of professional associations, codes of conduct, and standards of care in the development of climate adaptation guidelines

In Canada, there is a growing acknowledgement that the Earth's climate is changing at an unprecedented pace due to anthropogenic activities leading to the emission of greenhouse gases. The Intergovernmental Panel on Climate Change (IPCC) has emphasized that a temperature increase of 1.5 °C or more significantly raises the threats of long-lasting and irreversible changes to the Earth's climate and ecosystems (IPCC 12). In British Columbia, independent research suggests that by 2050 most regions will experience hotter, drier summers; an increased intensity and frequency of precipitation and extreme events; warmer winters with lower snowpack; and longer growing seasons. These physical changes are already beginning to profoundly affect the social, natural, and built systems in which architects, forest professionals, technologists, engineers, and geoscientists bear significant responsibilities. Every now and then, Canada looks to trained individuals with special expertise to make bold decisions about a wide range of climate issues. Given the important role of professionals in helping individuals and society at large respond to climate change, and to prepare for its impacts, professional associations should be very explicit about how their members are expected to act when dealing with climate change (Dickson & Arcodia, 2010; Parada et al., 2010).

It is essential for mass transit agencies such as Translink to adopt technologies and adaptation strategies that can offer them long-term advantages with respect to climate change. Professional associations often govern the activities of their members through codes of conduct and ethics, standards of practice, policy statements, and other guidelines. Professional associations form key agents in the dissemination of knowledge and technological development (Swan & Newell, 1995). This is mainly because members of professional associations working in an organization may act as boundary spanners who, through their engagement with professional associations can network to learn and cultivate innovative ideas on technological development. An overview of regulatory frameworks and role of professional associations in climate change adaptation has been discussed in this chapter.

4.1 Engineers and Geoscientists BC's Climate Action Plan

4.1.1 EGBC's Regulatory Framework

EGBC is the regulatory body for professions associated with engineering and geosciences. It was established under British Columbia's Engineers and Geoscientists Act (Engineers & Geoscientists British Columbia, 2021). Since February 2021, EGBC transitioned to operating under a new framework that sets continuous governance standards for BC's self-regulated professions and introduces new tools for regulating practices, processes, and requirements. The new framework constituted the code of ethics which needed EGBC to develop the Climate Change Action Plan (CCAP) in order to better serve the public interest and protect the environment. The development of CCAP and activities related to CCAP provided EGBC the opportunity to enhance its role as a regulator of professionals, engaged in the design, construction and maintenance of physical systems, developmental processes, and decisions impacted by a changing climate (Engineers & Geoscientists British Columbia, 2021).

In development of the CCAP, EGBC sought advice from registrants, stakeholders, and wider professional community on approaches to tackle climate change issues, particularly through practices centred around engineering and geosciences. The overview and structure of the plan has been discussed in the following section.

4.1.2 Plan Structure and Overview

Figure 2.1 demonstrates the key actions that EGBC plans to implement in a phased approach to achieve the desired outcomes of climate adaptation

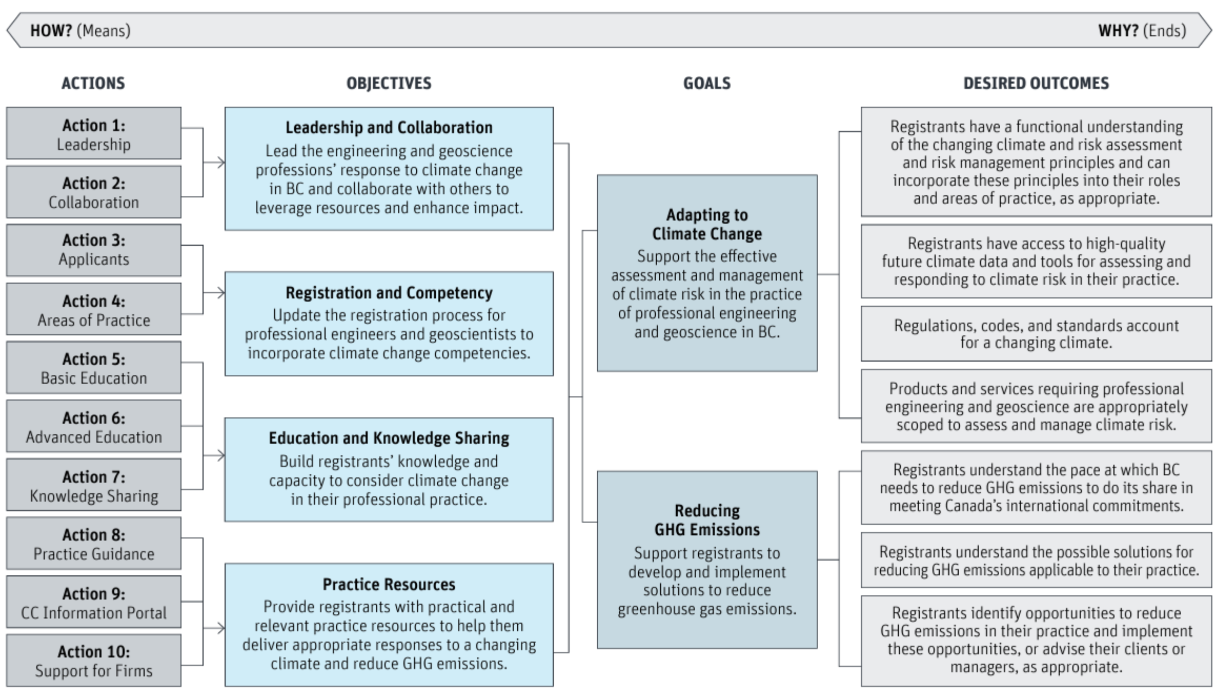

Figure 2.1 Structure of EGBC's Climate Change Action Plan

.

4.1.3 Climate Objectives and Actions

1. Leadership and Collaboration: Most of the leadership and collaboration activities of EGBC aims at raising awareness and demonstrating the need for action against the climate change impacts with the goal of incorporating climate change as a professional responsibility.

EGBC plans on actively collaborating with Engineers Canada, Geoscientists Canada, and other regulatory bodies to provide inputs on climate change issues of provincial and national relevance (Engineers & Geoscientists British Columbia, 2021). EGBC would partner with organizations and experts from academic or industrial disciplines to access the latest information, tools and opinions on climate action, data, expertise, and training.

2. Registration and Competency: To ensure members and registrants in BC meet minimum knowledge requirements on climate change, EGBC plans to introduce competency assessments as a part of the application procedure for professional registration. Additionally, climate change resources will be made available for registrants through online seminars.

3. Education and Knowledge Sharing: During the development process of the CCAP, registrants expressed the need of support for improving their access to education and knowledge sharing opportunities with respect to climate change. To ensure that all registrants have access to basic education and knowledge sharing opportunities on climate change, EGBC initiated the provision of free or low-cost educational sessions on climate change as a part of the ethical and regulatory learning opportunities of the Continuing Education Program.

EGBC also introduced advanced course offerings through other channels to advance skills and knowledge for climate change adaptation for reducing greenhouse gas emissions. Networking events for sharing knowledge on challenges and opportunities for climate change were introduced as well.

4. Practice Resources: Lastly, EGBC plans on providing guidance on climate change adaptation for specific professional practice applications. EGBC will also continue to develop its portal on Climate Change Information and provide registrants with guidance/training on climate change adaptation with respect to the disciplines of engineering and geosciences.

4.1.4 Implementation

Figure 1.2 Implementation of the CCAP as proposed by EGBC

EGBC plans to successfully implement the CCAP by following the course of actions shown in Figure 2.2.

4.2 Canadian Institute of Planners' Policy on Climate Change Planning

The Canadian Institute of Planners (CIP) advocates for planning professionals in Canada by providing numerous membership services. CIP is a member-based organization similar to EGBC, with its management complemented by volunteers who support and contribute to its activities in various spheres.

CIP recognizes that climate change planning is essential to reduce the impacts of climate change and work towards a resilient future of our built environment (Canadian Institute of Planners, 2018). Climate change informed planning refers to planning activities that seek to mitigate or adapt to climate change (Canadian Institute of Planners, 2018). CIP envisions a future in which communities are well planned, designed and developed to be more resilient to the unavoidable impacts of climate change. To achieve climate goals, CIP has laid down policy objectives for its built, natural, and social environments. The policy objectives have been discussed below for:

1. Built environment: Some of the policy objectives for climate resilient planning of the built environment include:
    - Regional and local planning should include an integrated approach towards mitigation, adaptation, and climate disaster risk-reduction.

- Communities have robust multi-modal transport systems for public transit, and evolving zero emissions vehicular technologies.
- Regional and metropolitan bodies incorporate robust strategies to incorporate climate considerations for upcoming developments.
- Communities are designed to support circular economy, which minimizes the use of virgin materials having longer lifecycles.

2. Natural and rural environments:
    - Communities plan, assess, prioritize assets, and mitigate threats posed by extreme events.
    - In areas facing extreme changes in physical surroundings, land use and infrastructure are adapted to meet new evolving circumstances.
    - Natural areas and ecological biodiversity should be conserved as they play a vital role in mitigating climate change.
3. Social environment:
    - Impacts and associated hazards of climate change on mental health are minimized.
    - Communities are more livable and successful, as climate change solutions are adopted to bolster other principles of good planning.
    - Local indigenous knowledge and traditions are valued and integrated into resiliency planning.

4.2.1 Guidelines for climate change adaptation for planners

CIP recognizes the key role of planners in reducing greenhouse gas emissions and has laid down the following obligations for practicing planners:

1. Ensure effective decision-making: CIP outlines the following best practices to ensure effective decision-making for planners:
    - Assuming a "no-regrets" approach while planning for worst case scenarios and incorporating risk mitigation measures into their plans
    - Founding planning strategies on climate and energy projections
    - Using established metrics and approaches for data collection and monitoring
    - Incorporating environmentally and socially responsible decision-making processes into their professional practices
    - Ensuring transparency in decision making process for community enhancement and improvement

2. Collaboration across sectors
    - Collaboration across several sectors, departments and jurisdictions within the organization to develop a comprehensive approach for climate resiliency planning
    - Collaborations with engineers, architects, scientists, sustainability professionals to develop climate change adaptation and mitigation strategies
    - Collaboration with experts to monitor the short-term and long-term impact of planning decision on greenhouse gas mitigation, and revise plans to adopt future climate change scenarios
3. Engage indigenous people, stakeholders, youth and the general public
    - Engage Indigenous leaders, private sector, elected officials, and the general public in all aspects of climate change planning
    - Being inclusive and respectful of Indigenous cultural practices and knowledge to ensure decisions and climate change interventions are culturally appropriate
    - Improve public awareness and support for climate adaptation by demonstrating multiple benefits from proper climate adaptation planning
    - Readiness to experiment and innovate in collaboration with academic and special interest groups

Chapter 5. Implementable approaches for climate adaptation at TransLink

Transportation infrastructure entails an intricate system of assets required to deliver a multitude of services and functions. Currently, as a part of Transport 2050, TransLink plans on undertaking several major expansion projects and renovations over the next several decades. The execution of these projects warrants the need for novel approaches towards long-term planning, asset management, project development, engineering design, and lifecycle planning.

