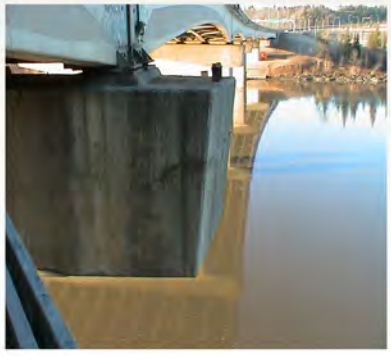

Adapting to Climate Change

Canada's First National Engineering Vulnerability Assessment

of

Public Infrastructure

April 2008

Appendix B-4
City of Greater Sudbury, Ontario

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THE CITY OF GREATER SUDBURY
INFRASTRUCTURE SERVICES DEPARTMENT

FINAL REPORT
March 25, 2008

FIRST NATIONAL ENGINEERING VULNERABILITY ASSESSMENT REPORT ROADS & ASSOCIATED INFRASTRUCTURE

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FIRST NATIONAL ENGINEERING
VULNERABILITY ASSESSMENT REPORT
ROADS & ASSOCIATED INFRASTRUCTURE

FINAL REPORT

Prepared For:

The City Of Greater Sudbury
Infrastructure Services Department

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DENNIS CONSULTANTS
CIVIL ENGINEERS
a division of R.V. Anderson Associates Limited
436 Westmount Avenue Unit 6
Sudbury Ontario Canada P3A 5Z8
Tel 705 560 5555 Fax 705 560 5822
Web www.rvanderson.com

RVA 071522

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FIRST NATIONAL ENGINEERING VULNERABILITY ASSESSMENT REPORT ROADS & ASSOCIATED INFRASTRUCTURE

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APPENDICES

Appendix A1-1 –PIEVC Protocol
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Appendix A3-1 – Vulnerability Assessment Matrix Results (Step 3)

1.0 INTRODUCTION TO PIEVC PROTOCOL

Engineers have relied upon historical design standards based on historical data to design long-lasting, safe and reliable infrastructure. Climatic conditions are now changing these stationary datasets and must now be considered by the design professional. Projections lack the precision and reliability of historical data, but the application of historical data without consideration of climate and other changes that affect design parameters lacks validity. This creates major challenges to existing design practices.

This project was undertaken with support from the Climate Change Impacts and Adaptation Program, Natural Resources Canada (NRCan and Engineers Canada). To meet the climate change challenge, Engineers Canada and its partners have established the Public Infrastructure Engineering Vulnerability Committee (PIEVC) involving all three levels of government and non-governmental organizations.

PIEVC is a major Canadian initiative systematically examining the broad implications, from an engineering perspective, of infrastructure vulnerability to climate change. Amendments to existing codes, standards and practices for the design, operation and maintenance of infrastructure components likely will result once evaluation of the vulnerability of Canada's infrastructure to climate-change impacts is completed.

The PIEVC Engineering Protocol for Climate Change Infrastructure Assessment (Appendix A1-1) is a step-by-step process to assess the impact of a changing climate on the performance of infrastructure. The process has five major steps, with subordinate tasks as outlined in Table 1.

Initial "scoping" studies have been completed to examine the current state of each infrastructure, availability of climate data and indicators of adaptive capacity. The studies resulted in the development of an Engineering Protocol that has been evaluated through a pilot project to assess the water supply for Portage la Prairie.

To assess the application of the Protocol to predict climate change vulnerabilities four categories of Public Infrastructure were selected, namely: Buildings; Roads and Associated Structures; Stormwater and Wastewater Systems; and Water Resources.

This report summarizes the results obtained from the application of the climate change protocol process and vulnerability to road-related infrastructure in the City of Greater Sudbury to climate change.

Table 1: PIEVC Protocol

Primary Function	Sub-Steps
Step 1: Project Definition	1. Identify the infrastructure. 2. Identify climate factors of interest. 3. Identify the timeframe. 4. Identify the geography. 5. Identify jurisdictional considerations. 6. Perform a site visit. 7. Assess data sufficiency.
Step 2: Data Gathering and Sufficiency	8. State infrastructure components. 9. State climate baseline. 10. State the climate change assumptions. 11. State the time frame. 12. State the geography. 13. State specific jurisdictional considerations. 14. State other potential changes that affect the infrastructure. 15. Assess data sufficiency.
Step 3: Vulnerability Assessment	16. Consult with the owners and operations personnel. (The Workshop) 17. Prioritize several of climate-infrastructure interactions (relationships). 18. Use a matrix to record and compare initial assessments (using EXCEL, QUATTRO, other spreadsheet software). 19. Populate the columns of the matrix. 20. Populate the header row of the matrix. 21. Use the matrix (that is, add probability and severity scale factors, multiply to get the Priority of the relationships, which are combinations of infrastructure subcomponents and performance response). 22. Evaluate potential cumulative effects. 23. Sort prioritized climate effects. 24. Identify data sufficiency, and return to Step 2 if data can be obtained with more effort or add a recommendation for data collection or research under Step 5 if data cannot be obtained.
Step 4: Indicator Analyses	25. Calculate the existing load (using information that should have been collected in Steps 1 and 2.) 26. Calculate climate change loads. 27. Calculate other climate change loads. 28. Calculate total loads. 29. Calculate the existing capacity. 30. Calculate the maturing change in existing capacity. 31. Calculate additional capacity. 32. Calculate total capacity. 33. Calculate the vulnerability ratio. 34. Calculate adaptive capacity ratio. 35. Calculate capacity deficit. 36. Assess data sufficiency, and if there is insufficient data, identify a process to get that data.
Step 5: Recommendations	37. Identify limitations of the assessment arising from assumptions, availability of information, the use of generic or samples to represent populations, uncertainty and related concepts, and other limitations that may exist. 38. Prepare recommendations including infrastructure components requiring remedial action, management action, nor further action or additional study.

It should be noted that several of the items (sub-steps) are sequential, that is, satisfactory completion of an item may require information from a previous step or item (sub-step).

