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CHAPTER 9: URBAN

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KEY FINDINGS

- **Enhancing redundancy (particularly across modes) in urban transportation networks increases resilience to climate change.** A redundant system gives travelers choices so that if one option performs poorly, other effective options are available. Redundancy becomes even more important in emergency situations (including those arising from extreme weather conditions) as it allows travelers to complete trips, and economies to function, even when major service disruptions occur.
- **Extreme weather events influence the perspectives and actions of urban decision-makers.** Events with severe socioeconomic impacts demonstrate to municipal decision-makers that human activity, short-sighted planning decisions, or failure to act, can exacerbate weather-related damages. Expropriating floodplain lands and re-routing roadways away from vulnerable areas are examples of policy changes made in response to extreme weather events in some Canadian cities.
- **"Low-regret" or "no-regret" adaptation strategies offer municipalities opportunities to enhance the resilience of transportation infrastructure at key points in infrastructure lifecycles, at little additional cost.** One example is enhancing stormwater management capacity to reflect probable future precipitation conditions, when existing infrastructure reaches a renewal period. These strategies also build public support for adaptation efforts if benefits are tangible, communicated clearly, and realized quickly.
- **The cost of resilient infrastructure is considered a barrier to implementing adaptive actions.** In terms of both capital and operational funding, innovative financing tools and intergovernmental partnerships could help promote adaptation when addressing Canada's growing municipal infrastructure deficit.
- **There is a need for structured collaboration among government departments, transportation agencies, emergency services, municipal councils, engineers, climate change specialists, and civil society.** Collaboration helps to ensure adaptation is a community-wide endeavour and highlights key interdependencies for the urban transportation sector (for example, with electricity and telecommunications providers).
- **Canadian cities are undertaking a number of resilience-enhancing initiatives.** Examples from Whitehorse, Prince George, Toronto, and Moncton demonstrate the diversity of adaptive strategies required to deal with the range of geographic and climatic challenges across the country. These case studies also suggest that, increasingly, urban practitioners are moving beyond risk assessment and beginning to implement adaptive practices and build resilient infrastructure.

1.0 INTRODUCTION

Urban transportation systems are vulnerable to both extreme weather events and the incremental impacts of a changing climate. Extreme weather disrupts and delays urban travel by washing out roadways and transit routes, and by damaging the electrical and communications systems upon which these modes rely. Increased temperatures cause pavement rutting, buckling of rail lines, and damage to infrastructure built on permafrost in Northern communities. These and other climate risks can affect the cost, efficiency, and safety of urban transportation in Canada.

In this chapter, urban transportation refers to all modes of transportation that carry people and goods within cities and, more broadly, metropolitan areas. This includes infrastructure and vehicles (automobiles, buses), rail transit (including metros, light rail transit [LRT], and commuter rail), and active modes, such as walking and cycling. Note that airports, regional and national rail systems, marine ports, and ferry services[3] are discussed in regional chapters of this report.

The focus of this chapter is on the vulnerability of urban transportation to the impacts of both gradual changes in climate and extreme weather events, taking into account the interactions between cities' concentrated infrastructure, services, and populations. The chapter also explores current efforts Canadian municipalities are making, and those planned for the future, to increase transportation resiliency. While some of these adaptations can be costly, many can be classified as "no-regret" or "low-regret" actions – strategies which involve few additional costs, produce co-benefits, or prevent higher future costs. Integrating climate considerations into decision-making processes (i.e. mainstreaming), for example, in the development of Official Plans, financial management processes, and infrastructure investment decisions, makes it easier to identify this type of adaptation.

Statistics Canada has recently replaced the term "urban centre" with "population centre." There are three categories, including:

- Small population centres (with populations between 1,000 and 29,000);
- Medium population centres (between 30,000 and 99,000); and,
- Large population centres (populations exceeding 100,000) (Statistics Canada, 2011a).

This chapter primarily focuses on the last two categories, although "urban centres" and "population centres" are used interchangeably.

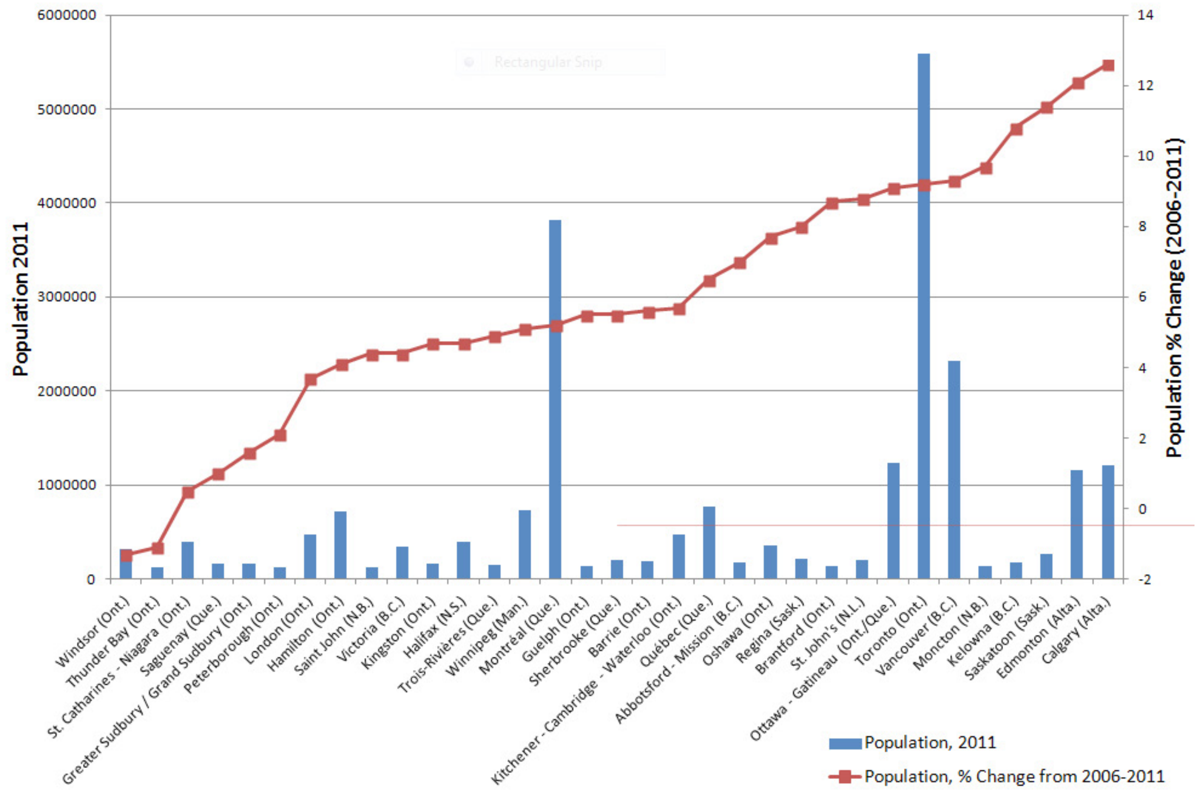
Recognizing that research examining climate impacts on urban transportation is limited in Canada, this chapter also draws upon relevant research from the United States, to supplement domestic content where appropriate.

1.1 TRENDS IN URBAN CANADA

Canada is growing increasingly urban. In the 2011 national census, 81 percent of Canadians indicated that they lived within medium or large population centres. Population trends suggest that the nation's largest urban areas – known as Census Metropolitan Areas (CMAs) – are growing rapidly, largely as a result of their ability to attract economic generators such as financial services, research and development agencies, and tourists, as well as newcomers to Canada (Filion and Bunting, 2010). Figure 1 presents the population growth in Canadian CMAs from 2006-2011.

[3] Ferries provide important transit services only in a few urban centres in Canada (e.g., Halifax and Vancouver).

Figure 1: Canadian CMAs with the highest growth rates from the 2006 National Census to the 2011 National Census. (Source: Statistics Canada)

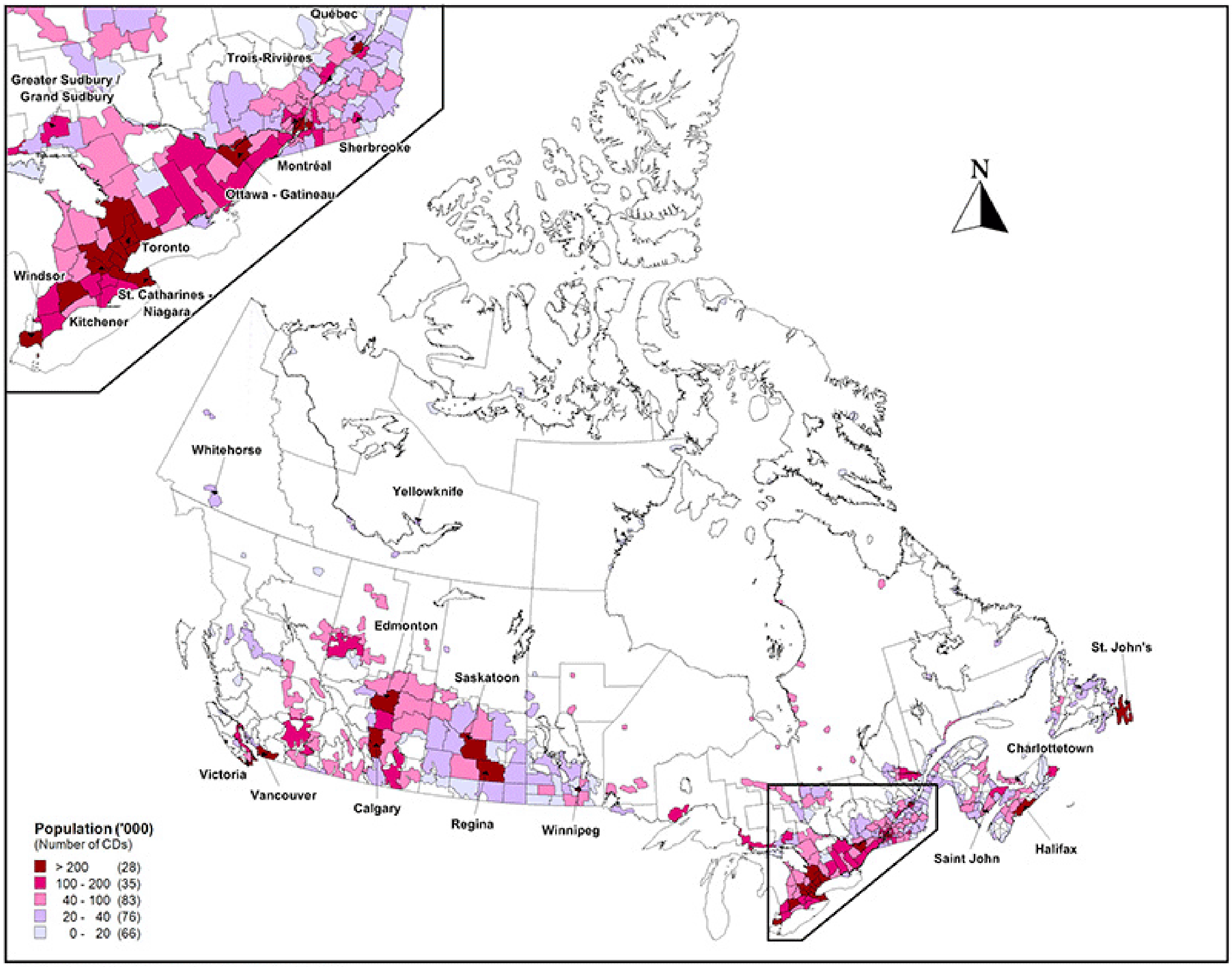


Both large and mid-sized cities are leading the urbanization movement in Canada. While the greater metropolitan areas of three cities (Montreal, Toronto, and Vancouver) now account for 35 percent of the Canadian population (Postmedia News, 2012), many smaller cities have experienced significant growth as well (e.g., Saskatoon, Kelowna, and Moncton). This is a trend experts expect to continue well into the 21st century. Thus, adapting to climate risks in Canadian cities will occur in tandem with managing urban population growth.

The degree to which Canadian cities will be affected by climate change and their capacities to adapt varies considerably. "Adaptive capacity" is a function of many factors, including geography. CMAs are distributed in a number of climate regions, including two in Canada's north (Whitehorse, Yukon, and Yellowknife, Northwest Territories), that face specific challenges related to rapid warming and thawing permafrost (see Chapter 3).