With an ever-changing climate, critical infrastructures such as telecommunications, water and sewerage systems, transportation, power generation, and other emergency services have become interdependent. A disruption in one infrastructure causes a ripple effect into other infrastructures. Over the course of this project, it became evident that the first step towards climate preparedness requires an understanding of infrastructure interdependencies at both local and regional scales. The subsequent steps include determining the criticality of assets, prioritizing upgrades, and monitoring metrics of system resiliency.

5.1 Assessing the criticality of assets within a transportation system

5.1.1 EPA Asset Management Approach

With relevance to a transportation system, criticality of an asset is defined as a measure of the importance of an asset to the overall resiliency of a system in maintaining its functional capacity and carrying out its services with minimal disruption. Criticality assessments are important to relieve transportation agencies of costs involved in bringing every asset to its highest standard for a climate event (EPA, 2014). An understanding of the relative criticality of assets within a transportation system helps in prioritizing asset upgrades, weighing mitigation alternatives, and reviewing emergency response plans. However, key challenges in the context of criticality include, what is deemed "critical" and which assets are in/out of the boundaries of vulnerability assessment. Consequently, it is necessary to define the purpose and the intended audience for the overall criticality assessment (EPA, 2014). The United States Environmental Protection Agency has defined a 10-step asset management process demonstrated in Figure 5.1.

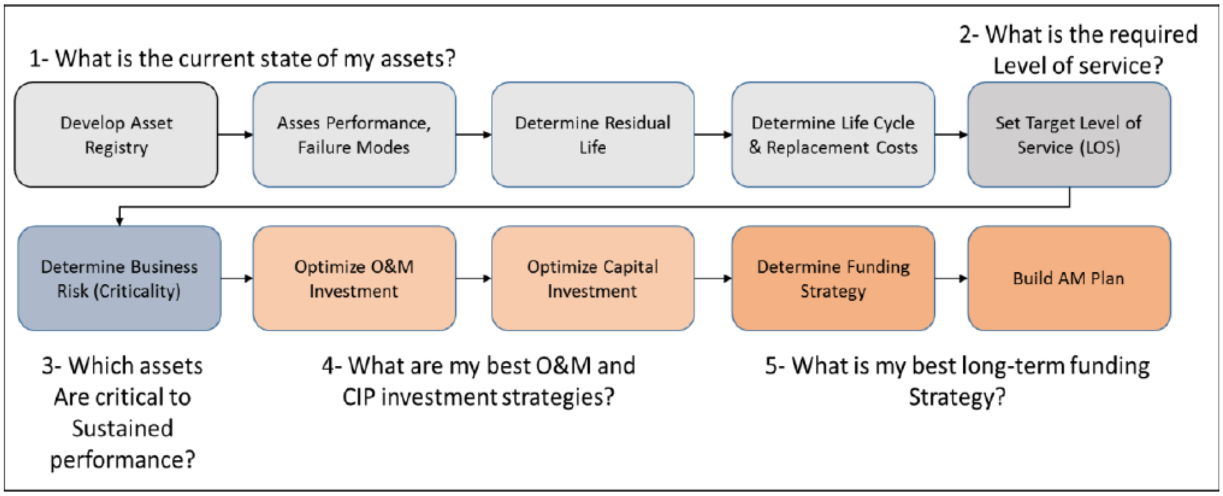

Figure 5. 1 EPA 10-step asset management approach (EPA, 2014)

The steps are briefly described as follows:

1. Development of an Asset Registry: Asset Registry is defined as a database of all assets within an asset group. An asset registry typically aids analysts to investigate the impact of the asset failure of one asset on the others. This brings out the interconnectivity among assets.
2. Asset performance and failure modes: Asset performance involves evaluation and monitoring of the performance of assets and identifying major failure modes. Asset functionality, level of service, availability, sustainability and reliability are common factors considered for evaluation of asset performance.
3. Determination of residual life of the asset: Residual life of the asset is often defined as the time left until failure and is crucial to the management of high-risk assets.
4. Determination of lifecycle and replacement costs: Lifecycle and replacement costs are all costs of owning and operating an asset from planning through its retirement and replacement.
5. Pre-setting target levels of service: Pre-setting target levels of service for each asset requires that equirements impacting the technical, managerial or financial components of the system, are met.
6. Determining criticality: Since assets are not equally important to the system's operation, an organization should identify the assets that are highly critical to its operation. This step specifies those assets that are high cost in detrimental levels of service, and consequences to the level of service at the time of their failure. Organizations should focus investment and attention to the assets within the system that matter the most

.

based on risk calculations. In the literature, many methods are used for evaluating risk exposure associated with the physical failure of assets. In the simplest terms risk is calculated as follows:

$$Risk\ exposure\ =\ Probability\ of\ failure\ \times\ Consequence\ of\ the\ failure$$

7. Optimizing Operations and Maintenance Investment: Criticality and asset management allows the agency to make well-informed decisions regarding the use of its operation and maintenance budget.
8. Optimizing Capital Investment Plan: Capital investment planning involves renewal and augmentation of existing projects. Overall, a good investment plan involves finding the right solutions at the right time for mitigating risks.
9. Funding strategy: Strategizing funding involves managing assets and discovering actions that are most appropriate to manage a system at the desired level of service and low cost.
10. Building an asset management plant – Developing a tactical road map by incorporating all the steps described above, that is amenable to all the stakeholders within the organization.

5.1.2 Recommended practices for determining asset criticality for making informed decisions in a Transit Agency by APTA

This section has been developed by compilation of key concepts of asset criticality from the *Recommended Practices* archives of the American Public Transportation Association.

ISO 55000[1] has deemed an asset to be critical if it has the potential to significantly impact the achievement of an organization's activities. However, without an understanding of what the organization strives to achieve, it can be difficult to prioritize resources for asset upgrades and development. A few examples of decisions supported by asset criticality have been demonstrated in Table 5.1 below.

APTA recommends three methods of asset criticality – based on consequence of failure, risk of failure, and total cost of ownership (APTA, 2021). Although, APTA has laid generic scenarios demonstrating the use of these methods, the use of these methods can be extended to the assessment of criticality of assets to risks from climate change.

Table 5. 1 Example decisions supported by asset criticality (APTA, 2021)

Objective	Given our limited resources…	Resulting asset criticality question	Potential criticality method[2]
Safety	For which assets is it most critical that we focus our efforts on maintaining or improving safety?	Which assets have the highest potential for impacting safety should they fail?	Consequence of failure on safety or risk of failure on safety
Levels of service (LOS)	For which assets is it most critical that we focus our efforts on ensuring that we meet our desired LOS?	Which assets have the highest potential for impacting service should they fail?	Consequence of failure on LOS or risk of failure on LOS
Cost reduction	For which assets is it most critical that we streamline our maintenance practices?	Which assets account for the greatest proportion of maintenance costs?	Maintenance cost
Operational performance	For which assets is it most critical that we define operational contingency plans?	Which assets have a high operational consequence of failure (but a low likelihood)?	Consequence of failure
Life cycle cost reduction	For which assets is it most critical that we focus our life cycle cost reduction efforts?	Which assets account for the greatest proportion of life cycle costs?	Total cost of ownership
Environmental	For which assets is it most critical that we focus our greenhouse gas reduction efforts?	Which assets produce the most carbon dioxide through their life cycle?	CO_2 emissions

The three methods of asset criticality are discussed below.

Method 1: Asset criticality based on consequence of failure

Under criticality assessment of assets potential failure modes of respective assets are identified, along with the impact of the consequences of their failure on a particular object of the organization that the asset achieves (APTA, 2021). The example below demonstrates the criticality of two assets – elevators A and B, which are derived by considering the consequences of each of their failures on three agency objectives: safety, level of service (LOS), and cost reduction. Instead of relying solely on expert judgment, a more sophisticated approach involves utilizing historical data to quantify the consequences of failure. By using consistent units of consequence, preferably expressed in monetary terms, it becomes possible to enhance the comparison of different assets. The example has been illustrated in Table 5.2.

.

Table 5. 2 An assessment of asset criticality of two assets (A and B) based on assessment of failure (APTA, 2021)

A.

Elevator A Sole elevator at a busy station, subject to third-party maintenance contract		**Safety**	**Level of Service**	**Cost Reduction**	**Average Consequence by Failure Mode**
Failure mode	Cable snap, elevator falls	**5** Could result in serious injury or fatality	**4** Will be out of service for a month, with no other elevators at the busy location	**4** Requires expensive repairs and safety checks	4.33
Failure mode	Doors fail	**1** Customers may experience discomfort should they become entrapped, but not a major impact on safety	**2** Will be out of service for a day while third-party maintainers arrive, with no other elevators at the busy location	**2** Requires expensive third-party maintenance call	1.67
Average consequence by objective		**3.00**	**3.00**	**3.00**	**3.00**

B.

Elevator B One of three elevators at a moderately busy station, maintained by agency staff		**Safety**	**Level of Service**	**Cost Reduction**	**Average Consequence by Failure Mode**
Failure mode	Cable snap, elevator falls	**5** Could result in serious injury or fatality	**2** Will be out of service for a month, but other elevators exist at the location	**4** Requires expensive repairs and safety checks	**3.67**
Failure mode	Doors fail	**1** Customers may experience discomfort should they become entrapped, but not a major impact on safety	**1** Will be out of service for an hour, but other elevators exist at the location	**1** Fix can be performed by local maintenance crew	**1.00**
Average consequence by objective		**3.00**	**1.50**	**2.50**	**2.33**

Based on the example illustrated in Table 2, of an agency seeking to prioritize work based on the reduction in impact of failure of the two elevators on safety, there is no difference in ranks between the two elevators. If the agency were seeking to prioritize work to maintain or improve its level of service, the example illustrates that elevator A should be ranked above elevator B when it comes to prioritizing its maintenance or upgrades. In doing so, the agency can increase the inventory of spare parts to reduce the length of time elevator A stays out of service, or even install additional elevators to neutralize the impacts from the failure of elevator A. Similarly, if the agency plans on prioritizing work to reduce its costs, the above analysis suggests that elevator A should be ranked above elevator B. For example, the agency can explore options on moving the maintenance of the elevator in-house to avoid more expensive third-party maintenance contracts.