2.0 STEP 1 - PROJECT DEFINITION

2.1. City of Greater Sudbury

The City of Greater Sudbury is the largest city in Northern Ontario and the 24th largest metropolitan area in Canada. It is approximately 340 km NW of Toronto and 425 km west of Ottawa. Greater Sudbury was created in 2001 by amalgamating the cities, towns within the former Regional Municipality of Sudbury and the annexation of several unincorporated townships.

Figure 1: Study Area/Project Area - City of Greater Sudbury

Sudbury, with an area of 3627 kms, lies on the Canadian (Precambrian) Shield and has 330 lakes within its boundaries; more lakes than any other Municipality in Canada. Among the most notable is Lake Wanapitei, the largest lake in the world completely contained within the boundaries of a single city, and Lake Ramsey, just a few kilometres south of downtown Sudbury, which held the same record before the municipal amalgamation in 2001.

In the 2006 census, the City's population was set at 157 857 a decline from a peak in 1996 of 165 336. Recently however, the City has been experiencing an economic boom based primarily on a renewed demand for world ore together with the sale of the City's major employers, Falconbridge to Swiss company Xstrata and INCO to Brazilian company – Companhia Vale Do Rio Doce (Vale Inco Limited).

From a humble beginning as a mining camp developed as a result of the construction of the Canadian Pacific Railway in 1883. Blasting and excavation for the construction of the railway revealed high concentrations of nickel-copper ore at the edge of a large geological structure known as the Sudbury Basin, which is widely believed to be the remnants of a 1.85-billion year old meteorite impact crater. As the demand for world ore increased, the population of the community grew rapidly. Sudbury became a town in 1893 and a city in 1930. While mining remains a major influence on the local economy, Sudbury has evolved into a major centre of financial and business services, health care and research, education and government. The City of Greater Sudbury also functions as the service hub for North-Eastern Ontario. Presently,

Sudbury has fully diversified economically and has become the “East-West Gateway” for Northern Ontario.

Historically the City of Sudbury's economic growth has been hindered at times by taxation issues pertaining to natural resource companies. Sudbury has limited ability to levy municipal taxes directly on Xstrata and Vale Inco, thereby resulting in less municipal tax revenue. As a result, fully 75 percent of the City of Greater Sudbury's tax base comes from residential property taxes. This creates unique challenges to maintaining the City’s infrastructure, compared to most cities where other industries are the major employers.

Sourcing Municipal funds primarily from property taxes is not the only challenge when it comes to operating the City. As with many Ontario Municipalities, amalgamation and service downloading has had its effects on the ability for the City of Greater Sudbury to effectively maintain services and infrastructure. In addition, several other conditions, such as economic growth, age, and weather conditions, have conspired to place assets within the City’s portfolio in an almost dire condition. Nowhere is this more apparent than the community’s road infrastructure.

2.2. Timeframe

The lifecycle of the roads, streets and related infrastructure components in the City of Greater Sudbury is generally considered to be around 30 years. At the end of the lifecycle, full reconstruction or replacement is required depending on the type of road and its classification (see Figure 2 for a typical improvement strategy for a road segment). The Municipality, however, is required to implement interim rehabilitation strategies for the infrastructure to reach its full-expected lifecycle. Not maintaining the infrastructure during its expected lifespan will render the components beyond regular rehabilitation and below a manageable condition rating, which may force a Municipality into immediate reconstruction efforts.

2.3. Infrastructure of Interest

The City of Greater Sudbury is the only census division in Northern Ontario that maintains a system of numbered municipal roads similar to the county road system in the southern part of the province. In addition, the roads in the City of Greater Sudbury are classified based on function. The infrastructures of interest were considered to consist of those listed in Table 2, and

were considered to apply to arterial, collector as well as urban and rural local roads. Current road classifications are highlighted in Table 3.

Table 2: Infrastructure of Interest

Surface - Gravel	Bikepaths
Surface - Surface Treatment (LCB)	Embankments/Cuts
Surface - Asphalt	Bridge/Structures
Curb	Municipal Signage
Sidewalk	Road Sub-Base
Traffic Signals	Storm Sewer Systems
Street Lighting	Distribution Systems
Utility/Poles	Collection Systems
Boulevards and Shoulders	Underground Utilities
Ditches	Administration/Personnel
Interlock Pavers	Maintenance (Markings, Crack Sealing)
Catch Basins	Winter Maintenance
Culverts	Record Keeping
Maintenance Holes	