Canada's urban development in the postwar period has been characterized by low-density, sprawling suburban development outward from traditional downtown cores, which encourages (and often requires) the daily use of automobiles (Blais, 2013). Road congestion is taking an increasingly heavy toll on Canadian urban regions, accounting for $6 billion to $11 billion in lost economic productivity annually in the Greater Toronto and Hamilton Area, and $500 million to $1.2 billion annually in the Metro Vancouver area, depending on the specific metrics applied (Dachis, 2013; Dachis, 2015). However, many Canadian municipalities have begun to recognize the importance of compact and walkable neighbourhoods for improving the efficiency and sustainability of their urban environments (Ontario Ministry of Infrastructure, 2013; Metro Vancouver, 2011; Haider et al., 2013). As a result, there is a general movement to build "up" rather than "out," and population density is increasing along with population growth: in CMAs, population density increased by an average of 6 percent from 2006-2011 (Statistics Canada, 2011a; see Figure 2).

Figure 2: Urban density and agglomerations in Canada. (Source: Statistics Canada)



When assessing climate impacts on cities, density (of both population and infrastructure) is a complicating factor. Localized impacts, such as strong winds and heavy rainfall, disrupt a higher volume of traffic and economic activity, and affect more individuals and infrastructure components in urban centres than in less densely-populated areas (Revi et al., 2014; Solecki et al., 2011).

The deteriorating condition of municipal infrastructure further complicates the ability of Canada's highgrowth and increasingly dense cities to accommodate a growing population. The 2016 Canadian Infrastructure Report Card (CIRC), which assessed the condition of Canada's municipally-owned infrastructure, graded 14 percent of sidewalks, roads, and bridges, as "poor" to "very poor", with a total replacement value of $50.4 billion. The CIRC provided these same grades to 17 percent of public transit infrastructure (vehicles, mobile technology, security systems, signalization equipment, and terminal facilities), with a replacement value of $9 billion (Canadian Infrastructure Report Card, 2016). The report indicated that under current investment/maintenance conditions, most urban transportation infrastructure will require significant and increasing investment as it ages – even infrastructure presently in "fair" to "very good" condition (Canadian Infrastructure Report Card, 2016). The pressure placed on this infrastructure by climate change is likely to expedite the need to replace or upgrade older assets.

Transit ridership per capita in Canada is also growing annually (Canadian Urban Transit Association, 2012), while rates of auto ownership in CMAs are decreasing (Perl and Kenworthy, 2010). Transit is attracting greater attention from all levels of government in Canada, with federal and provincial spending support for urban transit in Canada growing at a rate of 5.2 percent annually since 2008 (Transport Canada, 2013). This is consistent with a broader international trend in urban governance to enhance public transportation modes as a method to reduce traffic congestion and improve public health (Bradford, 2008).

Finally, it is worth considering the interactions of multiple infrastructure systems in cities. Vehicles and at-grade rail systems rely heavily on drainage infrastructure to manage storm runoff. Rail transit networks in cities such as Calgary, Edmonton, Toronto, and Montreal depend on reliable electricity to power vehicles and communications networks. Vehicles and bus transit systems also rely on municipal electricity and emergency response resources for traffic signals and safety. This provides important context for this chapter, as both the public and private sectors in Canada are challenged to maintain or improve this array of interrelated urban infrastructure while simultaneously enhancing the resilience of transportation networks to changing climate conditions.

1.2 ADAPTATION TO A CHANGING CLIMATE

A number of strategies can be used to reduce the impacts of observed and anticipated changes in climate and extreme weather on urban transportation systems. The strategies discussed in this chapter fall into the following general categories:

- Investing in more resilient materials, infrastructure, and operational practices for transportation infrastructure;
- Improving redundancy within transportation networks – this refers to the availability of multiple paths or modes for urban travel with similar user costs;
- Updating the climate design criteria used in engineering standards to better reflect future conditions;
- Improving land use policies and controls (e.g., zoning amendments or construction requirements in vulnerable areas); and
- Enhancing the resilience of communities to extreme weather and climate effects through social adaptations.

2.0 CLIMATE AND URBAN TRANSPORTATION

Understanding the historical interactions of climate, weather, and geography are important to determine how climate change will affect urban transportation in Canadian cities in the 21st century. Location is an important factor in urban vulnerability to climate change, as many cities in Canada are located in low-lying areas next to significant bodies of water (Filion and Bunting, 2010). Floodplains, coastal regions, and other vulnerable areas could experience significant flooding, erosion, and infrastructure damage as a result of a changing climate and more frequent extreme weather events (Revi et al., 2014). While today's planning provisions often restrict development in vulnerable areas, this legacy of urban vulnerability persists, and is heightened by increasing population densities. Understanding how cities have dealt with climate impacts in the past helps vulnerable cities make informed decisions and investments, in order to adapt to emerging climate conditions.

This section provides an overview of climate and weather-related impacts on urban transportation in Canada, and projected climate conditions for the 21st century. Regionally-specific discussions of climate can be found in other chapters of this report.

2.1 CLIMATE SENSITIVITY OF URBAN TRANSPORTATION

Much has been learned about how to adapt to severe weather across all modes of urban transportation in Canada. Some examples are explored in this section.

REGINA CYCLONE, JUNE 1912

The Regina Cyclone, which occurred on June 12th, 1912, remains the most destructive tornado in Canadian history. It killed 30 residents, left 2500 homeless, and resulted in $1.2 million (approximately $25 million in 2015 dollars[4]) in property and infrastructure damage (Environment Canada, 2013a; Saskatchewan Archives Board, 2011). The damage was so significant that it took the municipality 40 years to pay back the debts it incurred (Saskatchewan Archives Board, 2011). The loss of the Canadian Pacific Railroad freight depot was particularly detrimental. The cyclone flipped railcars and destroyed grain warehouses, flattening a keystone of Western Canada's grain transportation network and affecting cities across the country that relied on western grain (Martin, 2012;).

In the century since this event, emergency management and communication protocols have changed significantly (including the use of electronic and social media to warn operators and travelers of impending threats), and urban building codes and materials are much more resilient to wind and rain (Martin, 2012). While the damage and disruption associated with a similar event would likely be severe, the transportation and other infrastructure impacts of a tornado would not be as devastating today thanks to more stringent building codes and improved materials (Martin, 2012).

FRASER RIVER VALLEY FLOOD, SPRING 1948

An unusually rapid warming of a heavy mountain snowpack caused the Fraser River, in British Columbia, to flood in May and June 1948. Floodwaters engulfed 2,300 homes, leaving 16,000 homeless and 10 dead (Robinson and Cruikshank, 2006). The estimated damage was $20 million (approximately $220 million in 2015 dollars) (Environment Canada, 2010).

The network of dykes set up to protect the urban areas of Chilliwack, Mission, and New Westminster were considered adequate for minor flood protection, but were unable to withstand the flood's high-water levels. On June 10, the river reached a peak height of 7.6 m in Mission, flooding streets and nearby highways, impeding vehicles, pedestrians, and two rail lines running through the town (McLean et al., 2007; Environment Canada, 2010). While only 0.5 percent of the 1,375-km floodplain is at risk of flooding today, this high-risk area includes a number of urban centres, and is home to two airports and key segments of highway and railway (Environment Canada, 2010).

Governments and decision-makers learned several lessons in the aftermath of the Fraser River floods. Better regional coordination, emergency planning, and awareness have catalyzed municipal, provincial, and federal governments to invest $300 million since 1948 to improve dykes and other flood-prevention measures in the region (to withstand a 200-year flood event); as a result, the adaptive capacity and resilience of these communities has been increased (McLean et al., 2007).

While significant improvements in flood control have been made, the Fraser Valley's urban regions face heightened risks to similar or more significant events in coming decades as a result of a changing climate.

[4] All conversions of historical to contemporary dollar values in this chapter have been derived from the Bank of Canada's Inflation Calculator, which provides conversions via consumer price index data. This tool can be found online at http://www.bankofcanada.ca/rates/related/inflation-calculator/.

Figure 3: Flood of the Fraser River at Mission, 1948. (Source: Environment and Climate Change Canada)

HURRICANE HAZEL, GREATER TORONTO AREA, OCTOBER 1954

Hurricane Hazel, which hit the Greater Toronto Area (GTA) in October of 1954, may be Canada's best-known weather-related urban disaster, and remains one of the most costly storms in the region's history. A wet autumn season left Ontario's soils supersaturated (Environment Canada, 2013a), which worsened the impact of 210 mm of rain that fell in a 36-hour period. Severe flash floods killed 81 people (Toronto and Region Conservation Authority, 2016). Damages totaled $100 million (approximately $900 million in 2015 dollars), half of which was spent replacing damaged or destroyed transportation infrastructure (Robinson and Cruikshank, 2006).

Disruptions to transportation systems were significant:

- Many train routes were delayed or otherwise affected, and a CNR railcar was overturned (Environment Canada, 2013a).
- CNR reported a dramatic increase in train travel during the storm due to widespread road flooding. 14,000 people traveled by train during Hurricane Hazel, compared to the daily average of 1,000 (Environment Canada, 2013a), demonstrating the importance of redundant transportation options in maintaining mobility during extreme events.
- Major flooding and washouts occurred on Highways 400, 11, and 12, stranding motorists. Sections of these highways, in the storm's peak, were under approximately 1m of water.
- A total of 40 bridges were damaged and 10 were de-commissioned. Many bridges serving key arterials, including connections over the Don River, York Mills, and Bayview Avenue, were severed, causing considerable social disruption (Environment Canada, 2013a).

The GTA took adaptive action after Hazel to address the hurricane's immediate effects and reduce vulnerability to similar future events. The city placed specific focus on emergency management policy and infrastructure decision-making. For example, the proposed location of Toronto's Gardiner Expressway route was amended, elevating the roadway and setting it back further from the shore of Lake Ontario. This busy highway running through downtown Toronto, yet to be built in 1954, would have been almost entirely washed out by a hurricane of this magnitude if built as initially planned (Environment Canada, 2015). In Hazel's wake, the City also placed greater emphasis on restoring transit services in a timely manner to alleviate road congestion during and after emergencies (Environment Canada, 2015).

Hurricane Hazel also shifted decision-makers' perspectives in Ontario. They no longer framed natural disasters as "acts of god" – rather, an important and transformative link was made between weather-related damage and planning decisions (Henstra, 2011). Hazel prompted the Toronto and Region Conservation Authority to make many policy changes that resulted in greater resilience to extreme weather and flood events. Specifically, the Authority:

- Expropriated floodplain lands near watercourses and prevented development in these areas;
- Increased the amount of water-absorbing green space in the city; and,
- Improved watercourse management infrastructure and techniques (Robinson and Cruikshank, 2006).

Figure 4: Personnel of the Canadian Army clearing away debris in the aftermath of Hurricane Hazel. (Source: Library and Archives Canada)

Prior to Hurricane Hazel, volunteer groups typically led storm clean-up efforts in Ontario. Hazel gave municipalities the impetus to leverage provincial and federal governments for resources to adequately prepare for and recover from extreme weather events (Robinson and Cruikshank, 2006).

EASTERN CANADA ICE STORM, JANUARY 1998

From January 4th to 10th, 1998, significant amounts of freezing rain accumulated from eastern Ontario to Nova Scotia. Greater than 100 mm of ice fell in more than 80 hours of precipitation, leaving over 4 million people without electricity, and resulting in significant transportation disruptions. Electrical wires, utility poles and tree branches blocked roadways, and power outages disrupted traffic signals. Roads were closed and public transit services were delayed and cancelled, while icy conditions caused accidents and made travel dangerous (Bertin, 1998). More than 16,000 Canadian Forces personnel were deployed to manage the aftermath; Environment Canada estimated the initial insurance claims to be more than $1.5B, with a total exceeding $3 billion (Environment Canada, 2013b).

Figure 5: Fallen tree branches following the ice storm. (Source: Environment and Climate Change Canada)

Following the ice storm, several measures were implemented based on the lessons learned. For example, the province of Quebec adopted legislation requiring all municipalities to prepare emergency plans and created better communication between the provincial and municipal governments (Institute for Catastrophic Loss Reduction, 2016). Hydro-Quebec also took measures to prevent power outages such as reinforcing transmission towers, adding additional hydro lines and burying power lines (The Canadian Press, 2008). While these measures were largely focused on public health and safety, better emergency planning, communications and electricity systems also support the resiliency of transportation systems.

HURRICANE JUAN, HALIFAX, SEPTEMBER 2003

Cities in Atlantic Canada have also experienced severe impacts from extreme weather events, and climate models suggest the frequency of these events will increase in this region in the 21st century (AMEC Inc., 2011). Hurricane Juan, that struck Halifax on September 29th, 2003, was the most destructive storm in the city's history, due to effects of storm surge (temporary sea-level rise), intense flooding, and strong winds (Environment Canada, 2013a). Sustained wind speeds reached a maximum of 160 km/h. Halifax Harbour experienced wind gusts up to 230km/h and storm surges of 1.5-2m, leading to severe shoreline erosion and the loss of railway tracks (Bowyer, 2003a). Containers were blown off ships in the port, and several rail cars were washed into the Atlantic at the Dartmouth rail yard (Bowyer, 2003c). The storm's volatility and disruption to transportation services contributed to the closure of businesses and schools for five days (Bowyer, 2003b). The estimated cost of damages related to Hurricane Juan totaled $200 million (Environment Canada, 2013a). The event prompted decision-makers in Atlantic Canada to improve planning and preparation processes for extreme weather events: clearer channels were created for communication and coordination among provincial and local emergency response departments, and hurricane-specific training for emergency personnel was mandated in the immediate aftermath (Government of Nova Scotia, 2003).