Method 2: Asset criticality based on risk of failure

Although the consequence of failure is commonly used to determine asset criticality, certain organizations choose a risk-based approach instead. This means that an asset that fails frequently could have a greater overall impact compared to a highly reliable asset that has a more severe consequence when it fails. This approach incorporates the likelihood of each failure mode occurring, along with its consequences, building upon the previous method (APTA, 2021).

In the example below illustrated in Table 5.3, likelihood of failure is determined by asking subject matter experts to use their asset knowledge and judgement in rating each failure mode associated with an asset in a scale of 1-to-5. In such scale, 1 would represent a failure mode which is very unlikely to occur whereas, 5 would represent a failure mode which is very likely to occur. Alternatively, a sophisticated approach might review the historical failure rate for each failure mode to derive a probability for each. Note that the likelihood of each failure mode as judged by subject matter experts can differ depending on their knowledge, expertise, and past experience.

Table 5. 3 An assessment of asset criticality of two assets (A and B) based on risk of failure (APTA, 2021)

A.

Elevator A		Safety	Level of Service	Cost Reduction	Average Consequence by Failure Mode	Likelihood	Average Risk by Failure Mode
Failure mode	Cable snap, elevator falls	5	4	4	4.33	1	4.33
	Doors fail	1	2	2	1.67	2	3.33
Average consequence by objective		3.00	3.00	3.00	3.00	Total average risk score	
Risk by objective		3.50	4.00	4.00	3.83		

B.

Elevator B		Safety	Level of Service	Cost Reduction	Average Consequence by Failure Mode	Likelihood	Average Risk by Failure Mode
Failure mode	Cable snap, elevator falls	5	2	4	3.67	1	3.67
	Doors fail	1	1	1	1.00	5	5.00
Average consequence by objective		3.00	1.50	2.50	2.33	Total average risk score	
Average risk by objective		5.00	3.50	4.50	4.33		

Based on the example illustrated in Table 5.3, if the agency were to prioritize work to reduce safety risks, elevator B would be prioritized over elevator A. Additionally, if the agency were to prioritize risk associated with level of service, elevator A would be ranked above elevator B. If the agency were to prioritize upgrades based on reduction in cost, elevator B would be ranked above elevator A.

Method 3: Asset criticality based on total cost of ownership

In this approach, the organization utilizes past data on capital, maintenance, and risk to calculate the annualized total cost of ownership (TCOO) for each asset. The TCOO includes estimated costs for ongoing renewal (such as replacement or refurbishment), planned preventive maintenance, reactive corrective maintenance, and the cost associated with realized asset risks throughout its lifespan (APTA, 2021).

By determining the TCOO for each asset, the organization can rank them in descending order, with assets having higher TCOO representing a larger portion of the agency's costs. If the organization aims to reduce overall expenses, it can prioritize assets with higher TCOO for cost-cutting initiatives. By focusing on optimizing life cycle management strategies for these assets, there is a greater potential for achieving cost savings, as they contribute significantly to the overall TCOO.

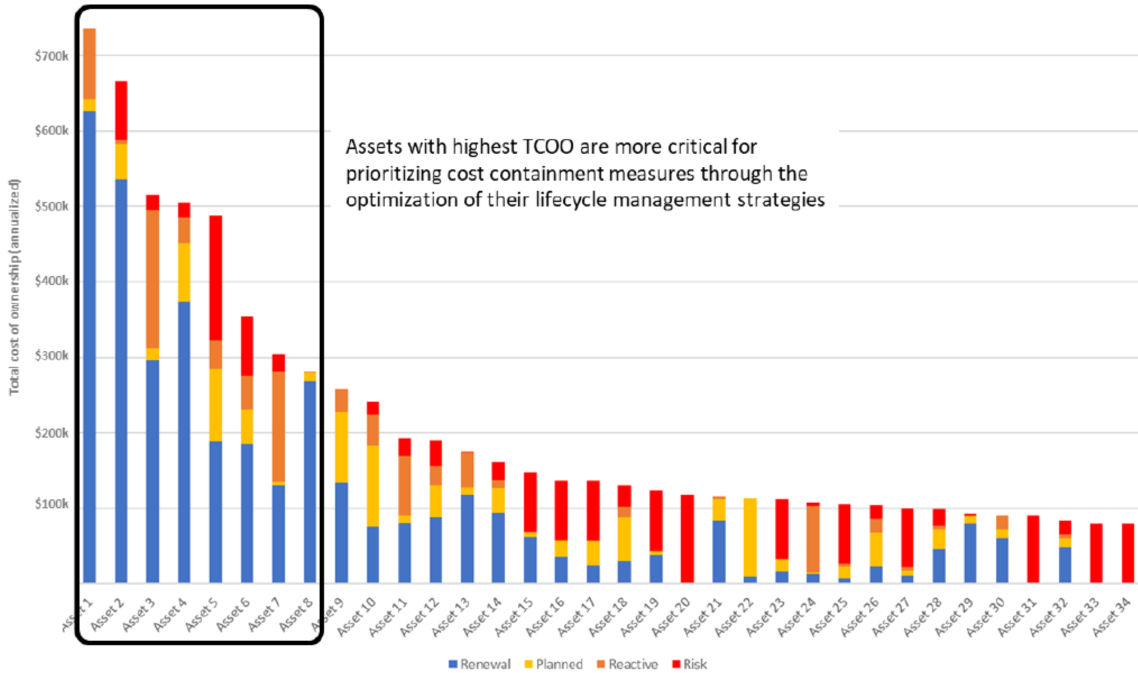

Figure 5. 2 Criticality assessment using total cost of ownership (APTA, 2021)

For instance, in Figure 5.2, assets 1 and 2 show a significant proportion of renewal costs. While this may be suitable for these specific assets, the organization could consider investigating alternative life cycle strategies that can decrease the ongoing renewal costs. This could involve adjusting the frequency of renewals, potentially extending the intervals between renewals. By doing so, the organization has the potential to lower the total cost of ownership (TCOO) for these two assets.

This further suggests that simply accepting the current renewal schedule may not always be the most cost-effective option. It encourages organizations/agencies to critically evaluate and challenge existing practices in order to identify opportunities for optimizing life cycle management strategies and reducing overall costs.

By considering alternative approaches, organizations can potentially achieve significant cost savings. This approach recognizes that focusing on assets with the highest TCOO offers the greatest potential for achieving substantial financial benefits through targeted cost-cutting efforts. It encourages a proactive mindset in managing assets, aiming to maximize cost-efficiency while maintaining operational reliability.

5.1.2.1 US DoT Federal Highway Administration Handbook for Addressing Resilience to Climate Change & Extreme Weather in Transportation Asset Management

The USDoT FHWA developed a handbook designed primarily for transit agencies interested in developing federally required transportation asset management plans. The handbook offers methods, tactics, and illustrations for managing risks linked to severe weather and climate change in asset management. It outlines ways to tackle risks associated with existing and future environmental conditions, natural disasters, rising sea levels, and extreme weather occurrences. Additionally, the handbook presents feasible approaches to incorporate resilience into both immediate and long-term asset management processes, aiding in the optimization of investment choices (U.S. DoT FHWA, 2023). The document builds upon the Vulnerability Assessment and Adaptation Framework, which has been demonstrated in Figure 5.3.

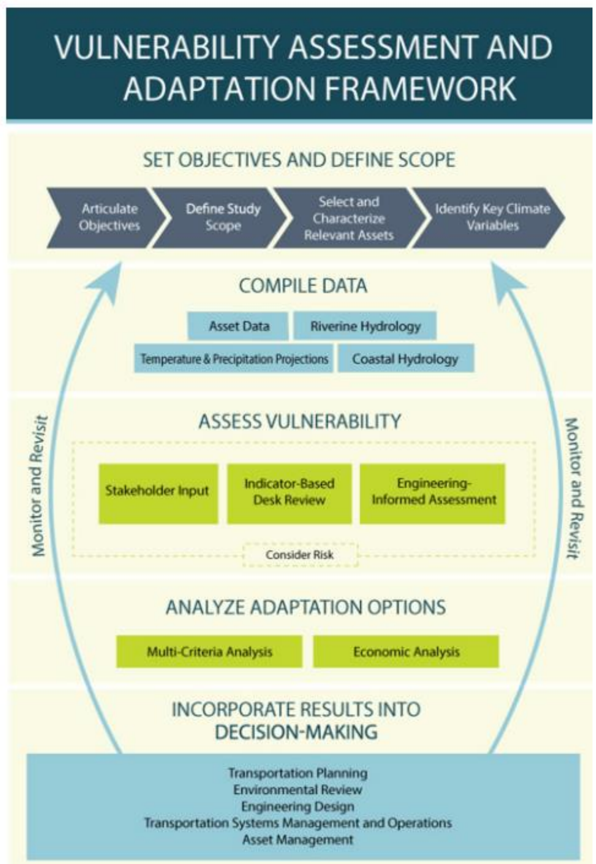

Figure 5. 3 Vulnerability assessment and adaptation framework by FHWA (U.S. DoT FHWA, 2023)

Steps involved in the Asset Management approach include:

- *Developing an asset inventory:* The initial stage in creating an asset management plan usually involves constructing an inventory of assets and gathering relevant information about their condition. This inventory presents a chance to identify sets of assets that are susceptible to extreme weather events and evolving environmental circumstances, primarily due to their geographical location, sensitivity to hazards, and their ability to adapt. By grouping and recognizing these vulnerable assets within the inventory, their specific considerations can be integrated throughout the entire asset management plan. To incorporate vulnerability data into the asset inventory and asset condition information, organizations can utilize the findings from vulnerability assessments to identify vulnerable assets that should be evaluated separately as a group (U.S. DoT FHWA, 2023).

Threats to infrastructure can have long-lasting impacts on costs and strategies throughout their lifespan. Assets that were expected to have predictable service lives may behave differently in the future due to factors like higher temperatures or increased flooding. Weather events can lead to higher costs due to increased demand or reduced service life. By utilizing the asset inventory to identify assets that may perform differently in the future compared to the past, it becomes possible to make informed decisions regarding life-cycle management and investment strategies. Assets that are prone to damage more frequently in the future will incur higher costs as a result of increased repair requirements. Such assets may require more frequent inspection, cleaning, or maintenance to mitigate their vulnerability, and these factors need to be taken into account when developing the financial plan. Transportation agencies can utilize the findings of a vulnerability assessment to classify classes or subgroups of assets based on specific hazards or stressors, such as extreme temperature risks or flood risks. An advantage of categorizing assets into hazard categories is the ability to establish suitable asset management strategies for multiple assets, and in some instances, across different asset classes. This approach allows for the development of cohesive strategies, for example, addressing the needs of timber bridges that are susceptible to flooding, rather than dealing with each asset individually. An example summary table demonstrating the establishment of hazard categories has been presented below in Table 5.4.