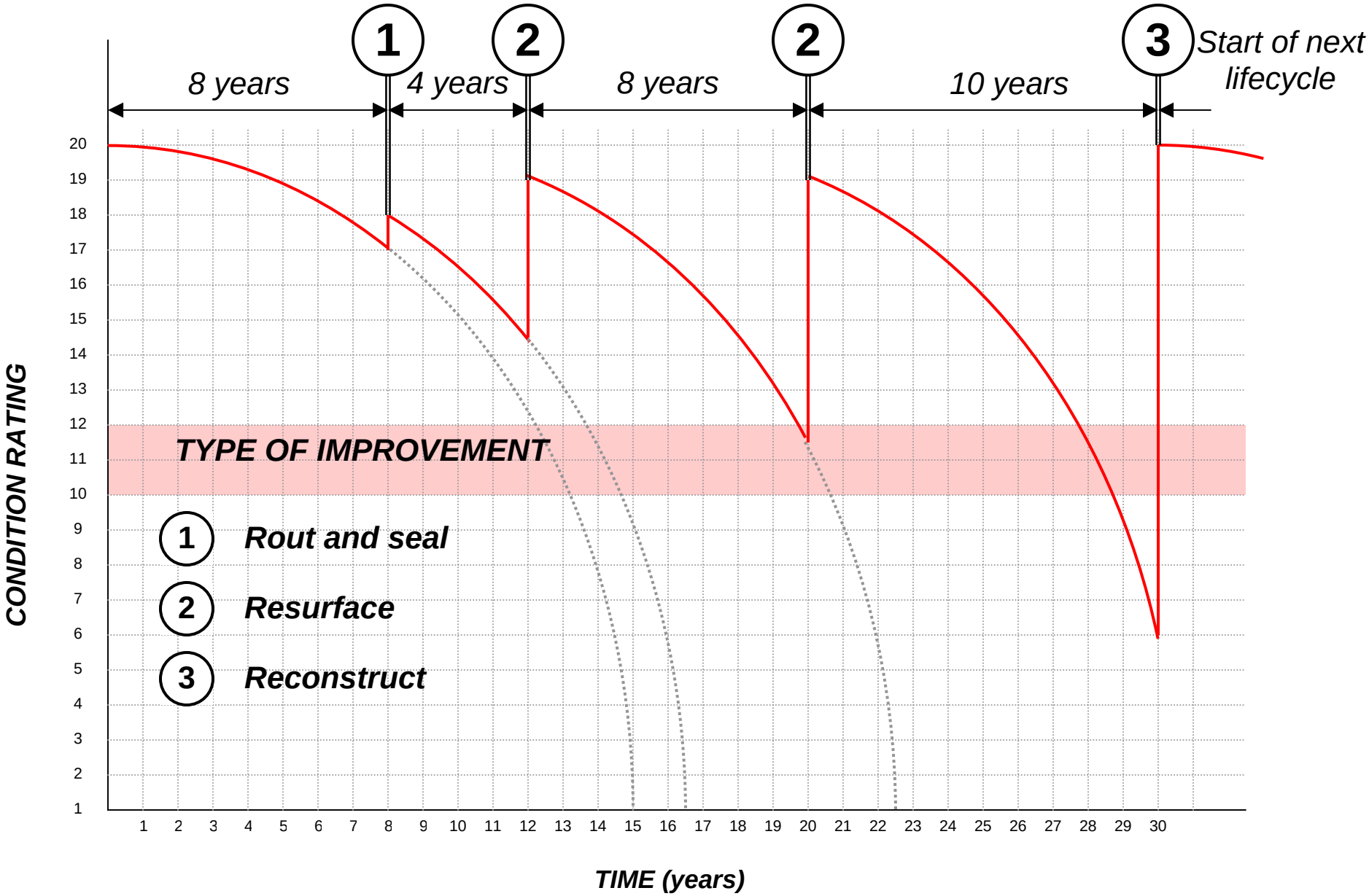

Figure 2: Typical Life Cycle Profile of Road Assets

Class of Road	Jurisdiction	Function	Access	Daily Traffic Volume	Design Speed	Minimum Intersection Spacing (m)	Other Regulation
Primary Arterial (Major Highway)	Province or City	• Connecting City with other major centers outside the City and/or inter-connecting settlements. • Long distance person or goods movement travel through the City between major activity areas within the City. Traffic movement primary consideration.	• Intersections with other arterial roads and with collector roads. • Access form adjacent property strictly regulated and kept to a minimum (rigid access control).	10,000 – 30,000	60-100 km/h	400 m	• No on-street parking. • Buffers between the roadway and adjacent urban and rural areas.
Secondary Arterial	Province or City	• Connecting two or more settlements or major activity centers within the City. • Connecting between two primary arterial roads; or • Connecting a settlement or activity center with a primary arterial road. • Trip origin and/or destination along it, an intersecting tertiary arterial intersecting collector or a local street intersecting with the collector. Traffic movement major consideration.	• Intersections with other roads. • Access from adjacent property strictly regulated and kept to a minimum.	5,000 – 20,000	50-70 km/h	200 m	• No on-street parking. • Buffers between roadway and adjacent uses.
Tertiary Arterial	City	• Connecting small settlements; or • Connecting settlement to primary or secondary arterial leading to a recreational area. • Trip origin and/or destination along it, along an intersecting collector or along a local street intersecting with the collector. Traffic movement major consideration.	• Intersections with other roads. • Access from adjacent property strictly regulated and kept to a minimum.	5,000 – 20,000	50-70 km/h	200 m	• No on-street parking. • Buffers between roadway and adjacent uses.
Collector	City	• Connecting neighbourhoods; or • Connecting a neighbourhood with an arterial road. • Trip origin and/or destination along it or an intersecting local street. Traffic movement and land access of equal importance.	• Intersections with other roads. • Regulated access from adjacent property.	1,000 – 12,000	50-80 km/h	60 m	• On-street parking may be permitted. • Greater setbacks from roadway of adjacent uses.
Local	City	• Connecting properties within a neighbourhood. • Trip origin and/or destination along its right-of-way. • Traffic movement secondary consideration, land access primary function.	• Intersections with collectors or other local roads. • Access form adjacent property permitted.	<1,000	30-50 km/h	60 m	• On-street parking generally permitted except in un-usual circumstances. • Goods movement restricted except for that having origin or destination along road.

Table 3: Road Classifications - City of Greater Sudbury

Road design and construction has challenged the local civil engineering community because of the diversity in soils conditions in which a road component is constructed. New road installations are placed on foundation conditions that can change from Precambrian Shield rock to swamp, within a few meters.

The City of Greater Sudbury devotes a good deal of its annual $489 million annual budget (2007) to operating and maintenance costs of the City's approximately 3500 km of roads. During the past several years, capital spending has not kept pace with maintenance requirements resulting in higher repair costs. Only recently has the City of Greater Sudbury increased its road budgets in order to mitigate the years of neglect.

There are several factors that contribute to these costs, such as:

- Climate, particularly freeze/thaw cycles.
- The amount of capital funding available for roads.
- Current age of the infrastructure components.
- The volume and type of traffic utilizing municipal roads.
- Approved Budget and Service Levels.
- Municipal definitions of maintenance and capital reconstruction.
- Current/past construction and design standards.

NOTE: Operating Costs are considered to be physical maintenance on the infrastructure such as frost heave/base/utility cut repair, cold mix patch, hot mix patching, shoulder and surface maintenance, surface sweeping and flushing and surface maintenance which includes crack sealing, spray patching and slurry.