Figure 6: Storm surge causes wharf damage in Halifax Harbour. (Source: Environment and Climate Change Canada)

FLOODING, GREATER TORONTO AREA, JULY 2005 AND JULY 2013

Several extreme summer storm events have caused substantial disruption and damage to the Greater Toronto Area (GTA). In August 2005, intense rainfall and flooding cost the City of Toronto $47 million (insurance covered the additional $500 million in damages) (McLeod, 2011). One major culvert on Finch Avenue sustained $4 million in damages due to wash-out (City of Toronto, 2014; McLeod, 2011; see Figure 7).

Figure 7: A section of Finch Avenue washed out during the heavy rainstorm of August 19, 2005. (Source: City of Toronto)

Similarly, during a severe storm in July 2013, 126mm of rain fell on the GTA within two hours, resulting in $850 million in insurance claims (Environment Canada, 2014). While the hourly rate of rainfall (intensity) was higher during this event than during Hurricane Hazel, damage was significantly less severe due in part to improvements in Ontario's emergency planning policy framework after Hazel (Henstra, 2011; Aulakh, 2013). Transportation disruption was significant nonetheless. Subways were closed due to flooding, GO trains were evacuated by police boats, and drivers faced washed-out roads. However, transportation networks in the city were almost completely restored by the following day (CBC News, 2013). A number of adaptive actions were identified in the aftermath of this crisis, including the development of more robust flood management and prevention plans for the Don Valley, and the installation of emergency back-up power at key bus and locomotive maintenance facilities.

CALGARY FLOOD, JUNE 2013

An important final example relates to the flooding of the Bow River in Calgary, Alberta in June 2013. At the storm's peak, 200mm of rain fell within approximately 16 hours on supersaturated soil and, in some places, still-frozen ground (Davison and Powers, 2013). As Canada's costliest climate-related disaster to date, damages in Calgary are estimated to surpass $6 billion. Damage included bridges, culverts, roads (over 1,000 km) and public transit infrastructure (Environment Canada, 2014). In addition, scour (the removal of supporting earth by fast-moving water) caused the Bonnybrook Bridge to partially collapse, leaving six Canadian Pacific Railway freight cars hanging over the Bow River; shortly thereafter, the bridge was de-commissioned (Canadian Press, 2014). The Transportation Safety Board

(2014) ruled that "unprecedented flood water was to blame for the derailment," and recommended more frequent bridge inspections, reduced train speeds in scour-prone areas, and investment and research into early-detection technologies for structures vulnerable to scour and erosion.

Figure 8: Rail cars sit on the collapsing bridge after a train derailed on Bonnybrook Rail Bridge on June 27, 2013. (Source: Transportation Safety Board of Canada)

2.2 CLIMATE TRENDS AND FUTURE PROJECTIONS

This section provides a summary of projected climate conditions for 21st-century Canada, with a focus on climate elements of particular relevance to urban transportation. These include:

- Greater variation and extremes in seasonal and annual air temperature;
- Changing precipitation patterns;
- Increasing intensity and duration of wind speed, particularly during storm events;
- Changing patterns of sea and lake ice;
- Increasing permafrost degradation;
- Changing water levels, along both coastal and inland waterways; and,
- Combinations of these changing climate elements.

AIR TEMPERATURE

Average air temperature in Canada increased by 1.5˚C from 1950-2010, and is projected to increase by about 1.5-2.5˚C by mid-century (in a low-emissions scenario), with increasing frequency of extreme heat and decreasing frequency of extreme cold (Bush et al., 2014). In cities, these trends are exacerbated by the urban heat-island effect, referring to the difference between surface and air temperatures (typically 10-15˚C for surfaces and 1-3˚C for air) in urban centres and surrounding rural areas. The heat island effect occurs due to a combination of factors (Figure 9), including:

- The lack of vegetation in cities (which regulates temperature);
- The low solar-reflective capacity of urban infrastructure;
- The high heat-absorbance of urban materials (e.g., black asphalt) – highly-developed areas have less surface moisture available for evapotranspiration (which cools surrounding air) than natural ground cover, due to impervious surfaces like pavement and concrete (75-100 percent cover in most cities);
- Anthropogenic (human-caused) heat production (e.g., air conditioning, vehicles, industrial activities); and,
- Urban topography (e.g., narrow streets limit the capacity of buildings to radiate heat at night and limit the passage of cooling winds) (United States Environmental Protection Agency, 2008).

Urban heat islands have implications for the integrity of transportation infrastructure, particularly pavement. Figure 10 provides an example of an urban heat island map for Montreal, Quebec.

Figure 9: An illustration of an urban heat island profile. The impacts of heat waves tend to be greater in urban, rather than suburban or rural areas, likely owing to the 'heat island' effect. (Source: Natural Resources Canada)

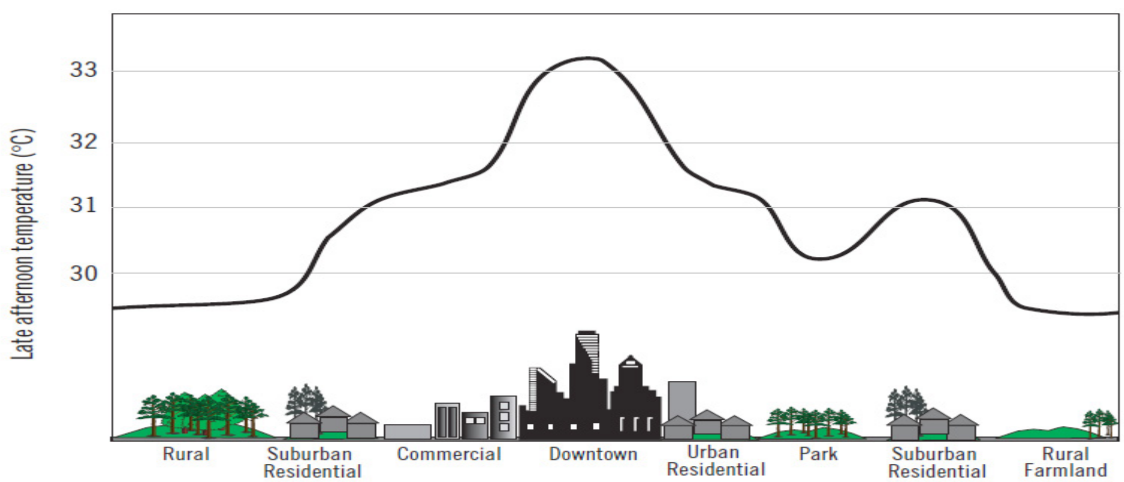
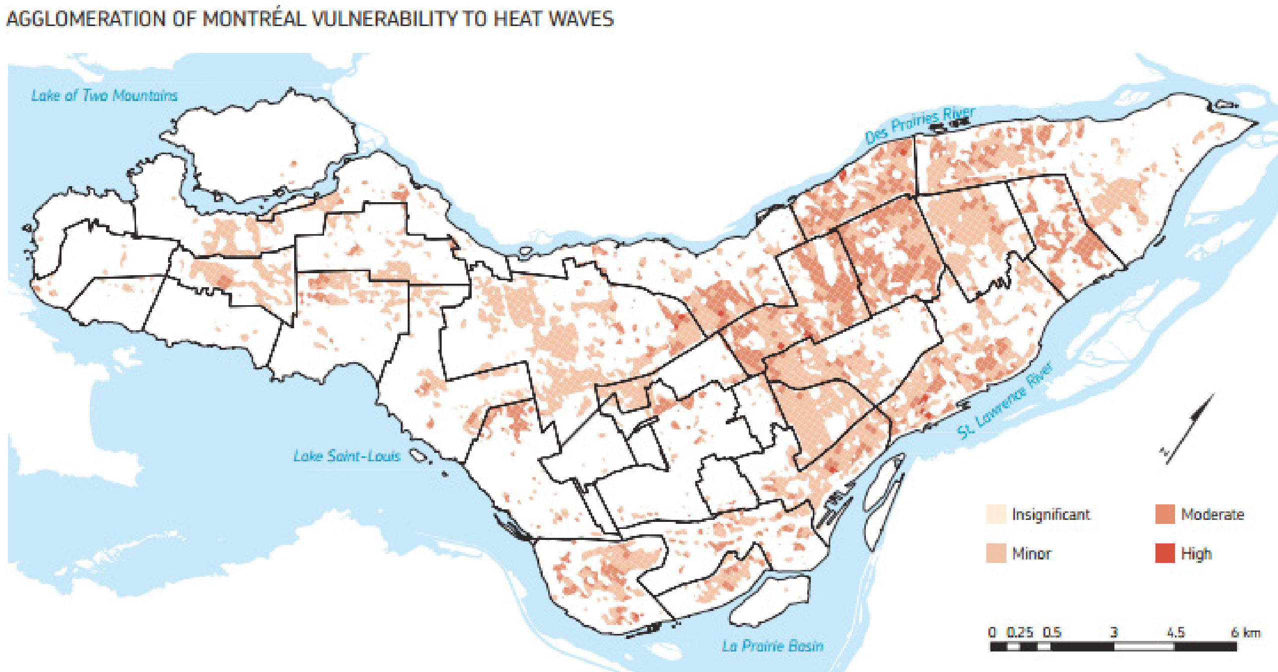


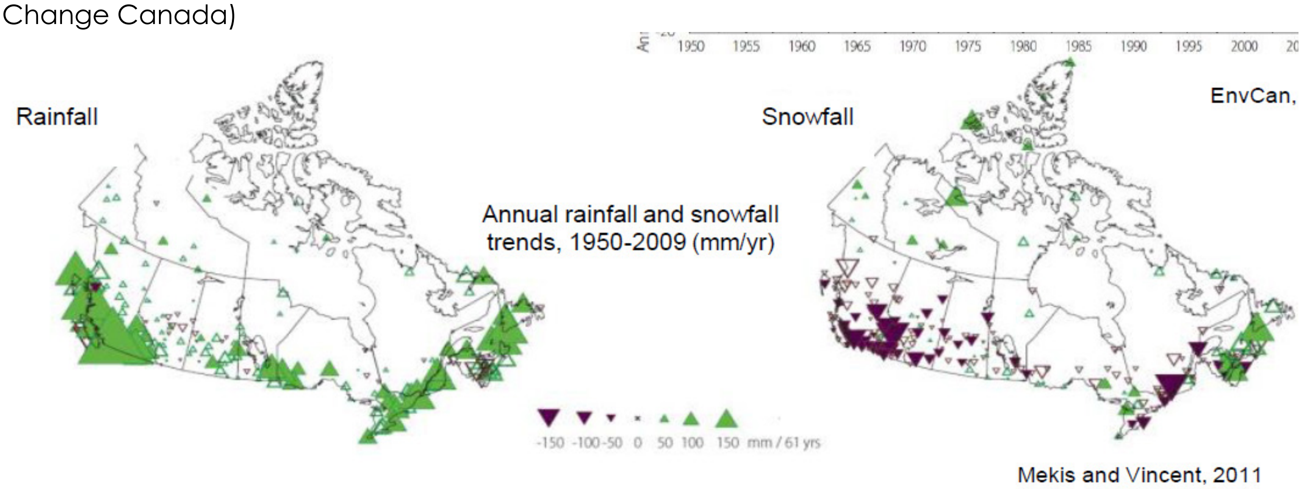
Figure 10: Urban heat island map for Montreal, Quebec. (Source: City of Montreal)



PRECIPITATION

Projected changes in precipitation in Canada, include an increase in British Columbia and Atlantic Canada, as well as changes to the seasonal distribution of precipitation across the country (Bush et al., 2014). Precipitation is expected to increase in all seasons across most of Canada, with the exception of a summer decline in the southwest (Bush et al., 2014). Figure 11 shows changes in precipitation patterns in Canada over the last 59 years.

Figure 11: Changes in precipitation in Canada, 1950-2009. (Source: Environment and Climate Change Canada)



WIND

Changes in patterns of wind relate to temperature and precipitation trends and extremes. One study suggests that the intensity of average daily wind speed will increase by 10-30 percent across Canada by the late 21st century, compared to baseline conditions in the period from 1955-2009 (Cheng et al., 2014). However, the extent of these changes remains uncertain.

LAKE, RIVER, AND SEA ICE

Changing patterns of lake, river, and sea ice pose risks to urban regions next to watercourses and oceans. The extent and seasonal duration of inland ice is likely to decrease as winters warm; however, shifting patterns of spring break-up pose risks in terms of ice-jam flooding and infrastructure management on rivers and lakes (Bush et al., 2014). For example, in spring 2015, this phenomenon prompted the emergency evacuation of Perth-Andover, New Brunswick (see Chapter 8) (Canadian Press, 2015a).