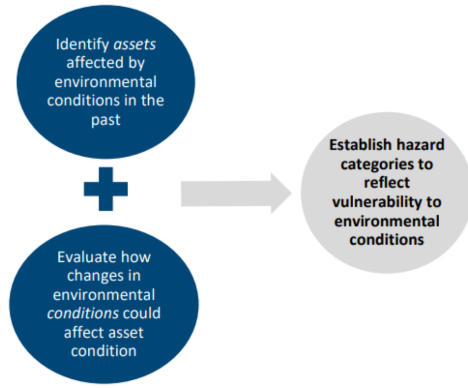

Figure 5. 4 Integrating resilience into asset inventory. (U.S. DoT FHWA, 2023)

- ***Conducting a performance gap assessment***: Secondly, a performance gap analysis assesses whether current and future asset condition and performance will meet the agency's objectives. An agency can examine its current conditions against its targets and review modeled predictions of future asset conditions to assess if these will be acceptable. Conducting the performance gap assessment can be done with the following list of actions:

  What to analyze: Determine if performance gaps are due to environmental conditions by:

1) Consulting experienced staff members to investigate whether low-performing assets have been affected by disruptions or damage caused by severe weather conditions in the past.
2) Utilizing the results of vulnerability assessments to determine if there is a correlation between low-performing assets and high vulnerability scores.
3) Comparing the low-performing assets to the asset/hazard categories established during the asset inventory process. This comparison can help determine if the performance issues are associated with specific environmental conditions.

Table 5. 4 Sample inventory and condition summary for categorizing hazards (U.S. DoT FHWA, 2023)

Asset Class	Asset Sub-Group	Hazard Category	Inventory			Asset Condition		
			Units	Quantity	Lane Miles or Square Meters	% Good	% Fair	% Poor
Pavements	Asphalt	High inland flood vulnerability						
		High sea level rise vulnerability						
	Concrete	High inland flood vulnerability						
		High sea level rise vulnerability						
Bridges	Moveable	High inland flood vulnerability						
	Timber	High sea level rise vulnerability						

- ***Setting resiliency objectives, measures, and targets***: Transportation agencies can enhance their ability to achieve management goals and targets by actively addressing extreme weather events and climate change risks. Defining agency objectives that specifically target these risks is crucial in establishing the strategic direction of the transportation asset management plan and influencing various aspects of the asset management process. For instance, one resilience objective could involve preventing any increase in the extent of roadway vulnerable to sea level rise. Alternatively, the agency may aim to reduce the number of slopes at risk of failure due to fire or flood hazards. Another resilience objective could focus on improving outfalls that are susceptible to being submerged by rising river or sea levels (U.S. DoT FHWA, 2023).
  Resilience measures and targets play a vital role in assessing progress towards increasing resilience and aid in making well-informed investment and management decisions. These measures can be incorporated into existing targets and metrics or developed as independent benchmarks, tracking strategies designed to enhance the system's resilience and mitigate the impact of specific extreme weather risks. If an organization determines that current goals are impractical or unsuitable in light of anticipated environmental circumstances, it should seek input from both internal and external stakeholders to revise the existing objectives and align them more accurately with the evolving challenges posed by natural hazards. For instance, a transportation agency may have objectives related to

system preservation and performance. However, gradual changes in environmental conditions like temperature and flooding can increase deterioration rates. As a result, the agency could modify current objectives to explicitly address future environmental condition considerations (e.g., strategically preserve, repair, or replace assets based on environmental condition projections over the lifespan of the asset).

- ***Establish risk management process***: When transportation agencies incorporate risk management into their asset management practices, they can examine the potential damages caused by extreme weather events and climate change. By doing so, they can develop strategies to effectively manage and invest in their transportation systems. Extreme weather events, which may be intensified by climate change, can have significant cost implications for both transportation agencies and system users. The internationally recognized risk management frameworks generally consist of five steps. The process begins with identifying risks that could impact the condition of assets. In the context of resilience, these risks may include extreme weather events, climate change, and seismic activity. To prioritize locations and identified risks, assessing the likelihood and impact of these risks occurring may involve utilizing existing vulnerability assessments or conducting new ones.

  Risk management is an essential aspect of developing strategies to respond to risks, also known as risk mitigation. It involves assessing both the likelihood and consequences associated with different risks. Certain risks may have low likelihood but high consequences, such as extremely rare 500-year storm events or large-scale earthquakes. On the other hand, some risks are more frequent but have relatively low consequences, like minor flooding occurring annually or occasional minor rockfalls from unstable slopes. By considering the combination of likelihood and consequence, transportation agencies can evaluate and compare diverse risks to prioritize their response efforts. A risk matrix has been illustrated in the Figure 5.5.

  There are numerous ways to identify likelihood and consequences. Workshops involving knowledgeable stakeholders are typically the primary method used to conduct vulnerability assessments, although online tools or virtual platforms may also be utilized to gather and consolidate input from stakeholders. Due to the unique nature of risks associated with evolving environmental conditions, the elements of the vulnerability assessment process can inform the agency's understanding of likelihood and consequence.

.

Liklihood	Values	Risk Scores			
Almost certain	5	5	50	200	350
Probable	4	4	40	160	280
Possible	3	3	30	120	210
Rare	2	2	20	80	140
Exceptionally rare	1	1	10	40	70
		Value/Consequence Relationship			
		1	10	40	70
		Low	Moderate	High	Severe

Figure 5. 5 Risk matrix from AASHTO guide for Enterprise Risk Management (U.S. DoT FHWA, 2023)

The risk management process should take the following into consideration regarding likelihood:

- Timeframe: Transportation agencies have the option to adopt a comprehensive, long-term strategy for asset management throughout the entire lifespan of their assets. In line with life-cycle cost analysis, agencies can select an analysis period that aligns with the service life of the asset, which is typically around 75 years for bridges. While the likelihood of risks is often expressed as an annual probability, such as a 1% annual probability storm event, it is also important to consider the cumulative probability over the relevant timeframe during risk analyses. Over an extended period, assets are more prone to encountering extreme weather events.
- Changing likelihood of events: In numerous areas, future projections indicate that extreme weather events, including heavy rainfall and heatwaves, are expected to occur more frequently and with increased intensity (USGCRP, 2018). For instance, what is currently considered a 10-year precipitation event today may occur more frequently, potentially becoming a 2-year event in the future. Additionally, future 10-year events may bring higher levels of precipitation compared to the current 10-year events, although local conditions may vary.
- Future scenarios: In conducting resilience assessments, various climate change scenarios are utilized, with Representative Concentration Pathways (RCPs) being commonly employed by transportation agencies and other organizations (USGCRP, 2018). It is important to note that no single RCP is considered more probable than others, although lower scenarios may become increasingly unlikely as greenhouse gas concentrations continue to rise. As a result, assigning probabilities becomes

challenging. Instead, for risk assessments, agencies may choose to consider both a higher scenario (e.g., RCP 8.5) and a lower scenario (RCP 4.5) to assess the likelihood and consequences of extreme weather events and climate change. While a higher scenario is suitable for identifying and screening risks, it is essential to test the effectiveness and cost efficiency of risk mitigation measures across a range of possible future scenarios.

Additionally, the risk management process should take into consideration the following regarding consequences:

- High-cost consequence: A high-cost consequence scenario could involve the recurrent flooding of a system interchange, leading to the disruption of travel on multiple heavily trafficked routes. The expenses associated with mitigating this vulnerability, such as elevating the interchange or implementing protective measures, could be substantial. This would amplify the impact in terms of financial costs for the transportation agency and the interruption of service within the transportation network, consequently increasing user costs. Low-lying interchanges or sections of freeways that are susceptible to such issues are considered crucial components of the freeway system. Their long-term enhancement may necessitate extensive planning, encompassing design, financing, and reinforcement efforts that span several years.
- Loss of key routes during emergency events: Loss of vital routes during emergency situations represents another form of consequence. These routes may include key evacuation paths or alternative routes that can be utilized in case major routes or structures become damaged, making them crucial for ensuring resilience. Even temporary disruption of service on these critical facilities can intensify the consequences of severe weather events and other disasters. Therefore, it is essential to identify and prioritize these routes for appropriate measures to enhance their resilience.
- Loss of operational support infrastructure: Critical components such as transportation management centers (TMCs) can be at risk of power outages, flooding, or wind damage during events like hurricanes. These facilities play a crucial role in the performance of the National Highway System (NHS) and, therefore, should be regarded as important assets deserving measures for reinforcement or redundancy to ensure their functionality and resilience.

Finally, all of this can be compiled into a risk register which looks as follows:

.

Risk Statement	L *	C †	Rating	Owner(s)	Mitigation	Timeframe	Status
Higher storm surges will increase the frequency and duration of pavement inundation in our coastal areas, leading to increased pavement deterioration.	5	40	200	Pavement modelers	Track changes in pavement conditions to determine if increased deterioration accompanies increased inundation.	By Dec. 31, 2022	Analysis of deterioration rates under development.
				Design staff	Develop design plans for mitigation including enhanced drainage, selected roadway section elevation.	By July 1, 2025	Roadway sections under analysis for prioritization. Design manual update under way.
Higher storm surges will increase the frequency and duration of pavement inundation in our coastal areas, leading to increased road closures and service interruptions.	5	40	200	Maintenance engineer	Develop quick response plan for each section subject to flooding to establish closures, and post-event cleanup protocols.	By Dec. 31 2020	Each affected garage developing its draft response plan by June 1, 2020.

* Likelihood
† Consequence

- Establish resilient investment strategies and financial plans: An effective approach for investment strategies involves establishing a range of funding programs that are linked to specific objectives or targets. These programs encompass various types of work, such as initial construction, maintenance, preservation, rehabilitation, and reconstruction. This format allows for a systematic allocation of funds towards achieving specific goals and addressing different aspects of infrastructure development and management. Examples of resilience investment strategies can be summarized as follows (in Table 5.5)

.