Surface treatment, hot mix overlay and hot mix patching equal to or greater than 150 metres long are considered **Capital Costs.**

The following Table 4 is a breakdown of operating costs on paved and unpaved segments of road infrastructure.

Table 4: Road Operating Costs

	2003	2004	2005	2006
PAVED: Operating costs (millions)	$4.4	$5.8	$7.0	$6.8
PAVED: # Lane Kilometres	2887	2901	2974	2974
UNPAVED: Operating costs (millions)	$2.3	$1.9	$2.1	$2.0
UNPAVED: # Lane Kilometres	635	635	598	598

Source – Municipal Performance Measurement Program

In addition to standard operating costs, operating costs for **winter control maintenance** is the most significant cost contributor of the road infrastructure and has steadily increased over the years. Winter control maintenance can be influenced by several factors, including the following:

- The number of severe winter storms – amount of snowfall and length of storms.
- The extent of the road network located in urban areas.
- The impact of snowfall temperature variances on road salt effectiveness.
- Public expectations (e.g. for bare pavement).
- The amount of snowfall removed from the streets.
- The age and type of equipment used.
- The Municipality's policy (service threshold) for responding to a winter storm.
- The Municipality's service standards for road conditions after a storm.
- Timing of snowfall with respect to premium hourly pay.

NOTE: Winter maintenance can be considered costs of maintaining the usability of the infrastructure during a climatic event. This type of maintenance can be defined as plowing, salting, sanding, snow removal, winter drainage etc. The City of Greater Sudbury maintains a bare pavement standard for arterial and collector roads despite above average Northern Ontario snowfalls.

The following Table 5 is a breakdown of winter maintenance costs on paved and unpaved segments of road infrastructure.

Table 5: Winter Maintenance Costs

	2003	2004	2005	2006
Winter Maintenance costs (millions)	$10.9	$10.8	$9.7	$12.9
# Lane Kilometres	3522	3536	3572	3572

Source – Municipal Performance Measurement Program

Winter maintenance costs have been less than consistent over the past decade, which is directly related to climate variability (shown in the costs deviation between 2005 and 2006). This makes it difficult for the City of Greater Sudbury to consistently forecast funding for this infrastructure expense segment.

2.4. Climate Factors of Interest

Weather in Northern Ontario can be particularly challenging on a City's road infrastructure. The fact that roads and its components are exposed to the elements and constant public use make this portion of the City of Greater Sudbury asset portfolio particularly challenging to maintain. Despite being one of the sunniest communities in Ontario, the Sudbury area has a frost penetration of over 1.80 metres and can reach up to 3.00 metres deep depending on the freeze-thaw cycles. Daily temperatures in the winter months can drop as low as -35°C and summer months will run in the upper 30's. Add heavy traffic loads, and the life cycle of a new road component can be severely affected.

The following Table 6 depicts the amount of weather events that have impacted the infrastructure over the past few years. These weather related events can be defined as significant amounts of snowfall, wind-blown snow, sleet, freezing rain, frost and black ice. Note the relationship between Table 5 (above) and Table 6.

Table 6: Winter Events

	2003	2004	2005	2006
Number of Winter Events	64	70	55	56
Snowfall Accumulation (cm)	256	288	176	286

Source – Municipal Performance Measurement Program

A list of weather variables developed for the review is depicted in Table 7.

Table 7: Climate Events and Change Factors Variables

Climate Elements	Potential Change Factor
Temperature	o Rate of change
	o Mean values
	o Extremes • High summer • Low winter
Precipitation as Rain	o Frequency (One-Day, Short Duration Less than 24 hours, Multi-Day)
	o Total annual/seasonal precipitation and rain2
	o Intensity of rain events (One-Day, Short Duration Less than 24 hours)
	o Proportion of annual and seasonal precipitation as rainfall
	o Drought conditions
Precipitation as Snow	o Frequency
	o Total annual/seasonal precipitation and snow
	o Magnitude of snow events
	o Frequency and intensity of rapid snow melt events
	o Rain on snow events
Wind Speed	o Mean values (one hour mean winds) • Monthly • Seasonal • Annual
	o Extremes/gusts
	o Thunderstorm winds
Ice	o River or lake ice build up
Hail	o Frequency of events
	o Magnitude of events
Frost	o Freeze thaw cycles
	o Change in frost season
Ice Accretion	o Change in frequency/intensity of ice storm events
	o Ice build up on infrastructure elements

Significant contributions regarding climate change on the City's roads resulted from interviews with City staff, who are currently maintaining the components of the infrastructure. They were able to relay information regarding what has been occurring over the past decade and what sub-components within the road classification system are considered "soft" or more vulnerable to climate change. For example, a new weather event such as an extended (over 1 day) mid-winter thaw, which now occurs regularly during the months of January and February, is considered a significant maintenance problem. This is an example of a new event now affecting the City's infrastructure that was likely not impacting these components back when they were initially installed. Unfortunately, all of the information comes from anecdotal accounts of the events as opposed to actual "hardcopy" records.

3.0 STEP 2 – DATA GATHERING AND SUFFICIENCY

During the data gathering and sufficiency segment of the protocol, the infrastructure and climate factors of interest previously identified were defined in more detail, the performance responses of the infrastructure to the climate factors were identified, data related to the infrastructure and climate factors were acquired, and the sufficiency of this data was evaluated. Details of these activities are presented in the following sub-sections.

3.1. Infrastructure Components

The infrastructure components that were identified to be of interest during this study contained both above ground and below ground components, and were presented in Table 2.

3.2. Performance Responses

In order to evaluate the potential impacts of climate change effects on the infrastructure components of interest, specific performance responses were identified. Table 8 below presents the performance responses that were considered to best describe the expected climate change impacts.