Figure 12: Ice jam prompts evacuation order in Perth-Andover in spring 2015. (Source: Perth-Andover Fire Department)

WATER LEVELS

Both inland and ocean water levels are projected to change significantly in Canada, although the direction of change will vary geographically. While most of the Atlantic and Pacific coasts will experience sea level rise, much of the northern coast will experience relative sea-level decline due to a phenomenon known as "glacial isostatic rebound," in which land formerly covered by glaciers slowly decompresses and rises (Atkinson et al., 2016). While water levels on some inland waterways are expected to decline (such as the Great Lakes) as a result of greater evaporation, others will rise, at least temporarily (Bush et al., 2014).

PERMAFROST

Thawing permafrost is a significant issue in Canada's north, where infrastructure is built on soils underlain by permafrost (Prowse et al., 2009; Transportation Association of Canada, 2010) (see Chapter 3).

Temperature variations may also change the nature of transportation hazards in winter. For example, areas traditionally challenged by snowfall may face increased freezing rain and black ice.

2.3 CLIMATE RISKS TO URBAN TRANSPORTATION

Roadways, rail transit systems, and active transportation networks are vulnerable to climate risks and extreme weather in two key ways. First, operations can be disrupted by extreme weather events and obstructed rights-of-way, as described in Section 2.1. Second, infrastructure is structurally and physically vulnerable to the increasing range of some climate variables (i.e. temperature and precipitation) expected under future conditions. Infrastructure may be exposed to weather extremes unaccounted for in original engineering designs, which assumed that past climate extremes accurately represent future conditions (see Box). Severe weather and shifting "average" conditions can therefore shorten infrastructure life spans, reduce performance, and increase maintenance and operating costs (McLeod and Stevanovic-Briatico, 2014). The following sections provide an overview of climate impacts to urban transportation systems summarized in Table 1.

REGULATORY VULNERABILITIES: CODES, STANDARDS, AND RELATED INSTRUMENTS (CSRI)

The failure to sufficiently consider changing climate conditions in the development and application of engineering and land-use standards might be termed "regulatory vulnerability." A survey of case studies which used the Public Infrastructure Engineering Vulnerability Committee (PIEVC) Engineering Protocol[5] considered the role codes, standards and related instruments (CSRI) play with respect to resilient infrastructure (Engineers Canada, 2012). The survey found that some jurisdictions apply national codes directly; some modify national codes; and others develop location-specific codes to reflect local geography and risk-tolerance preferences. The report concluded that adopting a "climate adjustment factor" into CSRI at the national level may not revolutionize local practices, but the authors suggest that frequent updates based on climate model projections would assist practitioners in adapting their CSRI. Other inputs to CSRI, including professional judgment and management direction based on local conditions; accepted practices of the era; maintenance, operability, and procurement considerations; and other social, environmental, and economic factors, were considered robust in Canada (Engineers Canada, 2012).

[5] The PIEVC Engineering Protocol, led by Engineers Canada, was developed as a 5-step process to analyze the engineering vulnerability of individual infrastructure systems based on current climate and future climate projections. Further information can be found at http://pievc.ca/.

3.0 URBAN ROAD INFRASTRUCTURE

Urban road infrastructure includes roads for vehicles, (i.e. trucks and buses, whether electrified trolleys or diesel); electricity for traffic signals, signage, and lighting; bridges; and stormwater management infrastructure (culverts, ditches, etc.). While per capita vehicle-km travelled (VKT) in Canadian cities is modestly declining (Perl and Kenworthy, 2010), roadways remain critically important to urban economies for the movement of both freight and passengers. This is particularly the case in cities without strong transit links between urban centres and outlying suburban communities.

PRECIPITATION

Precipitation affects urban roads and bridges in a variety of ways. Washouts (due to soil/slope instability when water infiltrates a roadway's substructure) and flooding often result in delays, detours, and closures that reduce mobility and increase travel times for both automobiles and bus transit (United States Federal Highway Administration, 2015; Andrey and Mills, 2003). High-intensity precipitation events disrupt power to traffic signals and other supporting infrastructure, cause roadway disruptions when runoff volumes exceed the capacity of culverts and runoff ponds, and overwhelm the permeability of construction materials, reducing road safety (increasing the risk of accidents), and increasing the risk of bridge scour (Andrey and Mills, 2003; Transportation Research Board, 2008; Revi et al., 2014). For example, on May 29, 2012 in Montreal, 45 mm of rain fell in under an hour, resulting in flash flooding and closing streets.

While the proportion of snow as winter precipitation is likely to decline throughout Canada over the 21st century (Bruce, 2011), extreme winter storms producing heavy snowfall will continue to disrupt roadways and transit operations. This can result in significant service delays, as was the case in Ottawa, in 2013 when heavy snowfall caused buses to lose traction and become stuck (CTV News, 2013).

Freezing rain is likely to become more frequent in many parts of Canada (Cheng et al., 2011), causing ice build-up, road blockages, and power outages due to fallen tree branches and utility lines, and posing risks to road safety in urban areas (Andrey, 2010; Andrey et al., 2013). Increased salt usage to combat icy road conditions corrodes concrete infrastructure, and carries negative implications for the well-being of roadside ecosystems and urban water supplies (McLeod and Stevanovic-Briatico, 2014).

TEMPERATURE

Climate-induced stress to pavement mixtures is a growing issue for road operators. While most asphalt and concrete used in Canada is designed to withstand temperatures between -20˚C and 30˚C, projected temperatures for many Canadian cities in the 21st century exceed this range. In extreme heat during summer months, softening, rutting, flushing, and bleeding of asphalt are expected to increase in frequency and severity (Mills and Andrey, 2002). Softening and rutting occur when vehicles depress hot pavement (Mills et al., 2009). Bleeding refers to asphalt moving above a pavement's surface treatment (the waterproof layer upon which vehicles drive); flushing refers to the upward movement of asphalt to the fringe of the surface treatment, though not beyond the aggregate seal. While bleeding leads to more serious roadway damage, both phenomena reduce pavement integrity (Texas Department of Transportation, 2006). Softened pavement also leads to reduced maximum loads on municipal roadways, reduced ride quality and vehicle performance, increased maintenance costs, and reduced lifespan of roads, bridges, and culverts (McLeod and Stevanovic-Briatico, 2014). In extreme heat, trucks and buses wear more heavily on roads than automobiles due to their more substantial chassis and passenger loads, exacerbating pavement rutting and shearing issues (Savonis et al., 2008).

Extreme heat also produces heat stress for construction workers (Transportation Research Board, 2008); on especially hot summer days, it may not be safe or possible to carry out construction work during peak daytime hours (United States Federal Highway Administration, 2015).

Bridge infrastructure is also vulnerable to extreme heat. Bridges are designed to withstand some expansion and contraction through the use of flexible materials embedded between fixed points. However, as temperatures increase, the limits of these expansion joints can be exceeded, displacing material or cracking deck materials, especially at the interface with fixed points. This cracking can lead to substantial bridge deterioration, resulting in closures and lengthy detours (Cohen et al., 2005). In addition, both extreme heat and cold may result in malfunctioning traffic control signals (McLeod and Stevanovic-Briatico, 2014).

As seasonal temperature patterns shift, the frequency of freeze-thaw cycling is likely to increase throughout Canada, and the timing and onset of freeze-thaw events are likely to change, with implications for road infrastructure (Transportation Research Board, 2008). During periods of thaw, moisture seeps into small cracks, freezes and expands when cold returns, and melts (causing pavement weakness) during the next thaw (United States Federal Highway Administration, 2015). As a result, pavement is more likely to experience shearing (cracking) and rutting, reducing the strength and stability of roadways (Transportation Research Board, 2008; United States Federal Highway Administration, 2015). In northern climates, freeze-thaw cycling and temperature increases also contribute to further permafrost degradation, which poses risks to the stability of urban roads and their embankments (Woudsma et al., 2007; Transportation Association of Canada, 2010).

CHANGING WATER LEVELS

Bridge scour, which refers to the removal of supportive sand and rock sediment around bridges constructed over waterways (Transportation Research Board, 2008), has affected many Canadian jurisdictions during high-water events (Environment Canada, 2014). Similarly, flooding and storm surges pose erosion risks to coastal highways – this is particularly problematic in Atlantic Canada and British Columbia (AMEC Inc., 2011). Vancouver was recently named the 15th most-vulnerable city in the world to sea level rise, with likely impacts to road infrastructure by 2100 (at which point 1.1m of sea level rise is anticipated). These impacts include inundation, erosion, and washing-out of low-lying downtown streets (Mills, 2016).

WIND

Data suggest the intensity of wind gusts (on average and during extreme events) is likely to increase over the 21st century in Canada (Cheng et al., 2008), although with considerable regional variability (Cheng et al., 2014). Fallen debris (i.e. power lines, trees, and branches) from high winds can obstruct roadways, sidewalks, and cycling pathways (City of Montreal, 2015), while blowing snow disrupts visibility in winter months (Andrey et al., 2013). Strong winds may also temporarily close bridges – for instance, the Burlington Skyway near Hamilton, Ontario is closed when winds reach or exceed 85km/h (Craggs, 2014).

WILDFIRE

Changing patterns of temperature and precipitation affect the frequency and severity of wildfires, particularly in Canada's drier, western regions (i.e., the Prairies and British Columbia). Recent research suggests that the frequency of wildfires will rise over the 21st century, and that fire management agencies in both coastal and temperate areas may need to adapt their planning and response capacities to deal with potential changes in fire regimes (Wang et al., 2015). This has implications for transportation, particularly for emergency response planning. For example, during the catastrophic 2011 wildfires in Slave Lake, Alberta, emergency personnel successfully coordinated the evacuation of residents by road, despite the availability of only a handful of exit routes out of the town (which quickly became congested) and thick smoke. This success was attributed to planning and coordination amongst municipal departments and emergency personnel prior to the crisis (KPMG, 2012).

OPPORTUNITIES

There are also opportunities for road transport associated with climate change. In southern cities, for instance, construction seasons are likely to be longer, and winter road-maintenance costs are likely to be lower in warmer winters, despite an increasing proportion of freezing rain (Andrey and Mills, 2003; Fu et al., 2009). It remains to be seen, however, what impact increased freeze-thaw cycling might have on these cost savings.

4.0 URBAN RAIL TRANSPORTATION

Urban rail systems include subways, LRT, and streetcars. They also include urban freight systems, although information on the regional and national rail system can be found in the regional chapters of this report.

Ongoing and planned rail-transit projects, including those identified below, complement existing and well-used LRT and subway systems in Vancouver, Calgary, Edmonton, Montreal, and Toronto. Other jurisdictions with smaller populations are also beginning to recognize the benefits of investment in rapid transit. For example, the City of London is in the public consultation and mode-selection phase for rapid transit, and Victoria is in the planning stages of bringing LRT to its metropolitan area. These projects demonstrate renewed public interest in, and support for, rapid transit in general and rail-based modes in particular.

- **Toronto:** Eglinton Crosstown LRT and Scarborough subway extension (construction phase);
- **Kitchener-Cambridge-Waterloo:** ION LRT (construction phase);
- **The Greater Toronto and Hamilton area:** Electrification of the GO Transit network (planning phase); and,
- **Ottawa:** Confederation Line LRT (construction phase).

PRECIPITATION

Many urban rail systems rely on municipal electricity grids; therefore, locomotives and signals are vulnerable to power outages in extreme weather conditions (i.e. rainfall and snow). Track beds are also subject to a number of the same climate impacts as urban roadways, including reduced stability during flooding and erosion during extreme precipitation events (Mills and Andrey, 2002).

As with roads, precipitation can overload the stormwater management infrastructure that protects underground, surface, and elevated rail transit. Extreme weather events can result in flooding and inundation of rail systems, as was the case in Toronto in the summer of 2013 (Wooler, 2004). Extreme precipitation in Montreal during May 2012 (discussed in Section 3) also resulted in tunnel closures and the evacuation of several metro stations (City of Montreal, 2015).

TEMPERATURE

Rail infrastructure is prone to buckling in extreme heat, increasing the potential for sensor malfunctions, scheduling delays, speed restrictions, and – in extreme cases – derailment (Savonis et al., 2008). Tunnels used in underground rail transit systems can also experience operational challenges during extreme heat, including mechanical issues with ventilation. As a result, operators need to sufficiently consider passenger comfort, health, and safety (Office of the Federal Coordinator for Meteorological Services and Supporting Research (OFCM), 2002).