Table 5. 5 Resilience investment strategies(U.S. DoT FHWA, 2023)

Resilient Investment Strategy	Asset Type	Risk/ Vulnerability Addressed	Example
maintenance budgets	Drainage system	Sea level rise and storm surge	The **Rhode Island DOT** initial TAMP includes specific strategies and line items for stormwater maintenance and improvement. Although the program was started because of an environmental consent decree and not as a weather-risk mitigation, the program will consider sea level rise and storm surge improvements when addressing highway network drainage. The investment strategies allocate $72 million over 10 years for drainage capital improvements and $60.6 million for maintenance. Maintenance includes cleaning, flushing, removing sediment, and other routine maintenance to keep the system functional (RIDOT, 2018).
Develop standalone risk mitigation investment strategy	Bridges	n/a	Although not related to weather, a risk-driven analogous funding program is the **Washington State DOT's** bridge seismic risk program. WSDOT identifies seismic risks separately from bridge-condition needs (WSDOT, 2018a). WSDOT has invested nearly $150 million since 1991 to strengthen its lifeline bridges. Approximately 1,600 retrofits are either completed or nearly so. If structures are not appropriate for retrofit, they are scheduled for replacement (WSDOT, 2015).
Include risk mitigation in rehabilitation budgets	Bridges	n/a	**Oregon DOT** amended its bridge rehabilitation program to incorporate a risk-based approach to seismic resilience. It conducted a study of its seismic vulnerabilities and noted that a majority of its bridges were built between 1950 and 1980 before many seismic standards were in place (Nako, Shike, Six, Johnson, & Dusicka, 2009). Of the 2,550 structures examined, 1,670 were found to have insufficient capacity to resist earthquake loadings. The high cost of retrofitting so many structures was beyond the agency's budget, so it pursued less costly options. The agency applied a portion of the existing bridge budget to retrofit some of the longer sections of highway to ensure mobility for greater areas if an earthquake did occur. The agency also established a design policy to include at least a Phase I seismic retrofit to vulnerable bridges that are scheduled for rehabilitation, which involves preventing the superstructure from separating from the substructure. Including the Phase I elements with bridge rehabilitation projects has been cost effective by reducing design and mobilization costs.

.

5.1.3 PIEVC Protocol

The Public Infrastructure Engineering Vulnerability Committee (PIEVC) was established by Engineers Canada in 2005 with the purpose of overseeing the development and implementation of a Protocol for evaluating the risks associated with climate change on physical infrastructure in Canada (Sandink & Lapp, 2021). The PIEVC Protocol has been utilized in more than 100 assessments, ranging from individual infrastructure projects to larger systems and portfolios. This Protocol outlines a systematic approach for assessing risks and offers the option of conducting engineering analysis to understand the impact of climate change on infrastructure. The insights, findings, and recommendations resulting from the application of the PIEVC Protocol provide a framework to facilitate effective decision-making processes (Sandink & Lapp, 2021). PIEVC finds its application in climate risk and resiliency assessment to support asset planning and management, asset portfolio assessment and evaluation, building of conceptual designs, and compliance to ISO 31000 and ISO 14090.

The PIEVC Engineering Protocol for Infrastructure Vulnerability Assessment and Adaptation to a Changing Climate can be divided into three sections:

1. Principles and Guidelines

- Description of the processes and organization for planning climate change risk assessments
- Applicable principles of risk management
- Principles of triple bottom line analysis
- Procedural description of the eight steps that comprise the full scope of the methodology

2. Risk Assessment Module

- Detailed procedures for executing an infrastructure climate risk assessment
- Worksheets for each step of the process

3. Triple Bottom Line Module

- Detailed for executing a triple bottom line analysis
- Worksheets covering each step of the process

The Protocol developed by the PIEVC is a qualitative method for identifying and assessing climate risks and vulnerabilities in infrastructure. It is based on the CAN/CSA Standard Q850-97 (R2009) Risk Management: Guideline for Decision-Makers. Unlike quantitative risk tools, the Protocol does not require extensive data and provides risk scores that can be categorized as high, medium, or low. This approach offers a broad understanding of climate risks, which is often sufficient for decision-making related to adaptation and resilience, particularly for smaller infrastructures and communities. It can also inform more detailed quantitative risk assessments by identifying key issues that require deeper analysis before actions and budget allocations can be determined.

The Protocol defines "infrastructure" as a combination of structural and non-structural components. Structural components include physical subsystems such as foundations, building envelopes, and mechanical systems. Non-structural components encompass personnel, policies, procedures, codes, standards, and local regulations. Additionally, the Protocol recognizes the role of infrastructure users and external service providers. Understanding the interactions between climate and these components is crucial during the analysis.

Another important aspect of the Protocol is determining the appropriate level of component definition. Defining more components increases the scope of effort required to assess climate-component interactions and associated risks. Generally, components are defined at a system or sub-system level as further granularity does not provide significant additional insight for the effort expended (Sandink & Lapp, 2021).

The scope of the risk and vulnerability assessment can be tailored by limiting the breadth and depth of component definition. This affects the information required and the stakeholders involved. While involving all relevant stakeholders is ideal, it may not always be practical or in the best interest of the infrastructure owner. Nevertheless, it is important to document any components or stakeholders that were not considered or did not participate and include these limitations in the final assessment report. Figure 5.3 provides an overview of the PIEVC Protocol Process.

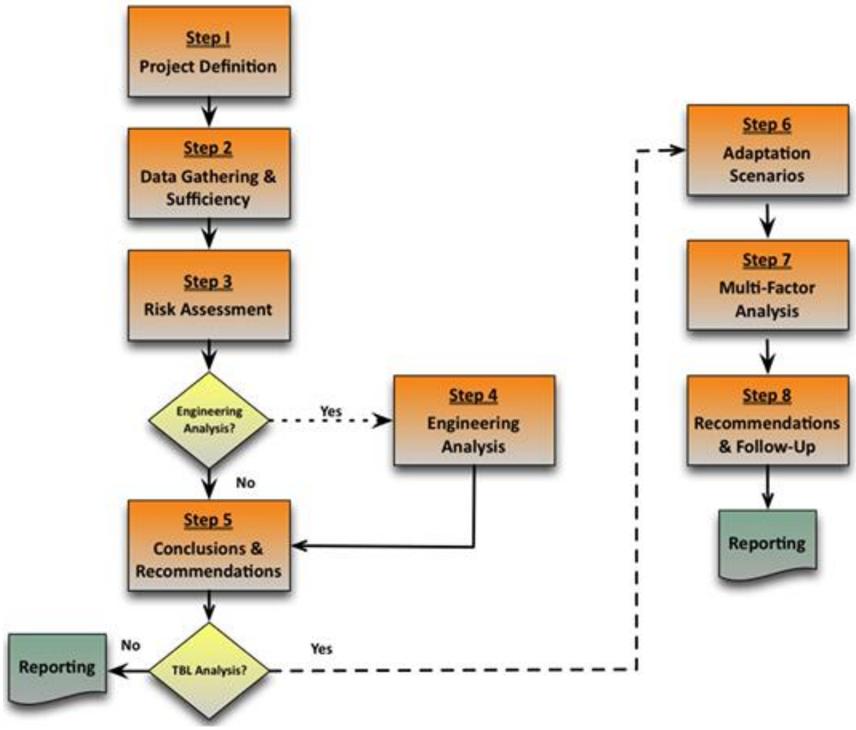

Figure 5. 4 Overview of the PIEVC Protocol (Sandink & Lapp, 2021)

5.1.3.1 A case study on application of the PIEVC protocol: Climate risk and resiliency assessment of Calgary Transit Fleet Electrification Planning Study

To illustrate the application of the PIEVC protocol, a case study demonstrating its use in risk and resiliency assessment of Calgary Transit Fleet Electrification Planning has been discussed in this section. The assessment had the following objectives:

- Identify, evaluate, mitigate, and manage risks associated with climate change throughout the project's design and operation phases. The assessment specifically focuses on assessing the potential impacts of climate change on built infrastructure, charging infrastructure, fleet assets, the environment, and people. The aim is to enhance resilience to climate change and minimize physical risks by developing adaptation options for the most significant risks (CITY OF CALGARY, 2022).
- Assess whether the assessment aligns with the approval criteria specified in the City's Capital Infrastructure Assessment requirements. The Project itself is undertaken in accordance with the City's Climate Resilience Strategy (City of Calgary, 2020) and its broader goals for climate action, which aim to create more efficient, productive, and accessible cities.

- Evaluate whether the assessment provides support for the City's application to Infrastructure Canada's Zero Emission Transit Fund (ZETF). The assessment was conducted following the City's Public Infrastructure Climate Risk and Resilience Assessment (CRRA) framework and risk assessment sheet (City of Calgary, 2020), which provide guidance on climate resilience. Additionally, the assessment aligns with the GHG+ PLUS Guidance Modules (INFC, 2021) provided by the ZETF, ensuring compliance with their guidelines for greenhouse gas reduction and related considerations.

Methods:

The methodology involved in the CRRA can be summarized by Figure 5.4. It can be described as follows:

Risk analysis: The risk analysis involved identifying and categorizing the various components of the project, as well as determining the relevant climate hazards associated with it. This analysis also considered the key impacts that occur due to the interaction between these climate hazards and project components. The assessment considered the impacts on built infrastructure, natural systems, and human systems, and describes them based on the identified climate hazards and their exposure.

Risk Evaluation: The risk evaluation involves assessing the likelihood of a climate impact occurring and the consequences associated with that impact. Likelihood is determined by evaluating the probability of a climate indicator exceeding a specified threshold, which aligns with the scores provided in the CRRA guidance (COC, 2021). Consequence is evaluated by considering factors such as health and safety, structural integrity, functionality, and environmental and financial impacts. In cases where adaptive capacity exists, the consequence scores may be reduced. The risk evaluation utilizes the City's risk classification matrix (COC, 2021) to assess the risk scores. It should be noted that the City's risk classification matrix was employed in this assessment, as it adopts a more conservative approach compared to the guidance provided by the ZETF.

Mitigation: Resilience measures were proposed for all risks with a medium or higher score, in accordance with the COC guidance (COC, 2021). Risks with very low and low impact scores were excluded from this step, as per the COC guidance. These resilience measures encompassed strategies that could be integrated into the design, construction, operation, and maintenance of the assets.

The residual risk was described qualitatively at a system category level, indicating the remaining risk after implementing the proposed resilience measures. The residual risk was not quantitatively calculated and depended on the extent and implementation of the resilience measures.

A high-level estimation of return-on-investment (ROI) was provided to indicate the potential benefits that the resilience measures could have on the project and help prioritize implementation options. Considering the planning stage of the project, the ROI estimation provided an approximate assessment using cost estimate ranges.