Table 8: Performance Responses of Interest

Structural Integrity	Conformity to the original structural design of infrastructure.
Serviceability	The ability to keep up the state of repair required to ensure a specified level of service of infrastructure.
Functionality	The ability of infrastructure to fulfill its intended purpose.
Operations & Maintenance	The effort required to provide a specified level of service for infrastructure.
Emergency Response Risks	The risk of interference with the use of infrastructure in the provision of emergency response services.
Insurance Considerations	The potential of changes in the functionality of infrastructure to impact surrounding properties, services or public safety.
Policies & Procedures	Changes in methods used to design, construct, operate, or maintain the infrastructure.
Economics	The financial impacts (both public and private) resulting from changes in the functionality of infrastructure of interest.
Public Health & Safety	Impacts and risks to the public wellbeing resulting from changes in the functionality of infrastructure of interest.
Environmental Effects	The environmental impacts resulting from changes in the functionality of, or the operations and maintenance efforts associated with the infrastructure.

3.3. Climate Baseline

The climate elements of interest (identified in Step 1 - Table 7) that allow the description of both baseline (or historic) as well as expected future climate conditions for the City of Greater Sudbury area were analysed by climatologists at Ouranos.

Ouranos is a research consortium on Regional Climatology and adaptation to climate change, is a joint initiative of the Government of Québec, Hydro-Québec and the Meteorological Service of Canada with the participation of UQAM, Université Laval, McGill University and the INRS. In order to provide coherent and equivalent results for this study, Ouranos was mandated to supply plausible and comparable scenarios of climate change.

As described in the Ouranos report, (see Appendix A2-1) the baseline climate conditions were determined using data from two (2) Environment Canada climate stations (Sudbury Airport station ID 6068150 and Monetville, station ID 6065250) and the present day condition results from two (2) Canadian Regional Climate Model v 4.1.1 simulations (ACU and ADC) for the simulated period 1961 - 1990. The climate elements of interest included: temperature, rainfall,

snowfall, ice events, wind and frost. The climate indices or factors that were requested for analysis were presented previously in Table 7, while the indices and factors that were available from Ouranos are presented below in Table 9. The results of the scenarios and the baseline conditions for which data were available are presented in Appendix A2-1 to this report.

Table 9: Data Availability of Climate Indices/Factors

Climate Element	Climate Indices/Factors	Data Available
Temperature	Monthly average maximum temperature	Yes
	Monthly average minimum temperature	Yes
	Average annual daily maximum temperature	Yes
	Average annual daily minimum temperature	Yes
Rain	Rainfall frequency 6 hour	Yes
	Rainfall frequency 1 day	Yes
	Yearly maximum rainfall	Yes
	Average total annual/seasonal rainfall	Yes
	Simple daily intensity index	Yes
	Average maximum annual dry spell length	Yes
	Average maximum annual wet spell length	Yes
Snow	Snowfall frequency 1 day	Yes
	Yearly maximum snowfall	Yes
	Average total annual/seasonal snowfall	Yes
	Simple daily intensity index	Yes
	Rain on snow events	Yes
	Rapid melt event	No
Ice	Ice build up	No
	Ice accretion	No
	Freezing rain	No
Wind	Monthly average 6 hour wind speed	Yes
	Yearly maximum 6 hour wind speed	Yes
	Hurricanes/tornadoes	No
	Thunderstorms	No
Frost	Average annual frost season length	Yes
	Freeze-thaw cycle frequency	Yes

3.4. Climate Change Assumptions

The climate change scenarios, for which changes in the climate indices or factors predicted were based on the IPCC A2 climate change model. Future changes in climate indices or factors were determined for three periods or horizons: horizon 2020 (the simulated period 2011 - 2040); horizon 2050 (the simulated period 2041 – 2070); and horizon 2080 (the simulated period 2071 – 2100). The changes in the climate indices or factors are calculated as either the difference between, simulated future conditions and simulated present day conditions. The results for the three horizons associated with the future scenarios, along with the simulated baseline climate conditions are presented in Appendix A2-1 to this report.

In order to facilitate the interpretation of the potential climate change effects on the infrastructure components of interest, the following sub-sections present an interpretation of the trends contained in the expected future climate information.

3.4.1. Temperature

All three of the temperature indices (monthly average max, monthly average min, and annual max and min temperatures) show an increasing trend. This trend mirrors the general warming trend that is projected for the planet, and indicates hotter summers, warmer and shorter winters.

3.4.2. Rainfall

Five of the six rainfall indices (6 hour frequency, 1 day frequency, average max rain, average total rain and the simple daily intensity index) show slightly increasing trends, while the predictions for the length of dry and wet spells are contradictory and do not show a clear trend. The information mirrors the general trends for eastern Canada and Ontario, and indicates a slight increase in the frequency, amount and intensity of rainfall (i.e. more precipitation will fall during more frequent and more severe storms), with the exception of the summer season (June, July and August) during which total amount of rainfall is expected to remain relatively unchanged from historic values.

3.4.3. Snowfall

The snowfall indices appear to indicate a general decrease in the total amount of precipitation that falls as snow, a general decrease in the number of minor snow storms (less than 20 cm of accumulation) an increase in the number of large snow storms (20 cm or more of snow accumulation) and an increase in the frequency and severity of rain on snow events.

3.4.4. Wind

No trends were apparent in either the monthly average 6-hour wind speeds or the average annual maximum 6-hour wind speed indices, indicating that no changes in the historic Sudbury wind trends are expected as a result of climate change.

3.4.5. Frost

The frost indices that were analysed indicated a decrease in the duration of the frost season (i.e. winters are expected to get shorter) and a decrease in the number of freeze-thaw events. Ouranos defines a freeze-thaw cycle as temperature changes from a daily high greater than 0^{o} C to a daily low below 0 ^{o}C over a 24-hour period. Extended freeze thaw cycles (greater than 24-hours) are not quantified by the Ouranos Report.

3.5. Cumulative Effects

Based on the results of a thorough review of potential interactions between infrastructure components and climate factors, no significant cumulative effects were identified that would warrant detailed analyses. For the purposes of this study, vulnerability of infrastructure to the effects of climate change was thus based on individual interactions between infrastructure components and climate factors.