Extreme cold also affects urban rail. For instance, the Toronto Transit Commission (TTC) subway system faced several extreme-cold power outages in the winter of 2015, due primarily to broken water mains flooding tunnels (McLeod and Stevanovic-Briatico, 2014). Cold temperatures can also cause frozen track signal switches, delaying trains (Canadian Press, 2015b). However, this may become less problematic in southern cities if the frequency of cold days and nights decreases as projected (Bush et al., 2014).

CHANGING WATER LEVELS AND STORM SURGE

During periods of seasonal ice-jam flooding, railways adjacent to water and their embankments may be inundated, washed-out, or eroded. Bridge scour is also a risk for rail bridges, as suggested by Calgary's experience in the summer of 2013 (see Section 2.1).

WIND

High-intensity wind events also pose risks to rail infrastructure and operations, such as damage to overhead cables and tall signalization equipment, and rail-car blow-over (OFCM, 2002). Similar to roads, rail lines may also be obstructed by fallen debris causing service delays.

OPPORTUNITIES

Investment in rail transit can enhance the redundancy of urban transportation networks, providing mass transit options when roads are closed, unsafe, or congested (Box 1). Rail transit projects could also benefit from longer construction seasons, as winters shorten (Transportation Research Board, 2008).

BOX 1: REDUNDANCY IN URBAN TRANSPORTATION SYSTEMS

Redundancy is one method to enhance the resiliency of transportation networks to extreme weather and a changing climate. A redundant system allows travelers choices so that even when major service disruptions occur (e.g., extreme congestion or wash-out), other options are available, and travelers can complete their trips and economies can continue to function. For example, in major cities like Montreal and Toronto, if localized flooding causes the subway system to stop running, users can still travel by foot, bicycle, and on public buses. An opposite example is the nearly singular reliance of travelers in the Greater Toronto and Hamilton Area on Highway 401 for travel between Toronto and points east and west. If Highway 401 were closed, the alternative roadway and transit networks would be insufficient to maintain reasonable travel times and reliability.

Improving redundancy does not mean building additional roads, particularly above the level of current demand in corridors. In North American history, the construction of extra roads has often stimulated latent (hidden) demand for road capacity, and done little to reduce congestion, improve network efficiency, or address issues associated with urban sprawl (Duranton and Turner, 2011).

5.0 ACTIVE TRANSPORTATION

Walking and cycling networks are critical to the movement of people within Canadian cities. Public transit users, cyclists, and auto travelers are all pedestrians at some stage in their journeys, and pedestrian and cycling facilities provide the most reliable forms of connectivity within cities. Active modes have increasingly been a focus of investment at the municipal level in Canada, addressing climate change concerns from both mitigation and adaptation perspectives (Younger et al., 2008; Ayres, 2014). While the social and environmental benefits of active transportation are well-publicized in municipal planning documents, these modes are also becoming more attractive for short trips as a way to save time as Canadian cities become increasingly dense and traffic-congested.

Active transportation modes also offer an important form of redundancy to urban transportation networks (Box 1). Walking and cycling offer a "safety net," permitting travel when mechanized transport is temporarily unavailable. Given the benefits of active transportation in terms of public health, relative insensitivity to climate change impacts, and low capital costs and environmental impacts, many cities in Canada (and globally) are increasingly investing in these modes.

PRECIPITATION

Active transportation systems face many of the same vulnerabilities as roadways in terms of pavement degradation, storm-water management issues related to runoff and permeability, and associated operational disruptions (e.g., flooding and washout). This is especially true for sidewalks and bicycle lanes next to urban roadways, which make up the majority of active transportation infrastructure in Canada (Transport Canada, 2011).

There tends to be a modal shift away from walking and cycling during precipitation events – all forms of precipitation reduce the proportion of trips taken by active modes (Koatse and Rietveld, 2009). Similarly, pedestrian safety decreases in bad weather, with the number of outdoor injuries increasing dramatically in response to winter precipitation (including snow, rain, and freezing rain) (Morency et al., 2012). However, active transportation remains an important form of redundancy. Travelers are likely to walk in poor weather conditions if roads or transit lines are incapacitated, which means the volume of commuter (i.e. essential) trips is not significantly affected by severe weather (Koatse and Rietveld, 2009; Sabir et al., 2010).

TEMPERATURE

Extreme temperatures also affect the use of active modes. Walking and cycling on hot days requires more exertion and may pose health risks, particularly to vulnerable populations (such as the elderly) (Younger et al., 2008), a phenomenon worsened by the urban heat island effect (see Section 2.2). Some research (i.e. Sabir et al., 2010) suggests that during extreme cold, cyclists shift to public transit and walking, while the opposite is true during periods of extreme warm weather. However, other research (i.e. Koatse and Rietveld, 2009) has found that both extremely high and low temperatures are likely to reduce cycling activity.

CHANGING WATER LEVELS AND STORM SURGE

As with roadways, walking and bicycle paths (especially along coastal roads, or in ocean-side parks) are at risk of inundation and wash-out due to sea-level rise and storm surge (Mills, 2016).

WIND

Active transportation infrastructure tends to be less vulnerable to structural impacts than road and transit systems, due to the absence of heavy, motorized traffic. However, elevated portions of walkways and bikeways, as well as signage, can be damaged by high winds during extreme weather events (OFCM, 2002). Strong winds are also associated with lower levels of cycling (Koatse and Rietveld, 2009). High winds will also pose a safety hazard to cyclist and pedestrians, due to flying and falling debris.

OPPORTUNITIES

Warmer winters with less snow in many Canadian cities will provide longer seasonal access to walking and cycling infrastructure. Some Northern cities view climate risks to roadway infrastructure as an opportunity to enhance active modes. Whitehorse, for instance, has placed significant emphasis on active transportation in recent years and invested in high-profile cycling facilities. This is, in part, due to a projected increase in the length of the season in which cycling and walking is possible for most trips (Transport Canada, 2011).

Table 1: Overview of impacts to each mode of urban transportation in relation to the climate elements identified in this section.

Climate factor		Impacts on urban roads, bridges, sidewalks and supporting infrastructure (stormwater management, signals, electricity)	Impacts on urban rail infrastructure, operations and supporting infrastructure (stormwater management, signals, electricity)
Precipitation	More extreme rainfall/ snowfall events; higher average annual rainfall	• Roadway flooding/inundation/ erosion/washout • Blocked culverts leading to culvert failure • Road blockage and disruption from snow storms/ice storms/ rainfall • Substrate/slope instability due to increased soil moisture • Travel delays, detours, closures • Bridge scour/closures • Bus transit delays/detours • Overloading of stormwater management infrastructure • More frequent slick-road conditions (increasing risk of vehicular accidents) • Utility disruption (e.g., loss of power) • Fewer active transportation trips • Flooding of bus storage depots	• Obstruction of rail lines and track switches • Rail transit delays/line/tunnel/station inundation, flooding, and closures • Utility disruptions (e.g., loss of power) for electric locomotives and signalization equipment • Reduced rail bed stability during flood events • Rail embankment/crossing erosion during rainfall • Flooding of train storage depots
	More freezing rain events	• More frequent icy-road conditions (in winter) • Modal shift to public transit/ automobile from active transportation • Utility disruption (e.g., loss of power) • Increased salt usage – ecosystem effects; signal box malfunctioning; concrete corrosion	• Utility disruption (e.g., loss of power) • Obstructed rail lines (e.g., fallen branches) • Increased salt usage – ecosystem effects; signal box malfunctioning; rail-crossing corrosion

	Climate factor	Impacts on urban roads, bridges, sidewalks and supporting infrastructure (stormwater management, signals, electricity)	Impacts on urban rail infrastructure, operations and supporting infrastructure (stormwater management, signals, electricity)
Air Temperature	Extreme heat	• Pavement and sidewalk softening/rutting/shoving/ bleeding/flushing • Reduced passenger comfort/ vehicle performance/lifespan of roads and sidewalks • Thermal expansion of bridges • Heat stress for labourers and active transportation users (impossible or unsafe daytime construction) • Traffic signal malfunctions • Higher road/vehicle maintenance costs • Decreased active mode share; modal shift to public transit/ automobile • Increased electricity demand, leading to loss of power	• Rail buckling (speed restrictions, spillage, derailment, scheduling delays, sensor malfunctioning) • Sensor malfunction on rail tracks
	Extreme cold	• Traffic signal malfunctions • Decreased active mode share; modal shift to public transit/ automobile	• Frozen track switches • Rail cracking • Utility disruptions (e.g., power loss, broken water mains causing tunnel flooding) for electric locomotives, signalization equipment, and tunnels
	Increasing and shifting freeze/ thaw cycles	• Pavement shearing and rutting/ pothole formation • Damaged stormwater management infrastructure (cracks and heaving)	• Damage to underground transit lines and tunnels
	Permafrost degradation (Northern)	• Winter road destabilization (e.g., heaving, slumping, embankment failures) • Walking/cycling pathway destabilization • Impacts to stormwater management infrastructure, water mains, underground utilities	• Rail bed/embankment destabilization • Slow orders, reduced train speed

Climate factor		Impacts on urban roads, bridges, sidewalks and supporting infrastructure (stormwater management, signals, electricity)	Impacts on urban rail infrastructure, operations and supporting infrastructure (stormwater management, signals, electricity)
Changing water levels/patterns of lake and sea ice	Ice-jam flooding	• Seasonal flooding of roadways • Utility disruption (e.g., power loss) • Overloading of stormwater management infrastructure • Bridge scour	• Seasonal flooding of railways (water-adjacent rails) • Embankment erosion/washout • Tunnel flooding (below-grade transit systems)
	Rising sea levels (coastal)	• Roadway, sidewalk, and bike path erosion/washout/inundation • Bridge scour	• Railway erosion/inundation/washout • Bridge scour
	Storm surges during extreme weather events	• Storm-surge flooding (inundation of coastal roads, bridges, highways, bike paths, and sidewalks) • Overloading of stormwater management infrastructure	• Storm-surge flooding (inundation of coastal railways) • Embankment erosion/washout • Overloading of stormwater management infrastructure
Wind	Increasing average daily wind speed/ more frequent extreme wind events	• Increased maintenance on tall structures (e.g., power lines and signals) • Malfunction and damage to traffic control signals • Unsafe working conditions due to flying debris • Blocked culverts (e.g., trees and debris) • Closure of/damage to bridges • Roadway, sidewalk, and bike path obstruction caused by debris (e.g., fallen power lines, trees, branches) • Utility and communication disruption due to loss of power • Damage to elevated walkways/ bike paths • Reduced cycling activity during high winds	• Railcar blow-over due to high-speed cross-winds • Utility disruption (e.g., power loss) • Obstruction and increased maintenance due to falling debris (e.g., fallen power lines, trees, branches) • Damage to overhead wires and signalization equipment
Wildfire	More frequent wildfire events	• Inaccessible/congested community access and evacuation points	• No examples found in the literature

6.0 CLIMATE CHANGE ADAPTATION PRACTICES FOR URBAN TRANSPORTATION

Reducing the vulnerability of Canadian urban areas to a changing climate and extreme weather requires effective governance and collaboration within and between governments, transportation agencies, and other municipal sectors. In Canada, federal, provincial and territorial policy frameworks and funding programs can support municipal adaptation efforts, while both public and private transportation agencies are responsible for providing safe and efficient services in the face of more variable weather and climate conditions.

Sharing knowledge about resilient infrastructure and operational practices is also critical. At the municipal level, there are a number of networks for climate adaptation knowledge-sharing, including ICLEI Canada (Local Governments for Sustainability). ICLEI Canada's Building Adaptive and Resilient Communities (BARC) initiative (Box 2) is an interactive web-based tool designed to help local governments identify and adopt climate adaptation strategies. Member municipalities receive one-on-one staff support for using the tool (ICLEI, 2010), and transportation is a key aspect of this program.

BUILDING ADAPTIVE AND RESILIENT COMMUNITIES (BARC) INITIATIVE

BARC operates through a five-step "milestone" process:

- ***Initiate***, in which stakeholders are identified and council resolutions made to address adaptation;
- ***Research***, which involves determination of likely climate changes and risk assessment;
- ***Plan***, in which adaptation objectives, actions, and budgeting are undertaken;
- ***Implementation***, in which actions are put into motion and political support is solidified; and
- ***Monitor/Review***, in which the effectiveness of action is determined, successes are communicated, and revisions are made (ICLEI, 2010).

Adaptation strategies can be placed into the following five categories according to their style of intervention, as per the Intergovernmental Panel on Climate Change (2014).

DISASTER RISK-MANAGEMENT STRATEGIES

These strategies are familiar to municipalities, and have helped many cities successfully reduce the impacts of severe weather events in the past (e.g., Halifax and Hurricane Juan, Slave Lake and wildfire). Examples include changing emergency-management procedures in light of experienced or expected climate-related impacts, and assessing organizational risk through programming and software applications; and others. Calgary and Toronto have recent experience with climate-related disaster response, as both cities experienced severe weather events in the summer of 2013 (Davison and Powers, 2013). Examples include updating flood-, fire-, tsunami-, and hurricane-preparedness plans, and updating floodplain maps.