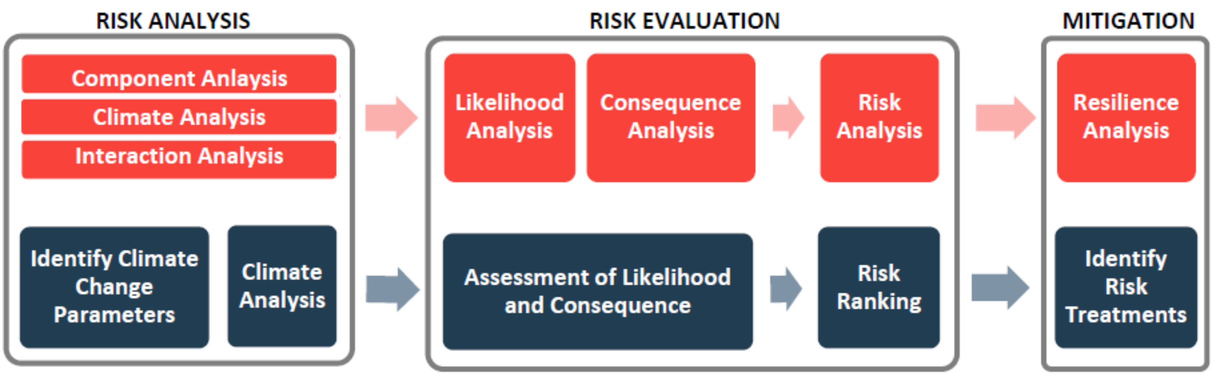

Figure 5. 5 Climate risk and resiliency assessment methodology (CITY OF CALGARY, 2022)

Steps involved in the assessment and their linkage to PIEVC protocol:

Project description: Project description involves the categorization of the assets and their classification into different infrastructure classes. Infrastructure classes such as built infrastructure, electrical charging infrastructure, and fleet infrastructure were used to categorize the assets. An example of asset class and its description for a built infrastructure class can be as follows (in Figure 5.6):

ASSET CLASS	DESCRIPTION
Structural	The structural system includes the roof superstructure, building superstructure, and foundation (substructure). — Includes existing steel frame superstructure, steel decking on open web steel joists, wide-flanged girder system, and hollow structural section (HSS) columns for all garages. Concrete foundations vary between locations and include piles, slab on grade, grade beams, and spread footings. — Proposed retrofits will require structural upgrades to accommodate increased dead load on the superstructure and related live loads. Micro piles have been included for consideration in structural upgrades.
Building Envelope	The building envelope systems include exterior walls, windows, skylights, exterior doors, roof membrane, and roof drainage. — The two existing garages have masonry block walls. Proposed new construction will include in-filled wind bearing steel studs and/or masonry block walls. Fenestration typically consists of glazing units with aluminum frames and exterior doors are commercial grade metal doors. Limited information is available regarding existing roof drainage and membranes.

Figure 5. 6 An example of asset class and description utilized for the assessment. (CITY OF CALGARY, 2022)

Assessment time scale: Three time horizons were considered for the assessment. These time horizons included a baseline period (1981-2010), the 2050s (2041-2070), and the 2080s (2071-2100). The baseline period refers to using historical climate data to identify climate conditions from the recent past. It serves as a reference point for comparison with future climate projections. For assets with a design life of approximately 30 years, such as mechanical, electrical, and communications systems, as well as some building envelope components, climate projections and associated risks for the 2050s are considered important. On the other hand, for assets with a longer design life of around 60 years or more, such as structural systems, site services, and certain civil infrastructure components, climate projections and associated risks for the 2080s are significant. The design life of new buildings is assumed to be 75 years, as outlined in the CSA S478: Guideline on Durability of Buildings.

Risk analysis: Risk analysis as illustrated in Table 5.6 involved a component analysis, climate analysis and the interaction between them. An example of a component can be Roof, Building and Foundation within the structural asset class in the built infrastructure category. Climate analysis includes climate hazards and their trends in the region. For instance, Extreme heat has an increasing trend and as a consequence, components within the asset classes should be resilient to extreme heat. Interaction analysis evaluates the impact of a climate hazard on a component. It can be illustrated by the Table 5.6 below.

Table 5. 6 Interaction analysis between asset components and climate hazard (CITY OF CALGARY, 2022)

ASSET CLASS	EXTREME HEAT	HIGHER AVERAGE TEMPERATURES	WILDFIRE	DROUGHT	SDHI RAINFALL	SEVERE STORMS	HIGH WINDS	HEAVY SNOWFALL
Structural	N	Y	N	N	Y	Y	Y	Y
Building Envelope	Y	Y	N	N	Y	Y	Y	Y
Mechanical	Y	Y	Y	N	Y	Y	Y	Y
Electrical	Y	Y	N	N	Y	Y	Y	Y
Civil Services & Utilities	N	Y	N	N	Y	N	N	Y
Hardscaping	Y	Y	N	N	Y	N	Y	Y
Charging Cabinet	Y	Y	N	N	Y	Y	Y	Y
Dispenser	N	Y	N	N	N	N	N	N
Battery Electric Bus	Y	N	N	N	N	Y	N	Y
Battery	Y	Y	N	N	N	Y	Y	Y
HVAC	N	N	Y	N	N	N	N	Y
Natural Infrastructure	Y	N	N	Y	Y	Y	Y	Y
Construction Personnel	Y	N	Y	Y	Y	Y	Y	N
Operations Personnel	Y	N	Y	Y	Y	Y	Y	Y
Users	Y	N	Y	Y	Y	Y	Y	Y

Risk Assessment: Risk assessment involves the assessment of risk based on likelihood and consequence. Likelihood, in this context, pertains to the probability of projected values for a specific climate indicator surpassing a predetermined threshold. Consequence, on the other hand, was assessed using a rating scale and expert judgment.

For the COC's risk assessment of assets, likelihood represented the probability of a projected climate variable exceeding a chosen threshold in a given time horizon. The likelihood for the assessment was adopted from a guidance document laid out by CRRA for the COC. The evaluation of impacts involved scoring them in five consequence categories. Three of these categories, namely health and safety, structural integrity, and functionality, were defined according to the COC CRRA guidance. Additionally, environmental, and financial (cost) categories were included to encompass considerations that are crucial in selecting adaptation options and indicating the severity of impacts on systems beyond the specific assessed asset component.

Each category was rated on a scale of 1 to 5 to determine the consequence score. In cases where the component or system already had resilience measures in place or could be easily modified to enhance resilience against a particular impact, it was considered to have adaptive capacity. As a result, the overall impact score was reduced by up to 1 point on the consequence scale, depending on the extent of adaptive capacity. This step adjusted the risk scores slightly to identify the most critical impacts based on the current condition of the component. The final consequence score, including adaptive capacity, was carried forward to the risk evaluation. Unfortunately, during the course of this study, access to the risk evaluation matrix could not be gained. However, an example for illustration the process has been demonstrated by Figure 5.7. Consequently, risk profiles have been presented in this document as per the publicly available report.

Likelihood

Score	Probability	
	Method A	Method B
0	Negligible Not applicable	< 0.1 % < 1 in 1,000
1	Highly unlikely Improbable	1 % 1 in 100
2	Remotely possible	5 % 1 in 20
3	Possible Occasional	10 % 1 in 10
4	Somewhat likely Normal	20 % 1 in 5
5	Likely Frequent	40 % 1 in 2.5
6	Probable Very frequent	70 % 1 in 1.4
7	Highly probable	> 99 %

Consequence

Score	Severity of consequences and effects	
	Method D	Method E
0	No effect	Negligible Not applicable
1	Measurable	Very Low Some measurable change
2	Minor	Low Slight loss of serviceability
3	Moderate	Moderate loss of serviceability
4	Major	Major loss of serviceability Some loss of capacity
5	Serious	Loss of capacity Some loss of function
6	Hazardous	Major Loss of function
7	Catastrophic	Extreme Loss of asset

Risk matrix

Infrastructure components	Drought		Extreme high rainfall in 24 hr period		High rainfall in 24 hr period		Sustained rainfall		Antecedent rain followed by significant rain event		Freeze-thaw cycling		Freeze / thaw 2		Spring thaw		Rain on snow		Rapid snow melt		Snow frequency	
Baseline / Future	B	F	B	F	B	F	B	F	B	F	B	F	B	F	B	F	B	F	B	F	B	F
Road features																						
Road prism	6	6	12	15	4	6	6	9	5	5	21	21	24	36	42	42	20	25	10	10	3	2
Cut fill and slope	4	4	12	15	4	6	6	9	5	5	14	14	8	12	7	7	20	25	10	10	3	2
Ditches	0	0	16	20	6	9	6	9	5	5	35	35	12	18	7	7	24	30	12	12	3	2
Cross drains	2	2	16	20	4	6	6	9	5	5	35	35	20	30	7	7	24	30	12	12	3	2

Figure 5. 7 Calculation of risk scores from likelihood and consequence scales

Table 5. 7 Risk profile for assets belonging to the built infrastructure class (CITY OF CALGARY, 2022)

RISK SCORE	NUMBER OF IMPACTS PRESENT	NUMBER OF IMPACTS 2050	NUMBER OF IMPACTS 2080
Very Low	4	4	4
Low	72	39	38
Medium	14	12	10
High	12	47	48
Extreme	0	0	2

The risks to built-infrastructure that were rated medium and higher relate to extreme heat, higher average temperatures, SDHI rainfall, wildfire and lightning. Similar, risk profiles were developed for fleet and charging infrastructure.

Recommendations: Recommendations for adaptation options were provided for risks categorized as medium, high, and extreme. When risk scores varied among time horizons, the highest score was used. These adaptation options were presented by system category and linked to relevant climate hazards. The recommendations were categorized based on the phase of the project lifecycle: (1) planning, design, and retrofit; (2) construction; and (3) operation and maintenance. Recommendations pertaining to the end-of-life of assets were generally addressed during the planning, design, and retrofit stage.

At a high level, the resilience recommendations included increasing the frequency and detail of monitoring and inspection, enhancing maintenance frequency, reviewing, and updating existing designs and operating plans, incorporating climate changes into future designs, reducing power and water consumption in specific operations, and implementing passive cooling solutions.

The implementation of resilience measures was expected to reduce the risk associated with climate hazards by mitigating the consequences if climate trends exceeded predefined thresholds. For example, updating pavement designs to withstand higher temperatures would decrease the consequence of exceeding a specific threshold for the number of hot days (assuming the threshold remained the same). The resulting risk, referred to as residual risk, described the remaining risk to an asset system or component after implementing adaptation measures. The level of residual risk depended on the effectiveness of the implemented resilience measures.

5.2 Multi-criteria decision making for climate adaptation in public transit systems

Multi-Criteria Analysis (MCA) is employed to dissect intricate decisions involving multiple viewpoints, utilizing both quantitative and qualitative systematic evaluation techniques for prioritization. MCA can amalgamate both monetary and non-monetary criteria, rendering it a highly appealing methodology for addressing environmental concerns. Nevertheless, MCA is not merely a technical procedure; it necessitates the participation of relevant stakeholders. Therefore, the accomplishment of successful MCA implementation hinges significantly on the adept design of social processes that structure and oversee the analysis.