4.0 STEP 3 – VULNERABILITY ASSESSMENT

The vulnerability assessment component of the PIEVC protocol assessed the Climate – Infrastructure Interactions (CII) and rates the relative severity of the interactions previously identified utilizing a workshop venue attended by owners and proponents of the project. Based on the results from this step, high scoring CII's are "advanced" to Step 4 – Indicator Analysis, of the PIEVC protocol in which a more detailed quantitative analysis is performed in an attempt to determine the vulnerability and adaptive capacity of the infrastructure components. The application and results of these calculations are presented in the following sub-sections.

4.1. Identify Climate – Infrastructure Interactions

The vulnerability assessment matrix is intended as a screening tool that will assign a relative rating to the probability of a climate event occurring and a relative severity score to the performance responses of the infrastructure components to these climate effects. The matrix was developed utilizing previously collected / identified documentation of the CII's. Specifically, the Climate Elements are Factors previously presented in Table 9. Infrastructure components

are summarized in Table 2; Table 10 identifies the performance responses that were deemed to be associated with the infrastructure of interest. The CII's that were deemed to be of significance as part of this vulnerability assessment are summarized in Table 11 (Refer to Appendix A3-1). Details regarding the manner in which probability scale factors and severity scale factors were assigned are presented in the following sub-sections.

4.2. Probability Scale Factor (S_c)

The PIEVC Protocol provided two (2) definitions for the probability scale factor (S_c). The first definition for the probability scale factor is shown as note 5 on page 25 of the protocol (revision 7.1, dated October 31, 2007), and reads as follows:

> *The practitioner is directed to express a professional opinion regarding the probability that a climate event will occur. This should not be confused with the consequences of that climate event. The practitioner is asked to assess the likelihood of the event and assess the severity and/or consequences in the next step of the protocol. In essence, this step establishes a list of likely events that are subsequently assessed for their impact on the infrastructure.*

The second definition for the probability scale factor (S_c) is provided in the glossary of the protocol (Appendix D), and reads as follows:

> *A factor based on an arbitrary scale (0 to 7) used to define the probability of loss of functionality of a particular infrastructure component.*

As the above two definitions differ slightly, the first definition, that is the probability of a climate event occurring rather than the probability of a loss of functionality as a result of this climate event was adopted during the implementation of the Sudbury workshop.

4.3. Severity Scale Factor (S_R)

Once again the Protocol provided two (2) definitions for the severity scale factor (S_R). The first definition for the severity scale factor is shown as note 5 on page 25 of the protocol (revision 7.1, dated October 31, 2007), and again, reads as follows:

Table 10: Performance Response Prioritization Methodology

Infrastructure Components	Sub-Component	Performance Response									
		Structural Integrity	Serviceability (Level of Service)	Functionality	Operations & Maintenance	Emergency Response Risks	Insurance Considerations	Policies and Procedures	Economics	Public Health & Safety	Environmental Effects
Above Ground Components											
	Surface – Gravel	✓	✓	✓	✓			✓			✓
	Surface - Surface Treatment	✓	✓	✓	✓			✓	✓		✓
	Surface – Asphalt	✓	✓	✓	✓	✓	✓	✓	✓		✓
	Curb	✓	✓	✓	✓			✓			
	Sidewalk	✓	✓	✓	✓		✓	✓		✓	
	Traffic Signals	✓	✓	✓	✓					✓	
	Street Lighting	✓	✓	✓	✓					✓	
	Utility/Poles	✓			✓				✓	✓	
	Boulevards and Shoulders	✓	✓	✓	✓					✓	✓
	Ditches		✓	✓	✓			✓		✓	
	Interlock Pavers		✓	✓	✓		✓	✓		✓	
	Catch Basins	✓	✓	✓	✓	✓	✓			✓	
	Culverts	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Maintenance Holes		✓	✓	✓		✓			✓	✓
	Bikepaths	✓		✓	✓		✓			✓	
	Embankments/Cuts	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Bridge/Structures	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Municipal Signage	✓	✓	✓	✓	✓	✓	✓		✓	▪
Below Ground Components											
	Road Sub-Base	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Storm Sewer Systems	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Distribution Systems	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Collection Systems	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Underground Utilities							✓	✓	✓	
Miscellaneous											
	Administration/Personnel		✓	✓	✓	✓		✓	✓	✓	
	Maintenance (Markings, Crack Sealing)		✓	✓	✓			✓	✓	✓	
	Winter Maintenance		✓	✓	✓	✓	✓	✓	✓	✓	✓
	Record Keeping				✓		✓	✓	✓	✓	✓

** INDICATE WHETHER A CLIMATIC EVENT WILL TRIGGER A PERFORMANCE RESPONSE FOR THAT PARTICULAR ROAD COMPONENT.
EXAMPLE - BOX #1 - WILL A CLIMATIC EVENT EFFECT THE "STRUCTURAL INTEGRITY" OF "SURFACE - GRAVEL"?
"✓" PLACED IN THE GRID WOULD INDICATE A PERFORMANCE RESPONSE FOR THE GRAVEL COMPONENT.

> *The practitioner is directed to express a professional opinion regarding the probability that a climate event will occur. This should not be confused with the consequences of that climate event. The practitioner is asked to assess the likelihood of the event …and assess the severity and/or consequences in the next step of the protocol. In essence, this step establishes a list of likely events that are subsequently assessed for their impact on the infrastructure.*

The second definition for the severity scale factor is provided in the glossary of the protocol (Appendix D), and reads as follows:

> *A factor based on an arbitrary scale (0 to 7) used to define the severity of the consequences of loss of functionality of a particular infrastructure component*

As the above two definitions are in agreement, and were adopted for the severity scale during the implementation of the Sudbury workshop.

4.4. Sudbury Workshop

On December 11, 2007 a workshop was held in Sudbury during which the vulnerability assessment (Step 3) of the protocol was completed. The workshop was attended by City staff from a broad background including administration, design and engineering, planning and operations as well as personnel from Ouranos, and Laurentian University. The workshop was mediated by the staff of Dennis Consultants.