SPATIAL AND LAND-USE ADAPTATION

This category of strategies includes changing procedures for land-use control and infrastructure design in certain areas to take into consideration past or expected climate impacts. Low-impact roadway designs include standards that aim to reduce total runoff and runoff rates, and natural methods to mitigate runoff (National Cooperative Highway Research Program, 2006), such as mandating the use of permeable materials (Credit Valley Conservation Authority, 2014). These are also relevant for active transportation – for instance, the North American City Transportation Officials (NACTO) guidelines for sidewalk and bikeway design recognize the importance of low-impact considerations for stormwater management. This includes increasing the permeability of construction materials (simultaneously reducing long-term infrastructure maintenance costs) to deal with excessive runoff (NACTO, 2012).

Another example includes zoning amendments or changes to construction requirements based on floodplain mapping, avoiding routing transportation through vulnerable areas, or requiring that infrastructure be elevated above a certain point (AMEC Inc., 2011). Municipalities increasingly recognize that by considering land-use and transportation at the same time, vulnerability to changing environmental conditions may be reduced (Larrivée, 2010).

STRUCTURAL AND PHYSICAL ADAPTATIONS

Perhaps the most tangible adaptation category, these strategies include engineering-based solutions to enhance the physical resiliency of urban transportation networks. To adapt to more frequent and intense rainfall events, practitioners may widen road culverts, shoulders, and ditches to improve stormwater management and sheet flow, and construct deeper gravel wells under roads and rails (Savonis et al., 2008). Flood risks due to sea level rise and storm surge can be mitigated by constructing dykes and employing other flood-management techniques around low-lying urban areas to protect roads and highways (AMEC Inc., 2011; Mills, 2016).

To adapt to changing temperatures, municipalities may employ alternative, more heat- and rut-resistant pavement materials, as well as rut-resistant pavement designs (i.e. thinner surfaces) (Andrey and Mills, 2003; United States Federal Highway Administration, 2015). For example, the Ontario Ministry of Transportation's "SuperPave" system is a materials selection system that uses local weather-station data and pavement-performance data to dictate appropriate heat- and rutting-resistant asphalt mixes for provincial highways and some municipalities in Ontario (Ontario Ministry of Transportation, 2013) (see Chapter 6). The City of Toronto has also installed cooling fans for traffic signals, and intelligent transportation system (ITS) infrastructure, to reduce risks from heat (City of Toronto, 2011).

For transportation infrastructure built on warming permafrost in northern cities, adaptation strategies include mechanical stabilization of embankments and the removal of permafrost before construction; however these methods are extremely costly (Cheng, 2005; United States Arctic Research Commission Task Force, 2003). Snow sheds, air ducts, and thermosyphons can also protect roads and rail lines from warming temperatures (Reimchen et al., 2009). Dawson City has installed light-coloured pavement on the city's main street to increase the reflectivity and reduce the impact of higher temperatures on permafrost (Walsh et al., 2009).

Other structural/physical adaptations include:

- Installing backup power infrastructure for overhead electricity (i.e. for trolleybuses, streetcars) and signals (McLeod and Stevanovic-Briatico, 2014).
- Elevating roadways and rail lines in flood-prone areas (AMEC Inc., 2011; Koatse and Rietveld, 2012).
- Undertaking comprehensive "flood-proofing" of transit corridors, in which culverts are replaced and flood sensors are installed on rail infrastructure (Transportation and the Environment Task Force, 2014).
- Waterproofing circuit breaker houses and other underground facilities that provide power to subways (McLeod and Stevanovic-Briatico, 2014).

- Performing regular maintenance of stormwater management systems, especially culverts, to maintain capacity, and designing drainage systems to direct runoff away from the roadbed (rather than parallel with the roadway), therefore avoiding erosion of the roadbed and exposure of utilities (City of Toronto, 2014).
- Maintaining positive cross-slope to facilitate the flow of water from road surfaces, and increasing culvert/ditch capacities (United States Federal Highway Administration, 2015).
- Sealing and/or elevating where appropriate street-level vents and manholes, protecting underground pump rooms, circuit breaker houses and other underground facilities that provide power to subway systems (McLeod and Stevanovic-Briatico, 2014).
- Elevating portions of vulnerable roads, sidewalks and bicycle paths above projected sea-level or flood lines (Schwartz, 2011).

INSTITUTIONAL ADAPTATION

Institutional adaptation refers to the adoption of policies targeting climate change. This includes changes to transportation agencies' service delivery, and approaches to infrastructure maintenance. For instance, on rail lines experiencing buckling, service or speed reductions might be implemented at least in the short term to ensure safety (Savonis et al., 2008). This category also includes:

- Innovative financing measures available to municipalities for adaptation, such as:
    - "Green" bonds (debt instruments used to raise private capital for projects with specific environmental purposes, including urban transit and active transportation);
    - Local tax rebates or incentives for green roofs and other stormwater management infrastructure and practices, which may produce benefits for transportation in terms of reduced runoff; and,
    - Intergovernmental grants targeted for resilient transportation infrastructure (Harford et al., 2015).
- Organizational practices identified through the PIEVC (Public Infrastructure Engineering Vulnerability Committee) climate change vulnerability assessment protocol. For example, recommendations from a PIEVC assessment of impacts related to higher temperatures and increased precipitation on roads and associated structures in Sudbury included the following:
    - More closely monitoring hydraulic data for culverts, as well as key pavement performance indicators (e.g., freeze-thaw cycles, average and extreme temperatures) annually;
    - Changing pavement mixtures to better withstand heat (i.e. SuperPave);
    - Performing sensitivity analyses on the slope stability of high-risk embankments; and,
    - Improving tree coverage on low-speed roads to reduce the urban heat island effect (Engineers Canada, 2014).
- Organizational planning, financial and risk management practices. One example is the work undertaken by TransLink to integrate climate risk into decision-making processes, which is a responsibility of their Chief Financial Officer (see Case Study 5).
- Intelligent Transportation Systems (ITS). These are becoming more prevalent, and have potential adaptive applications in urban centres. ITS technologies can help municipalities "adaptively manage" traffic flow, infrastructure maintenance practices, and investment patterns through the collection of data on operations, structural integrity of infrastructure, and other variables, including

climate data. Research suggests municipalities can optimize their winter road maintenance operations and save money with the assistance of real-time information (Fu et al., 2009). An example is the use of Roadway Information Systems in some Canadian cities, which provide real-time road condition and usage information for municipalities (Clean Air Partnership, 2012).

- Ice-reduction practices. Research suggests that “anti-icing, pre-wet salting with plowing and sanding all reduce accident occurrence” (Andrey et al., 2013) during icy road conditions. To avoid or resolve environmental issues related to increased salt use for icy roads, municipalities in Ontario have employed alternative, lower-impact melt solutions (i.e. beet juice, cheese brine) (Clean Air Partnership, 2012).

SOCIAL ADAPTATIONS

These adaptations include strategies designed to leverage social networks to increase awareness and response time during extreme events. For instance, many municipalities now use social media to help communicate travel advisories and alerts for road and active transportation infrastructure conditions (e.g., flooding) and public transit service delays during extreme weather events (Mims, 2010; White et al., 2009). Table 2 provides an overview of adaptation practices identified in this chapter.

The section to follow presents five case studies describing specific transportation adaptation approaches in Canadian cities, including discussion of where and how adaptations have been applied, benefits, costs, tradeoffs, and lessons-learned.

Table 2: Examples of adaptation practices for urban transportation (citations appear in Section 6.0).

	Climate hazards and impacts	Adaptations for roads, bridges, and associated infrastructure (including signals, stormwater management)	Adaptations for urban rail infrastructure and operations
Precipitation	Extreme precipitation; flooding; higher annual rainfall volumes	• Updating zoning by-laws to require low-impact construction standards (e.g., permeable pavements) • Expanding stormwater management capacity (e.g., widening culverts, shoulders and ditches); constructing deeper gravel wells underlying road beds to improve sub-drainage • Requiring the elevation/relocation of roadways away from flood lines • Sealing street-level vents and manholes • Protecting underground pump rooms • Installing back-up power sources for traffic signals • Improving drainage and maintenance practices and materials (e.g., porous/permeable materials) • Building dykes or other flood-management infrastructure • Conducting vulnerability assessments, updating emergency preparedness planning and revising floodplain mapping • Monitoring hydraulic data/pavement performance metrics for pavement performance • Increasing inspection frequency for culverts and bridges	• Requiring track elevation above flood-lines • Constructing deeper gravel wells under rail beds to improve permeability and sub-drainage; installing pumping systems for tunnels • Waterproofing street-level vents, circuit breakers, pump houses and other underground facilities that provide power to subways • Conducting vulnerability assessments, updating emergency preparedness planning and revising floodplain maps • Using advisories and updates from transit dispatch centres for urban rail users • "Flood-proofing" transit corridors (e.g., installing flood sensors on locomotives, undertaking culvert replacement/upgrades)
	Greater proportion of freezing rain in winter precipitation	• Improving salt management practices to control snow and ice (e.g., using lower-impact materials, adjusting the timing and mixture of applications and/or snow plowing) • Considering climate risks during infrastructure renewal • Improving real-time monitoring of road conditions	• Installing back-up power for overhead electricity and signals, key maintenance and fleet facilities • Issuing service change advisories in advance of closures/delays (i.e., through social media)

	Climate hazards and impacts	Adaptations for roads, bridges, and associated infrastructure (including signals, stormwater management)	Adaptations for urban rail infrastructure and operations
Temperature	Increased freeze-thaw cycles	• Monitoring of freeze-thaw cycles, traffic levels, and rehabilitation requirements to inform budgetary changes	• No examples found in the literature
	Extreme heat (thermal expansion of bridges, pavement degradation, rail buckling, etc.)	• Using heat-resistant pavement materials • Installing cooling systems for diesel engines • Increasing frequency of bridge maintenance • Installing traffic signal cooling fans/switch heaters and using them during periods of extreme temperature • Increasing the frequency of night-time construction • Using light-coloured pavement to enhance albedo	• Installing cooling systems and track signal switch heaters • Adopting speed restrictions and service reductions to cope with rail buckling • Changing rail distressing temperatures to reduce likelihood of rail buckling • Increasing the frequency of night-time construction
	Extreme cold (electrical malfunctioning, cracking of infrastructure, etc.)	• Implementing real-time monitoring of road conditions (i.e., RWIS)	• Heating for underground tunnel infrastructure (e.g., to prevent water main breaks)
	Permafrost thaw/ degradation (ground destabilization, embankment failure, etc.)	• Installing crushed rock cooling system, or insulation/ground refrigeration system • Using light-coloured pavement to enhance albedo • Installing permafrost preservation infrastructure, such as snow sheds, thermosyphons, longitudinal air ducts, side-slope snow clearing, etc. • Relocating vulnerable roadways • Revising winter road weight/ speed limits	• Increasing frequency of rail bridge maintenance/inspection • Using social media networks to issue service advisories/ alerts • Reinforcing embankments • Installing permafrost preservation infrastructure, such as snow sheds, thermosyphons, longitudinal air ducts, etc. • Clearing side-slopes on rail embankments • Revising weight/speed limits for trains passing over weakened areas
Changing water levels / patterns of lake and sea ice	Flooding due to changing patterns of lake and sea ice/ water levels (ice-jam flooding, storm surge, sea level rise, etc.)	• Investing in dykes, sea walls, or flow-management infrastructure • Improving stormwater management capacity (e.g., widening culverts, shoulders, ditches); constructing deeper gravel wells underlying road beds to improve sub-drainage • Using permeable pavements • Using social media networks to issue travel advisories/alerts • Elevating roadways, sidewalks, and bike paths above flood lines (or relocating if a recurring issue)	• Investing in dykes, sea walls or flow-management infrastructure • Using social media networks to issue travel and service advisories/alerts

	Climate hazards and impacts	Adaptations for roads, bridges, and associated infrastructure (including signals, stormwater management)	Adaptations for urban rail infrastructure and operations
Wind	Damage to signals, signs and associated equipment	• Improving structural design of tall infrastructure for more turbulent wind conditions (i.e. bridges, traffic signals) • Installing back-up power sources for traffic, pedestrian, and cycling signals	• Improving structural design of tall infrastructure for more turbulent wind conditions (e.g., bridges, rail signals) • Installing backup power sources for rail signals
Wildfires	Inaccessible/ congested community access points	• Updating emergency response/ contingency planning for evacuation • Developing a business continuity plan for extreme weather events so that critical services can be maintained	• No examples found in the literature
General		• Incorporating climate change considerations into financial risk management practices, asset management, and service delivery • Issuing "green bonds" to raise capital for environmentally-sound infrastructure projects • Implementing local tax rebates/incentives for private landowners to improve stormwater management • Accessing intergovernmental grants targeted for resilient transportation infrastructure • Improving redundancy within and between modes to enhance resiliency • Purchasing transit vehicles (buses and trains) better able to withstand adverse weather conditions • Increasing land-use mix to reduce the number and length of vehicle trips (reducing road wear and tear) • Establishing a schedule for assessing infrastructure usage/condition/ climate interactions • Conducting emergency drills across municipal departments (ensure personnel and equipment are prepared) • Undertaking/updating floodplain mapping to identify vulnerable community infrastructure and assets • Amending/updating zoning by-laws and standards to account for sea level rise, require set-backs, etc.	