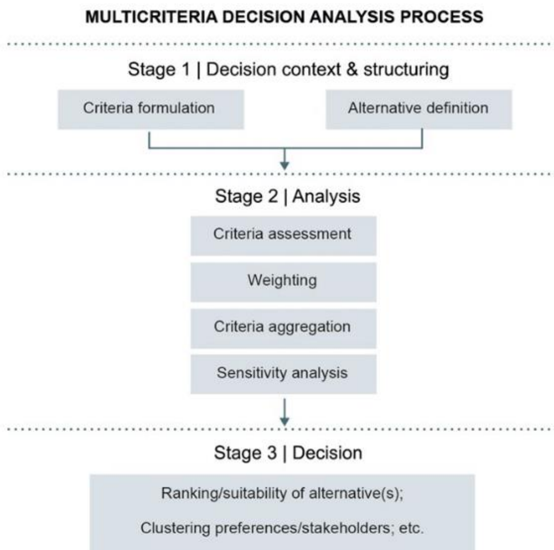

Figure 5. 8 Framework of Multicriteria decision analysis process (Maddalen Mendizabal et al., 2018)

The purpose of MCA is to act as a supportive tool for decision-making, though it does not directly make the decision itself. As a collection of techniques, MCA offers various means of breaking down complex problems, measuring how well options fulfill objectives, assigning weights to objectives, and reassembling these elements to present a cohesive overall view to decision-makers. This process entails establishing a framework for incorporating different decision criteria into a quantitative analysis, without assigning monetary values to all factors.

Through the use of weighting, an overall score for each adaptation option can be derived. The primary outcome of employing MCA is the ranking of options (in this context, for adapting to climate change), along with an understanding of the merits and drawbacks of each option's attributes (Maddalen Mendizabal et al., 2018). Typically, MCA techniques can be employed to determine the single most preferred option, to create a short-list of a limited number of options for more detailed assessment, or simply to differentiate acceptable choices from unacceptable ones. The framework of MCAs has been presented in Figure 5.8.

Different types of MCA exist but the Analytical Hierarchy Process (AHP), which is one of the most commonly used MCA methods will be discussed here due to its extensive use in the climate change sector. The Analytical Hierarchy Process (AHP) relies on a Linear Additive model, employing pairwise comparisons among criteria and options. These comparisons involve assessing the relative importance of criteria and options. For example, this process entails evaluating how the significance of Criterion A compares to that of Criterion B. Once the criteria have been defined, the next step in the process involves deriving weights. For every pair of criteria, stakeholders are required to participate in a pairwise comparison, indicating the relative significance of the two criteria using a scale. The outcomes of these comparisons are initially organized into a matrix, and subsequently, the weights are computed by calculating the geometric mean for each row, along with the total geometric means and normalized weights. Although the method may appear complex, there are computer-based tools available that simplify the process, making it more approachable and manageable. The mathematics underlying the method has been described elsewhere [Provide reference].

5.2.1 Multi-criteria decision analysis to optimize the siting of electric vehicle charging points – A case study of Winchester district, UK

In 2008, the United Kingdom became the first country and major economy to enact a Climate Change Act. This legislation committed the government to reducing emissions by 80% from 1990 levels by the year 2050. Furthermore, this target was augmented in 2019 to net-zero carbon emissions by the same date. At the national level, the majority of local authorities in the UK, approximately 74%, have formally declared a climate emergency. Many of these authorities have even established specific and measurable targets, aiming to achieve net-zero emissions for their cities or districts by certain designated dates. Winchester City Council (WCC) is among the cities that have taken this action (Mahdy et al., 2022). The District of Winchester declared a Climate Emergency in June 2019 and has since made a firm commitment to achieving carbon neutrality for the council itself by 2024 and for the entire district by 2030. The WCC directed its focus towards the mapping of optimum charging point infrastructure for electric vehicle (EV) rollout.

Regarding the mapping of optimum charging point infrastructure, there is a lack of information that exists on using a well outlined methodology to locate EV charging stations for both personal and public transportation (Mahdy et al., 2022). The analytical hierarchy process (AHP) coupled with spatial assessments using GIS was utilized for spatial siting optimization. In the process, the mapped area of study was divided into equal size grids where each pixel within a grid is referred to as a cell/alternative. Each cell contained location specific data, such as road infrastructure, geography and demographics. The methodology involved two stages – Boolean Mask and Factors Aggregation for calculating the weighted linear combination (WLC) aggregation. An example illustrating the methodology has been presented in Figure 5.9. The examples presents a map consisting of nine cells representing nine alternatives. The nine cells had a total of five criteria, which were divided into three constraints (c_1, c_2, c_3) and two suitability factors (x_1,x_2). For constraints, a boolean value of either 0 indicating constrained or 1 indicating non-constrained were assigned to the cells. These were multiplied to create the Boolean Mask Layer. The Factors

Aggregation calculation aggregated the suitability factors scores of each cell with a factor weight. The two masks were then multiplied to obtain the WLC. A score scale was developed to denote the relative suitability of locations within the map.

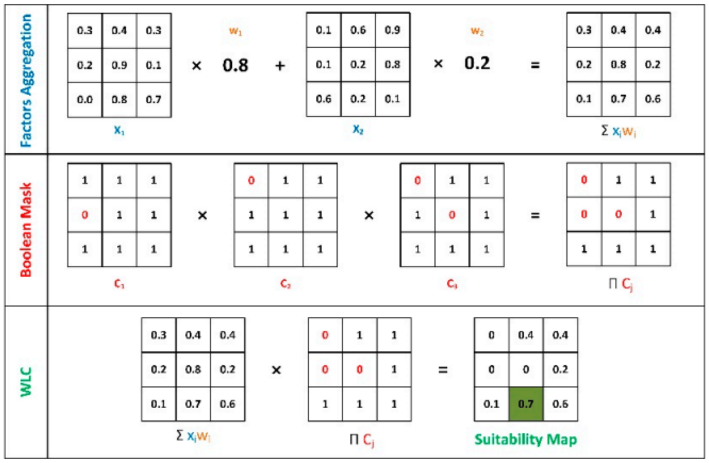

Figure 5. 9 Estimation of WLC

Constraints for such studies could be type of the road, access of the road, on-road parking, EV charging point, car parks. Constraints were non-negotiable criteria being used for the study. A summary of the constraints in the Winchester study have been summarized in the Table 5.8.

Table 5. 8 Constraints criteria (Mahdy et al., 2022)

Constraint	Description
1. Road type.	All roads with a speed limit greater than 30 mph, including motorways, dual carriageways and A-roads, were excluded for safety reasons and to comply with rule 249 of the Highway Code, where a vehicle must display parking lights when parked overnight on a road with a speed limit greater than 30 mph [24].
2. Road access.	All roads mapped as having Restricted Local Access, such as the road that provides alternate/secondary access to property or land not intended for through traffic, were excluded from the analysis in order to ensure equal access to all.
3. On-road parking.	Roads typically with limited or no on-road parking availability (B-roads, minor roads and secondary-access roads) were also excluded.
4. Road slope.	Roads with a slope of greater than 7% were excluded to (a) prevent potential breakdown hazards and (b) reduce electricity consumption from driving on the said slope [14].
5. EV charging points.	A buffer zone for current and future EV charging points or stations within the District was created to exclude nearby roads (within a 0.5-mile radius). It must be noted that all current and future EV charging points were located within or next to a car park; therefore, this criterion was merged with criterion 6.

Now, to illustrate the applicability of a constraint in this study, the road slope exclusion criterion has been discussed. The road slope exclusion criterion excluded roads with a slope > 7% as these roads can result in likely breakdowns and require higher consumption of energy. Through GIS data available on a public website, the road segments > 7% were identified as presented in Figure 5.10.

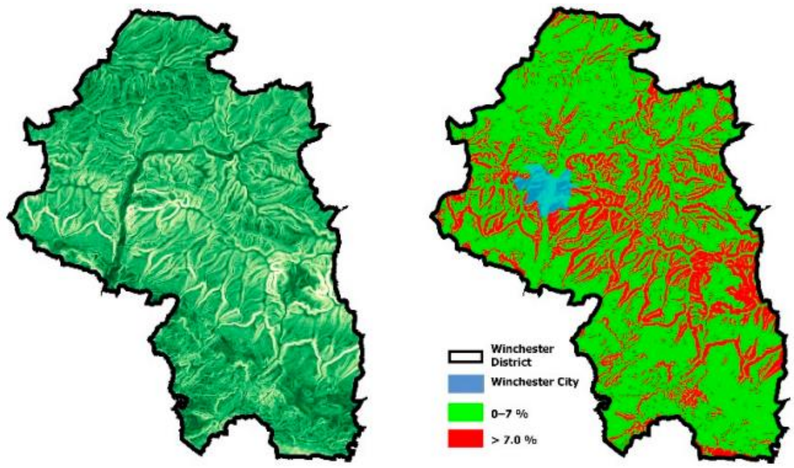

Figure 5. 10 Topographical map of Winchester district (left) green lines indicated the roads with a slope < 7% while red lines indicated roads with slope > 7% (right). (Mahdy et al., 2022)

Similar to the road slope criterion, other criteria such as road type, parking availability, walking distance, etc. were decided based on judgement from other stakeholders and through publicly available GIS data, several sites within WCC were include/excluded.

In the AHP, suitability criteria were used to find the most suitable locations for EV charging points within the district. A list of suitability criteria has been presented in Table 5.9.

Table 5. 9 Suitability factor criteria (Mahdy et al., 2022)

Suitability Factor	Description
1. Petrol stations	Roads with greater proximity to petrol stations are considered more suitable for EV charging points, in particular for hybrid EV drivers.
2. Population distribution	Roads in densely populated areas will be considered more suitable as each charge point will cater for a greater number of people.
3. Low-voltage electrical network	Provision of EV charge points will add additional electrical load to the local network; therefore, sites should be considered in terms of the relative resilience of the low-voltage electrical network.
4. Off-road parking	Houses with off-road parking facilities on own property are more likely to be able to install and operate a personal EV charging point.
5. EV ownership	Areas with relatively high levels of EV ownership are considered more suitable as they are likely to have higher usage.