During the Sudbury workshop, four (4) groups were formed, each segmented by road classification. The groups assigned probability and severity scores to all of the infrastructure component and potential climate event interactions that were deemed to be relevant. The classes of road infrastructure that were scored included: arterial, collector, local rural and local urban roads. Appendix A2-1 highlights a sample of the matrices as well as the results of the exercise for each of the four classifications or group, specifically, Table 11 and 12A presented in Appendix A3-1.

Although the assignment of probability and severity scores is subjective and varied with the background of the members that constituted each of the four groups, the results were found to be surprisingly consistent. The combined results are presented in Table 12B (Appendix A3-1). During the interpretation of the information presented in Table 12B (See Appendix A3-1), it should be noted that the Priority of Climate Effects (P_C scores) are based on the performance

response for the various infrastructure components and potential climate events that were deemed to be most severe or significant. Otherwise if the letter of the protocol were to be followed, the assignment of P_C scores would have to be evaluated for all ten (10) potential performance responses associated with all interactions between twenty-five (25) infrastructure components and nine (9) potential climate events. The combination of interactions would have resulted in a total 2250 (10 x 25 x 9) combinations that would need to be evaluated making it impractical for this study. As a result, only the most significant or severe performance responses were considered.

4.5. Prioritise Climate – Infrastructure Interactions

In an effort to focus the vulnerability efforts that will be conducted in the next step of the PIEVC protocol (Indicator Analysis or Step 4), the CII's were prioritized. During the Sudbury workshop, the vulnerability assessment matrices were populated based on a number of assumptions regarding trends and magnitudes of changes in climate data (Ouranos Report was not available at the time of the workshop). In hindsight, some of these assumptions were either proven to be incorrect or could not be confirmed due to lack of climatic data, reducing the number of infrastructure – climate interactions developed during the Sudbury workshop. Furthermore, in the interest of expediency, a number of infrastructure components in different road classifications were combined based on the similarity of potential climate events and anticipated performance responses. The following sub-sections present details regarding the prioritization of the CII's.

4.6. Data Sufficiency

No data was available on the expected changes in ice accretion or ice storms due to the effects of climate change. During the Sudbury workshop this potential climate event was deemed to be one of the more important potential effects of climate change on roads and associated infrastructure, impacting virtually all performance responses. However, the lack of data resulted in the need to eliminate the CII's from further consideration during the indicator analysis or Step 4 of the protocol forward.

4.7. Positive Trend

A positive trend in a climate factor was defined for the purposes of this pilot study, as a change in a climate factor that is expected to reduce the total load on an infrastructure component. For example, a decrease in the precipitation as snow eliminated the CII from further consideration in

the indicator analysis or Step 4 of the protocol. Based on the information presented in the Ouranos report and, as summarized in section 3.4, positive trends were identified for frost events, specifically, length of frost season, freeze / thaw cycles in addition to low temperature climate factors.

4.8. No Trend

The lack of a trend in a potential climate factor, meaning a non-expected change in load on the infrastructure due to climate change, allowed for the elimination of the CII based on this specific Climate factor from further consideration. The information presented by Ouranos as summarized in Section 3.4 of this report, indicated that the wind indices did not have trends and therefore was eliminated from further analysis.

4.9. Infrastructure Identification Considerations

Upon further detailed review of the information compiled during the Sudbury workshop, it was decided that a number of the infrastructure components used should not have been considered as sub-components of the roads infrastructure. Although the inclusion of these infrastructure components would be appropriate in the context of an asset management or an operation hazards or risk & criticality assessment, it was deemed not appropriate for the purposes of this vulnerability assessment and, after some discussion, were considered to be operations & maintenance factors. These previously included infrastructure components were: maintenance (markings, crack sealing, etc.), winter maintenance, administration/personnel and record keeping.

4.10. Combined Infrastructure Components

Following the reduction of the CII's as described above, a number of the remaining interactions used identical climate factors to quantify similar performance responses. In an effort to focus the vulnerability assessment for the indicator analysis portion, the bridges/structures, storm sewer systems, catch basins, culverts and ditches components were combined under a common "drainage" heading; the LCB and asphalt road surfaces – surface treatments were also combined to evaluate the performance responses associated with the "high temperature" potential climate event; while sidewalks, LCB, asphalt and gravel road surfaces were combined to evaluate the performance responses associated with the "snow" potential climate event.

4.11. Interactions Selected for Indicator Analysis

The CII that remained after the above process screening consisted of the following:

1. Drainage and rainfall (3 climate factors).
2. Road surfaces (LCB and Asphalt) and high temperatures (2 climate factors).
3. Road surfaces (incl. sidewalks and gravel) and snow (3 climate factors).
4. Road surfaces – gravel and rainfall (2 climate factors).
5. Embankments/cuts and rainfall (4 climate factors).

These five (5) climate – infrastructure interactions were brought forward to the indicator analysis portion of the protocol.

5.0 STEP 4 – INDICATOR ANALYSIS

The indicator analysis was performed in accordance with the PIEVC protocol. To improve the efficiency of the indicator analysis, a modified worksheet was developed. Evaluations of the modifications were made to the resulting worksheet. The modified worksheet, the results and highlights of the indicator analysis are presented in Table 13 and can be summarized as follows:

- A list of the infrastructure components;
- A summary of the climate elements and factors;
- The range of P_C scores that were assigned by each of the four workgroups during the Sudbury workshop;
- The performance responses that were deemed to be relevant to the climate infrastructure interactions;
- The manner in which each of these performance responses was evaluated, specifically, by either using a numerical calculation or engineering judgement/assumptions;
- The load on the infrastructure components;
- The capacity of the infrastructure components;
- The projected vulnerability of the infrastructure components;
- The adaptive capacity of the infrastructure;
- The capacity deficit calculations; and
- Comments on the general/data sufficiency for each interaction.