CASE STUDY 1

CASE STUDY 1: AN INNOVATIVE TOOL TO ASSESS CLIMATE RISKS AT THE CITY OF TORONTO

Adaptation is critical for large cities' transportation networks, given the social and economic importance of safe and fluid mobility. The City of Toronto anticipates that climate-related risks to its transportation system will significantly increase in coming decades (City of Toronto, 2008). Decisions made today regarding capital investments, program delivery, and relationships with key partners will be important to ensure that the City improves its resilience to climate change.

This reasoning underpinned the City of Toronto's decision to develop a Climate Change Adaptation Strategy. Toronto's City Council provided the necessary political capital, resulting in a report and program entitled "Ahead of the Storm: Preparing Toronto for Climate Change" (City of Toronto, 2008). This was a screening-level, cross-cutting exercise in assessing organizational vulnerability to climate change, including a review of international best-practices and tools. Transportation was a key focus area of a multi-stakeholder working group, featuring participants both internal and external to the City of Toronto. The resulting report recommended the development of a practical tool for assessing vulnerabilities and risks to the city's transportation infrastructure and operations, in the context of both extreme weather events and slow-onset climate change. The City selected a consultant consortium to create a Climate Change Risk Assessment Tool and Process (CCRAT). This software application enables service and infrastructure providers to identify and prioritize key environmental and climate change-related risks, as well as to assess the benefits of various mitigation and adaptation actions.

The City of Toronto's Transportation Services Division (TSD) demonstrated leadership and helped develop and apply the CCRAT pilot. The outputs included an overview document, an assessment process, a software tool, and a user manual. This was a ground breaking exercise for the City. Prior to this undertaking, the City did not know if it was feasible to deploy a risk assessment tool with available resources and knowledge.

In 2011, TSD applied CCRAT to evaluate the vulnerability and resilience of 90 high-priority assets and critical services to seven extreme weather events. Through a series of 15 half-day workshops, 14 risk assessors, looked at 1650 impact scenarios for the time periods 2010-2020 and 2040-2050. The team developed "risk scenarios" (combinations of extreme weather events and impacts) based on identified causes and vulnerabilities. Impacts could be multiple or cascading (i.e., up to "four-order impacts"), for example, economic impacts resulting from transportation delays caused by road or lane closures during extreme weather events. TSD's risk assessors also identified more than 60 existing initiatives that enhance adaptive capacity, as well as 100 short- and long-term adaptation actions. Examples of ongoing initiatives include:

- Adding heating and cooling fans in traffic signal controllers;
- Developing guidelines for the construction of "green" streets;
- Coordinating efforts to enhance the urban canopy to reduce heat-island effects; and,
- Using combination ploughing and salting vehicles to better react to freezing rain conditions (City of Toronto Environment Office, 2011).

The development and application of the CCRAT was an opportunity for the municipality to demonstrate its due diligence to citizens, and build organizational awareness. Another key output was the city's Climate Change Risk Management Policy, which established an institutional foundation for adaptation.

Practitioners involved with the CCRAT consider it a success. The use of both top-down (city-driven) and bottom-up (grassroots) approaches where appropriate was considered particularly beneficial, as was the establishment of a well-defined work program in which roles and responsibilities of all stakeholders were clearly delineated. Each functional group within TSD developed clearly-defined expectations for the services they deliver and the infrastructure they maintain. The appointment of specially-trained risk assessors for each group was viewed as integral to organizational cohesion. Selecting a chief risk assessor as a

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project manager – a team leader experienced with environmental management systems, risk assessment, and a comprehensive understanding of the organizational structure – was also crucial.

A number of lessons were learned:

- Practitioners suggest the CCRAT would have been more effective if interdependencies and "synergistic risks" between the public and private sectors (such as energy, communication, insurance and finance) were identified prior to its undertaking. Engagement and collaboration with these sectors reduces the risk of economic disruption to the community and enables opportunities for more adaptive and resilient infrastructure.

- Another potential shortcoming was that "residual risk" (the degree of risk that remains once an adaptation has been implemented) was not assessed for each proposed adaptation action as part of this phase. Residual-risk analysis and cost-benefit analysis can be useful and important mechanisms to assist municipal managers in prioritizing adaptation actions.

- Practitioners also identified challenges in effectively communicating the severity of climate change to the public. The Royal Academy of Engineering (2011) notes the importance of consulting users of the assets and services regarding potential new service levels in addition to the amount tax payers would agree to pay for a particular level of service. A significant challenge for both industry and politicians is how to best communicate to the public the limits of resilience and the need to modify demand for infrastructure.

Overall, the CCRAT has helped Toronto set clearer organizational goals on the issue of climate adaptation, and allows TSD to manage its assets and services in accordance with City Council's priorities of customer-service excellence and cost reduction in a transparent and fully-accountable manner. Critically, many of the adaptations CCRAT identified do not require major increases in capital or operating budgets. For instance, enhancing inventory databases, adopting environmental management systems, providing training, and improving coordination to reflect "best-management" principles and increase both adaptive capacity and organizational efficiency, involve little or no extra cost for the municipality. This is an example of "low-regret" adaptation. Focus is now shifting to ambitious, long-term actions which require additional investment. The summer of 2014 saw a high level of council support for these actions (such as a new culvert management system, approved for $350,000 to inventory all culverts less than 3m (in width) in the city's road network. In sum, the City of Toronto considers the CCRAT useful for both private and public sectors to assess their vulnerabilities to climate change and develop an adaptation path to resiliency.

Written with input from Nazzareno Capano (Transportation Services Division, City of Toronto) and Vesna Stevanovic-Briatico (Transportation Services Division, City of Toronto).

CASE STUDY 2

CASE STUDY 2: CLIMATE CHANGE ADAPTATION AT THE CITY OF MONCTON

Many Maritime cities have already begun experiencing climate-related impacts. In Moncton, New Brunswick, the frequency of flooding from extreme storm events and changing tidal patterns has increased over the past decade (City of Moncton, 2013). Moncton is located at the nexus of the Petitcodiac River and the Bay of Fundy, a region that experiences one of the largest tidal ranges in the world. Coastal and inland flooding, as well as erosion, pose significant risks to transportation infrastructure. The region is also expected to experience gradual sea-level rise and significant precipitation and temperature increases by mid-century (AMEC Inc., 2011).

From 2010 to 2012, communities in the Greater Moncton Area participated in the Atlantic portion of the Regional Adaptation Collaborative (RAC) program. This cost-sharing initiative with provincial and federal governments was designed to identify climate-change threats, vulnerabilities, and adaptation tools useful in addressing erosion, coastal and inland flooding, infrastructure design, and groundwater management. Transportation was an area of focus within this initiative, largely in recognition of historical problems in the region with transportation and sanitary-sewer infrastructure located below flood thresholds.

Specific recommendations for the City of Moncton emerging from the RAC exercise, were to:

- Develop new arterial roads to avoid low-lying areas and the floodplain of the Petitcodiac and its tributaries;
- Elevate new roadway and bridge infrastructure to ensure access to essential services during extreme weather events;
- Flood-proofing major roads at vulnerable elevations to minimize flood-related damage and ensure rapid system recovery; and,
- Mandate higher flood elevations in future transportation planning decisions (AMEC Inc., 2011). A minimum elevation of 10.5 metres was proposed to reflect the 100-year flood event line the region is likely to experience by 2100, informed by floodplain mapping.

In response, the City of Moncton produced a corporate Climate Change Adaptation and Flood Management Strategy in 2013, and has since introduced a series of policy changes. For example, the City:

- Changed its zoning bylaw to set minimum floor elevations for habitable space at 10.5 m;
- Will elevate new roadways and bridges, where feasible to do so, above the 10.5-m threshold;
- Developed extensive evacuation plans for existing vulnerable roadways in the event of a major storm surge event; and
- Offers a $500 rebate on the installation of an approved backwater valve, as part of an incentive program for local property owners.

Building on these initiatives, Moncton has developed a Regional Sustainable Transportation Master Plan that will help the City assess the vulnerability of all transportation modes in the network using detailed mobility and flood scenarios. The results will help the City prioritize network improvements and street upgrades. The models and flood scenarios allow for provincial officials to identify their interests (provincial infrastructure in the community) likely to be affected under future conditions. Recommendations will be made to council regarding infrastructure requiring upgrading or abandonment, with budgetary requirements made clear.

The effectiveness and timeliness of Moncton's adaptation planning, policies, and practices can be attributed to the support for adaptation from all levels of government. At the municipal level, the Climate Change Action Committee, composed of staff from most City departments, reports to council annually. Practitioners agree that it has done an excellent job of creating accountability on climate adaptation both within and between departments. Developing an integrated approach both within the municipality and with provincial and federal partners has proven invaluable.

Written with input from Elaine Aucoin (Environmental Management and Planning, City of Moncton) and Stephane Thibodeau (Engineering and Environmental Services, City of Moncton).

CASE STUDY 3

CASE STUDY 3: TRANSPORTATION ADAPTATIONS TO CLIMATE CHANGE IN THE CITY OF WHITEHORSE, YUKON

Whitehorse is a significant regional transportation hub, with rail, marine, and air transportation all playing important roles in the city's history. The city relies heavily on the Alaska Highway for external connectivity and on the automobile for urban mobility, although public transit services are also available. The city's climate is relatively warm (compared to other northern communities) and semi-arid due to its location within the range shadow of coastal mountains. In recent years, however, Whitehorse has experienced highly variable precipitation, including many winters with above-average snowfall. Climate changes of this nature pose a number of risks to the city's transportation network. Projected increases in wildfires and the intensity, duration, and frequency of storm events (and associated flood and drainage concerns) create indirect risks to road traffic. Local officials identify highway obstructions and washouts during extreme weather events as a key concern, as they can prevent the delivery of food and other essential goods. Other impacts to urban transportation include increased frequency of freeze-thaw cycles; strain on the road-maintenance budget in high-snowfall winters; and, greater stress on culverts due to increased summer and winter precipitation.

To address these concerns, the City of Whitehorse participated in the development of the community-based Whitehorse Climate Change Adaptation Plan in 2011 (Hennessey and Streicker, 2011). This project involved a diversity of community stakeholders. While not legally-binding (the document is policy-relevant, but not policy-determinate) the plan has helped to "mainstream" the changing climate into municipal decision-making processes, meaning that climate data and projections are incorporated into investment and planning decisions. The plan's broad goals include enhancing transit's mode share, intensifying development, and increasing the region's share of agricultural production through food security planning (including the production of more food in nearby greenhouses, reducing reliance on imports). Suggested adaptations for urban transportation include:

- Establishing annual budgets aimed at managing climate change concerns, including planning for increased snow removal requirements;
- Expanding the use of road monitoring stations;
- Conducting exploratory feasibility studies of automatic road de-icing techniques; and
- Increasing the porosity of road surfaces to improve re-charge following precipitation.

These adaptations include both "low-regret" and "no-regret" measures. For example, when road improvements are required due to the lifecycle or condition of the infrastructure, the Plan suggests that the City upgrade water and sewer systems to accommodate larger stormwater flows. This requires only a modest marginal-cost increase to the budget for the project. At the same time, this strategy means only those roads nearing the end of their lifespan or in very poor repair will be adapted in the near-term, given that the cost of replacing usable infrastructure with larger drainage capacity is prohibitive. For practical purposes, this is an adaptation approach that must be implemented in a piecemeal manner. A "no-regret" adaptation on the operational side involves proactive early-spring inspections of drainage to identify frozen storm drains and reduce flood risks.

Flooding is also a concern on Whitehorse's residential roadways, with some older subdivisions having experienced localized issues as a result of outdated drainage systems. As a result, stormwater infrastructure in new subdivisions is now designed with higher volume thresholds. Additionally, Whitehorse is using transportation redundancy as an adaptation solution on a small scale; subdivisions are no longer permitted to be built with only one road-access point in case of washouts, flooding, and wildfire hazards.

Written with input from John Streicker (City ofWhitehorse) and Jocelyn Beatty (University of Waterloo).