In the current study, only two suitable criteria were used for the evaluating the most suitable locations for EV charging points within the district. These criteria were the proximity of a location to fuel stations, and population distribution within the district. The analysis was augmented by considering the other suitability factors mentioned in Table 5.9. Visual Google Earth imagery was used to validate road segments that fit the criteria of low-voltage electrical network and off-road parking. Until 2022, in Winchester, the ownership of EVs was low but the ownership is expected to increase as the price gap between EVs and internal combustion engines is quickly shrinking due to upcoming government sanctions on the sale of new petrol and diesel cars by 2030. Now, with only two suitability factors being used for the current study, both the factors were given equal weighting in developing the factors aggregation matrix for the locations. Figure 5.11 shows the final suitability map development of locations in Winchester on the basis of factor aggregation. A scale of 0-0.4 was used to denote low suitability, whereas a score of 0.4-1.0 was used to denote high suitability of a geographical location as shown in Figure 5.11.

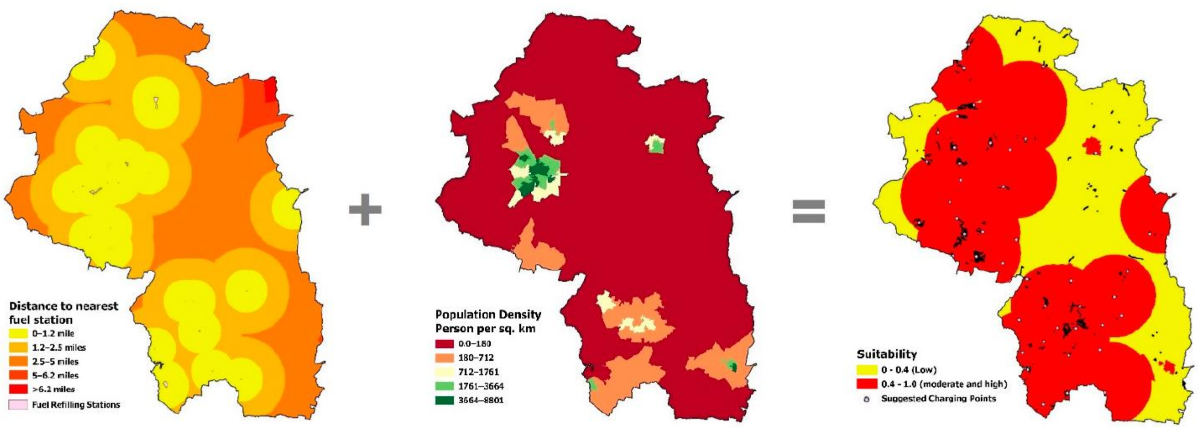

Figure 5. 11. Map demonstrating the evaluation of geographical locations based on suitability factors. (Mahdy et al., 2022)

Finally, combining both the suitability factors and constraints criteria, a map was obtained which has been presented in Figure 5.12

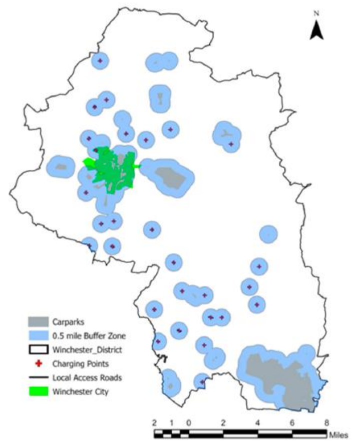

Figure 5. 12 Map containing final locations (Mahdy et al., 2022)

The global electric vehicle (EV) market is experiencing significant growth, creating a need for a robust method to determine the best locations for charging infrastructure, especially within urban areas. This study focuses on creating such a method by combining the multi-criteria Analytical Hierarchy Process (AHP) with Geographic Information Systems (GIS) technology. The goal is to strategically place EV charging stations for practical use. The chosen case study examines one of the UK's rapidly adopting EV cities, Winchester. Unlike the UK's average annual growth rate of 31.3% and Hampshire County's 37.9%, Winchester sees a remarkable 76.3% growth in registered plug-in cars. The AHP assessment for identifying suitable EV charging station sites incorporates criteria set by the Winchester City Council, using both constraints and suitability factors from their provided data. The methodology that was tested considered important criteria such as the type of road, access to roads, availability of on-road parking, road incline, proximity to existing fuel stations, current and planned charging locations, proximity to car parks, and distribution of population. As mentioned earlier, the main goal of this research was to provide the local government with the necessary information about EV charging infrastructure needs. This was achieved by developing a reliable and suitable methodology that could offer the required evidence.

To meet this goal, a multi-criteria decision approach was employed, utilizing the Analytical Hierarchy Process (AHP). This method was integrated with Geographic Information Systems (GIS) to evaluate potential sites. The methodology was specifically designed to analyze both the spatial layout and the demographic characteristics of the Winchester District. The ultimate aim was to strategically determine the optimal placement of charging points that cater to the identified demographic patterns.

5.3 Current approaches at TransLink

In discussion with the Resiliency Working Group at TransLink it was known that TransLink currently utilizes the PIEVC protocol, and the Vulnerability Assessment framework laid down by FHWA. These are robust and widely applied tools for risk and resiliency assessment in transportation infrastructure. The PIEVC protocol, provides TransLink the opportunity to conduct preliminary screening assessments for their upcoming infrastructure. These screening assessments are fruitful in narrowing down adaptation options and guidelines associated with them. The combination of such assessments with geographical data can provide additional opportunities to TransLink to make critical decisions with regard to their upcoming infrastructure. Scenario-based analysis, identifying optimal locations for upcoming infrastructure, and selection of appropriate adaptation options have been performed by supplementing risk and resiliency assessments with multi-criteria-decision-making methods. Potential of multi-criteria-decision-making methods at TransLink needs to be explored at TransLink.

Chapter 6. Conclusion

For organizations to thrive, succeed, and effectively provide public services, they must be capable of adjusting to evolving conditions and emerging demands. Climate change represents one of these pressing demands. This three-month project shed light on resiliency measures in public transportation from a professional practice perspective, asset management perspective, and from a decision-making perspective. A holistic approach that combines the three perspectives forms the hallmark of best practice for climate resiliency within an organization. TransLink currently has the opportunity to learn from major organizations and large infrastructure owners who have both successfully incorporated such perspectives to develop an organization-wide climate resiliency framework. Furthermore, novel methodologies for aiding climate-related assessments and decisions are abundant in academic literature. This report compiles some of the methodologies and approaches that can potentially benefit TransLink in developing climate resilient solutions by looking at climate change problems from the following perspectives.

- From a professional practice perspective
    - Inculcating the application of a climate adaptation lens to all infrastructure projects by professionals within the organization.
    - Engaging in periodical seminars, sessions, and group discussions that can facilitate knowledge-sharing, development, and awareness about climate change within employees in the organization.
    - Facilitating discussions among professionals from various spheres within the organization on lessons learnt from attending events and conferences conducted by professional associations such as EGBC, CIP, CSLA, etc.
- From an asset management perspective
    - Investigating the potential of endogenous asset management approaches for assessing asset criticality with the information currently available within the organization
    - Conducting preliminary screening approaches from known interactions between asset components and climate hazards
- From a decision-making perspective

- Using multi-criteria decision-making tools in conjunction with existing GIS-based approaches can be an effective for deciding upon optimum siting locations for upcoming infrastructure.
- Incorporating multi-criteria decision support systems in scenario-based analysis for selection of climate adaptation options

.

References

Amtrak. (2022). *2022 Amtrak Climate Resilience Strategic Plan*.

APTA. (2021). *Using Asset Criticality to Make More Informed Decisions in a Transit Agency* .

B.C. Ministry of Transportation and Infrastructure, Nodelcorp Consulting Inc., & Pacific Climate Impacts Consortium. (2014). *Considerations for Addressing Climate Change Adaptation for Transportation Infrastructure in Highway Management, Design, Operation and Maintenance in British Columbia Best Practices Document*.

Canadian Institute of Planners. (2018). *POLICY ON CLIMATE CHANGE PLANNING*.

Chiotti, Q. (2016). Planning for Extreme Weather and Climate Change: Advancing Resiliency and Adaptation Across Metrolinx. *TAC 2016: Efficient Transportation-Managing the Demand-2016 Conference and Exhibition of the Transportation Association of Canada*.

City of Calgary. (2020). *Climate Resilience Strategy and Action Plans*.

CITY OF CALGARY. (2022). *CALGARY TRANSIT FLEET ELECTRIFICATION PLANNING STUDY* .

Dickson, C., & Arcodia, C. (2010). Promoting sustainable event practice: The role of professional associations. *International Journal of Hospitality Management*, *29*(2), 236–244.

Ebinger, J. O., & Vandycke, N. (2015). *Moving Toward Climate-Resilient Transport: The World Bank's Experience from Building Adaptation into Programs. World Bank*.

Engineers & Geoscientists British Columbia. (2021). *CLIMATE CHANGE ACTION PLAN*.

EPA. (2014). *Reference Guide for Asset Management Tools* .

Jacob, K., Rosenzweig, C., Horton, R., Major, D., & Gornitz, V. (2008). MTA adaptations to climate change: a categorical imperative. *Metropolitan Transportation Authority*, *37*.

Maddalen Mendizabal, Saioa Zorita, & Karmele Herranz. (2018). *Standardising methods for prioritising adaptation options toolbox*.

Mahdy, M., Bahaj, A. S., Turner, P., Wise, N., Alghamdi, A. S., & Hamwi, H. (2022). Multi criteria decision analysis to optimise siting of electric vehicle charging points—case study winchester district, UK. *Energies*, *15*(7), 2497.

Morrison Hershfield. (2019). *Climate Change and Transit Infrastructure: The Benefits of Climate Vulnerability Assessments*.

Parada, M. J., Nordqvist, M., & Gimeno, A. (2010). Institutionalizing the family business: The role of professional associations in fostering a change of values. *Family Business Review*, *23*(4), 355–372.

Sandink, D., & Lapp, D. (2021). The PIEVC Protocol for Assessing Public Infrastructure Vulnerability to Climate Change Impacts: National and International Application. *Canadian Society of Civil Engineering Annual Conference*, 371–383.

SF Environment. (2021). *SAN FRANCISCO'S CLIMATE ACTION PLAN*.

Société de transport de Montréal. (2017). *SUSTAINABLE DEVELOPMENT PLAN 2025 - Excellence in Mobility*.

Swan, J. A., & Newell, S. (1995). The Role of Professional Associations in Technology Diffusion. *Organization Studies*, *16*(5). https://doi.org/10.1177/017084069501600505

Swanson, D., Murphy, D., Temmer, J., & Scaletta, T. (2021). *Advancing the Climate Resilience of Canadian Infrastructure*.

Translink. (2022). *TransLink Climate Action Plan*.

U.S. Department of Transportation. (2021). *Climate Action Plan - Revitalizing Efforts to Bolster Adaptation & Increase Resilience* .

U.S. DoT FHWA. (2023). *Addressing Resilience to Climate Change and Extreme Weather in Transportation Asset Management*.