CASE STUDY 4

CASE STUDY 4: ROAD SAFETY AND CLIMATE CHANGE IN PRINCE GEORGE

Prince George, located in the interior of British Columbia, is home to approximately 76,000 people. The city has a wide range of transportation modes, including rail, inland marine, and urban transit. While the city's transportation network faces a number of risks from climate change, warmer winter temperatures are likely to have the greatest impact, primarily due to increased freeze-thaw cycles, rain-on-snow events, and freezing rain. Flooding on the Nechako (due to ice jams) and Fraser (due to freshet) rivers is another key concern. Prince George developed a number of transportation-specific climate change adaptations in 2012, in recognition of the risks flooding poses to roads, active transportation infrastructure, and rail facilities. This was done in the context of a larger community adaptation plan.

A steering committee composed of local practitioners and experts from academia (to balance local needs with best practices) identified 23 forward-looking adaptation actions, in the areas of infrastructure, operations, emergency response and safety, and financing.

Through the process, the city also identified a number of ongoing initiatives that fall under the umbrella of climate adaptation. These included snow and ice control, salt management, road elevation, and dyke construction. For instance, following an ice-jam flood of an industrial area in 2008, the city elevated a roadway to a 1-in-200 year flood level, and constructed a 3.3 km dyke to protect local rail infrastructure (Picketts, 2012). The committee's final recommendations for immediate action included changes to winter road maintenance, improvements to road safety, and climate-sensitive design considerations (Picketts, 2012). The city listed transportation as its highest-priority area in the city for continued action (Picketts et al., 2013).

Prince George is now focused on implementing action items in key areas, with promising early returns. The city has begun to aggregate climate data and procedural information to better inform road maintenance decision-making, including data on vehicle and climate interactions. With respect to road design and stormwater management, a number of new permeable materials have been proposed for testing. Next steps include:

- Continuing partnerships with universities and the provincial government;
- Encouraging climate assessments for all new infrastructure projects;
- Incorporating climate data into decision-making criteria;
- Maintaining dialogue with the transportation industry; and,
- Encouraging the exchange of information among city staff members (Picketts, 2012).

The transportation component was considered successful by practitioners, given the high degree of public interest in mobility issues; the practical nature of the solutions that were explored; and the clear potential for significant cost savings. However, one drawback to the project's focus on winter road safety was relatively little attention was paid to active and public modes of transportation (Picketts, 2014). Feedback from practitioners involved in the implementation process highlighted four key areas for attention, with specific relevance to adaptation in mid-sized, northern communities:

1. Building and maintaining local knowledge and capacity for decision-making around climate adaptation;
2. "Mainstreaming" or normalizing adaptation into the plans, priorities, and professional practices of local officials;
3. Focusing on tangible projects around which the community can rally and easily identify results; and;
4. Linking adaptation actions to costs and priorities through clear communication to both politicians and members of the public (Picketts, 2014).

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This case study demonstrates how communities can successfully incorporate rigorous climate analysis into vulnerability assessments, shifting discussion from a general recognition of risks to the identification of explicit actions (Picketts, 2013). Achieving greater teamwork and the adoption of common goals within the municipal organization were also considered critical to sustaining the momentum this initiative has generated.[1]

Written with input from Dr. Ian Picketts (University of Northern British Columbia).

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1 An academic journal article summarizing the transportation work in Prince George is in the final stages of review for inclusion in a forthcoming issue of *Regional Environmental Change*.

CASE STUDY 5

CASE STUDY 5: ACCOUNTING FOR CLIMATE CHANGE RISKS AT TRANSLINK

TransLink is metropolitan Vancouver's regional transportation authority, with a system of assets and services that incorporates bus, commuter rail, cycling and walking paths, and roads. This network provides about 1.2 million trips per day.

The organization considers managing climate change risks important to service delivery and infrastructure maintenance/development, particularly given that it builds infrastructure to last 100 years. Projected population growth in the region is expected to compound these risks – Metro Vancouver is expected to grow by one million people over the next 30 years, placing greater demand on the region's transportation system.

TransLink began considering climate change impacts in 2010 and conducted a climate change vulnerability assessment of its assets in 2012 in support of its Asset Management Plan. Through this process, the organization identified the following key climate change risks to its services:

- Sea level rise, that could:
  - Flood assets now within "expanded" floodplains,
  - Reduce clearance under bridges
  - Impair operations of the SeaBus (ferry) terminal.
- Increased precipitation that could cause temporary flooding of TransLink's assets, such as bus loops, tunnels, transit stations and trolley electricity conversion ("rectifier") stations.
- Warmer temperatures, and more frequent and severe heat waves, that could affect passenger health and comfort on parts of the fleet without air-conditioning.

TransLink has also ensured that its Finance department and accountants play a core role in its adaptation efforts. The Chief Financial Officer (CFO) is responsible for seeing that climate change risks are considered in TransLink's decision-making process. TransLink considers this structure effective as it embeds climate change throughout the organization, with links to risk management, strategic sourcing, capital planning and review processes, and reporting.

Written by Kathy Palko, adapted from Chartered Professional Accountants Canada (2015) Adaptation Case Study #2[2]

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2 CPA (2015) Adaptation Case Study #2: TransLink Sector: Transportation. Retrieved from: https://www.cpacanada.ca/en/business-and-accounting-resources/other-general-business-topics/sustainability/publications/translink-climate-change-case-study-2

7.0 INTERDEPENDENCIES WITH OTHER URBAN SECTORS

Urban transportation networks depend on other infrastructure and utilities, (including electricity and telecommunications) to move large volumes of people and goods efficiently. The interdependencies among these systems, the economy, and society are explored in this section.

Electricity is one key interdependency. Growing dependence on the electrical grid for urban mobility (particularly for LRT and commuter rail systems, but also for automobiles and infrastructure) can create multi-sectoral vulnerability when extreme weather events disrupt the supply and distribution of electrical power. Ensuring traffic signals remain operational during and immediately following extreme weather is another concern.

Intelligent Transportation Systems (ITS) applications, used heavily for public transit and traffic management, also depend upon telecommunications infrastructure that can be affected by extreme weather (Revi et al., 2014). Without adequate coordination, interactions between water mains and underground public transit systems can potentially disrupt both sectors. This is the case under both slow-onset climate change and during extreme weather events. For example, pipes can freeze and rupture during freeze-thaw cycles or extreme cold conditions damaging the water distribution infrastructure and disrupting the underground public transit systems. This has been experienced by the Toronto Transit Commission's subway system in recent winters (McLeod and Stevanovic-Briatico, 2014).

The ability of transportation agencies to reduce damages associated with severe weather is therefore affected by how other municipal divisions and utility providers (e.g., telecommunications and energy supply) integrate climate change considerations into their own planning and service delivery. If one sector is at risk, so are many others. For example, if floods or heat waves disrupt the energy supply, all other services can be affected, causing failures to cascade. If road traffic is not flowing freely, the efficiency of an entire city may be reduced.

In locations where infrastructure is at risk of being compromised or failing as a result of climate impacts, Business Continuity Planning becomes important. This refers to planning that ensures services are not compromised by extreme or unforeseen events. Planning in advance how the workforce can be more effectively deployed in emergency and post-emergency situations is critical, particularly since climate change is anticipated to bring more frequent extreme weather events. Practitioners interviewed for this chapter indicated that interdepartmental coordination can be improved if decision-makers work closely with city engineers and technical advisory committees on climate adaptation strategies for transportation infrastructure and operations.

For example, the City of Toronto's Transportation Services Division (TSD) has collaborated with a number of other municipal sectors and agencies on climate change adaptation and preparedness activities. Table 3 identifies these ongoing initiatives. Interdependencies between sectors identified by TSD include power outages caused by extreme heat, wind, and freezing rain, as well as impacts on the traffic control system and communication infrastructure. Transportation practitioners suggest that a climate change risk assessment of the electricity sector would help to identify areas of the City most vulnerable under various climate scenarios. This information would inform the implementation and spatial deployment of adaptation measures, such as uninterruptable power supply technology to traffic control signals.

Disruptions to road and transit networks will also affect the ability of staff to travel to work, resulting in personnel shortages and, ultimately, impacts to municipal service delivery. Business continuity planning for extreme weather events can address these issues, by planning for alternative work arrangements, periodic training, trial-testing of emergency management procedures, and maintaining an emergency contact information database for staff (held by a supervisor and accessible at all times).

Table 3: Example of internal and external collaboration in adaptive planning for climate change and urban transportation at the City of Toronto.

Partnership	Coordinated action
Toronto and Region Conservation Authority (TRCA)	Flood Warning System: • TRCA provides flood warnings to TSD's Road Emergency Services Communications Unit (RESCU) for the Don Valley Parkway expressway and Bayview Extension. This real time monitoring, using cameras and communication protocol, helps TSD implement road closures and manage traffic. • TSD meets regularly with TRCA staff to review flood-response protocols and real time response to events, and to establish a more comprehensive response to flooding. Environmental assessment: • TRCA is undertaking an in-house environmental assessment and collaborating with TSD to identify risks and possible mitigation actions to enhance current control measures for flooding along the Don Valley parkway and Bayview Avenue (Don Valley Corridor).
Consultation with City of Toronto Energy and Environment Office; Toronto Transit Commission and Engineering and Construction Services; and other agencies, boards, commissions, and divisions	Climate Change Risk Assessment (CCRA) (See Case study 1): • This tool identifies and assesses risks due to climate change, including the effect of climate change on the delivery of services, management of infrastructure and protection of the natural environment. • The CCRA enables service and infrastructure providers to identify and prioritize key climate change impacts and risks, and assess benefits of various risk mitigation or adaptive actions.
Toronto Transit Commission (TTC)	Examples of some collaborative initiatives include: a) TSD developed a harmonized process for implementing concrete bus bays and stops; asphalt pavement surfaces at bus stops generally exhibit severe distortion (e.g., rutting) due to bus loads and extreme heat conditions; b) Installation of concrete bus pads on the roadway as part of resurfacing projects. These are typically applied only in situations where the existing asphalt surface is shoving or rutting moderately (>25mm) or more; c) TSD identified and prioritized 100 traffic signal locations for the installation of uninterruptable power supply (UPS) devices, including signals at railroads, major intersections and expressway ramp terminals. A pilot program was initiated to outfit 12 high-priority locations. d) A second-phase review is underway to identify UPS needs for critical intersections located on emergency routes; and e) TSD established contracted services for mobile diesel and gas trucks; third party fuel cards are available when supply of fuel is affected during extreme weather events.

Outside of municipal departments, there is also a need to fully engage urban civil society and provide information about the importance of adaptation to the public (Larrivée, 2010). Practitioners suggest that public engagement on adaptation tends to yield conversations about climate mitigation (the reduction of carbon emissions). The task of municipal agencies is to emphasize the importance of both policies in tandem to maximize social value from infrastructure investments. Public engagement is also necessary to prepare society to function – access jobs, health care and other activities – when transportation systems or infrastructure systems are performing at lower levels.

8.0 GAPS AND BARRIERS

Practitioners suggest that without buy-in from the executive to operational levels on the severity of climate change risks, adaptation planning efforts often fail to be fully implemented. In some instances, practitioners have found success by communicating the importance of avoiding more significant costs in future through proactive investments. Cost-benefit analysis can also support adaptation decisions, by helping practitioners prioritize infrastructure-upgrade investments and demonstrate the value of actions taken to reduce future vulnerability (Feltmate and Thistlethwaite, 2012). As more cities achieve and communicate long-term cost savings and economic competitiveness from adaptation measures, barriers to the widespread introduction of these measures are reduced.

Coordinating actions among multiple levels of government, agencies, and sectors is another challenge to adaptive decision-making. For example, municipal governments facing flood risks must coordinate emergency-response with other orders of government, in addition to dealing with the challenges of flood prevention and physical protection (Chiwizer and Tarlock, 2013).

9.0 CONCLUSION

This chapter has demonstrated many ways in which urban transportation networks are vulnerable to climate change and extreme weather, and has identified efforts that Canadian cities are making to manage these risks. While municipalities have historically taken adaptive action in the wake of catastrophes, the case studies identified in this chapter suggest that increasingly, municipalities and their partners are working to proactively adapt both infrastructure and operations in advance of climate impacts. Case studies in the chapter provide examples of Canadian urban regions engaging in vulnerability assessments, structural and physical improvements, and organizational change to improve their resiliency to a rapidly changing transportation environment. The literature identifies additional adaptation approaches that may be applied by transportation professionals in Canada, as appropriate. It is clear that solutions will involve an appropriate mix of proactive and reactive adaptations.

This chapter has also highlighted the importance of redundancy (of both routes and modes) to enhance resiliency, as well as the importance of "low-regret" adaptation strategies in building support for adaptation efforts within governments and communities. The high up-front costs of many adaptation strategies (particularly structural solutions) may be a deterrent, and the complex fiscal and operational environments of modern cities pose obstacles to adaptation. Therefore, it is increasingly important for transportation practitioners to work in collaboration with other municipal sectors towards common adaptation goals. With strong cooperative efforts, Canada's multimodal urban transportation networks can more successfully meet the challenges of a changing climate.

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