TABLE 13: INDICATOR ANALYSIS RESULTS (STEP 4)

No.	INFRASTRUCTURE	CLIMATE ELEMENTS & FACTORS	P_C Range	PERFORMANCE RESPONSE	NUMERICAL CALCULATION	ENGINEERING JUDGEMENT/ ASSUMPTIONS	Horizon	Calculation of Total Load (L_T): Existing Load L_E	Climate Change Load L_C	Other Load L_O	Total Load L_T (L_E+L_C+L_O)	Calculation of Total Capacity (C_T): Existing Capacity C_E	Maturing Capacity C_M	Additional Capacity C_A	Total Capacity C_T (C_E+C_M+C_A)	Vulnerability V_R = L_T/C_T	STEP 5 Y/N	Adaptive Capacity A_R = C_T/L_T	Capacity Deficit C_D = L_T - C_T
1	Drainage (Bridges/Structures, Storm sewer systems, Catch Basins, Culverts, and Ditches)	**Rainfall** Changed intensity (SDII)	15 - 35	Structural Integrity	x		(mm/day)	L_E	L_C	L_O	L_T	C_E	C_M	C_A	C_T	V_R	Y/N	A_R	C_D
				Serviceability	x		2020	8.84	0.49	0	9.33	n/a	n/a	n/a	n/a	-	-	-	-
				Functionality		x	2050	8.84	0.80	0	9.64	n/a	n/a	n/a	n/a	-	-	-	-
				Operations And Maintenance	x		2080	8.84	1.59	0	10.43	n/a	n/a	n/a	n/a	-	-	-	-
				Emergency Response Risks		x	Comments/Data Sufficiency:												
				Insurance Considerations	x		High intensity rainfall events could overload drainage infrastructure. - Overloading could result in overland flow that affects private property increasing **insurance** and **economic** considerations. - Surface ponding on roadway surfaces could impede **emergency response**. - **Procedures and policies** need to take into account increased rainfall intensity for design and maintenance. - **Public health** can be affected during intense rainfall events that result in surcharging of combined sewers. - In populated areas **public safety** could become an issue when unexpectedly high flows and velocities in confined channels and culverts take place. - **Environmental effects** could include increased erosion (carrying sediments and contaminants to water courses) and increased washing away of contaminants from the road surface into the drainage systems and water courses.								
				Policies and Procedures		x													
				Economics	x														
				Public Health and Safety		x													
				Environmental Effects		x													
2		**Rainfall** Changed frequency (>10mm, 1 Day)		Serviceability	x		frequency	L_E	L_C	L_O	L_T	C_E	C_M	C_A	C_T	V_R	Y/N	A_R	C_D
				Functionality		x	2020	0.0602	0.0096	0	0.0698	n/a	n/a	n/a	n/a	-	-	-	-
				Operations And Maintenance	x		2050	0.0602	0.0154	0	0.0756	n/a	n/a	n/a	n/a	-	-	-	-
				Emergency Response Risks		x	2080	0.0602	0.0319	0	0.0921	n/a	n/a	n/a	n/a	-	-	-	-
				Insurance Considerations	x		Comments/Data Sufficiency:												
				Policies and Procedures		x													
				Economics	x														
				Public Health and Safety		x													
				Environmental Effects		x													
							Calculations are based on precipitation predictions for frequency of rain events **greater than 10 mm**. - An increased frequency of larger precipitation events may impact **operations and maintenance**, and **policies and procedures** in order to mitigate any effects on the other Performance Responses. - Drainage systems are designed based on the frequency of past events. As the frequency increases, the existing capacity to convey flow decreases, reducing the **functionality**. The need for diligence in **maintaining** clear flow paths will increase. - Flood events could occur more often, requiring a higher degree of emergency preparedness and more frequent **emergency response**. - More water related damages may occur to public and private properties affecting **insurance considerations**. - Flood plain delineation may change and **policies and procedures** may have to be modified with respect to development in flood prone areas. - More municipal funds may have to be dedicated to increasing maintenance and emergency response (economics). - More frequent flooding/high intensity rainfall results in more frequent washing of harmful materials into watercourses.								
3		**Rainfall** Change in extremes (magnitude) (1 day, annual max)		Structural Integrity	x		(mm/day)	L_E	L_C	L_O	L_T	C_E	C_M	C_A	C_T	V_R	Y/N	A_R	C_D
				Serviceability	x		2020	48.32	2.66	0	50.98	n/a	n/a	n/a	n/a	-	-	-	-
				Functionality		x	2050	48.32	5.07	0	53.39	n/a	n/a	n/a	n/a	-	-	-	-
				Operations And Maintenance	x		2080	48.32	11.60	0	59.92	n/a	n/a	n/a	n/a	-	-	-	-
				Emergency Response Risks		x	Comments/Data Sufficiency:												
				Insurance Considerations	x		Calculations are based on predicted **maximum rainfall over a 1 day period**. - Greater rainfall results in greater drainage flows, increased runoff, and higher chances of flooding. - Bridges are at increased risk due to elevated water surfaces moving more quickly carrying ice and debris that impact the **structural** elements of the bridge. - Greater flows could carry more debris causing blockages to drainage infrastructure, increasing the chance that the design capacity of the drainage system would be exceeded (**functionality**). Higher magnitude events can result in greater and more extensive damage thereby increasing **operations and maintenance** costs, increasing **emergency response risks**, increasing the risks to **public safety**. - More widespread damage can also be expected from a higher magnitude event, increasing **insurance considerations** and affecting public **policies and procedures**. - Higher magnitude events can carry more sediment and debris which may have **environmental** impacts.								
				Policies and Procedures		x													
				Economics	x														
				Public Health and Safety		x													
				Environmental Effects		x													
	Catch Basins	Rainfall	15 - 35	Grouped with drainage															
	Culverts	Rainfall	20 - 35	Grouped with drainage															
4	**Culverts**	**Snow** Changed Intensity (SDII)	12 - 20	Serviceability	x		(mm/snow day)	L_E	L_C	L_O	L_T	C_E	C_M	C_A	C_T	V_R	Y/N	A_R	C_D
				Functionality	x		2020	5.28	0.16	0	5.44	n/a	n/a	n/a	n/a	-	-	-	-
				Operations and Maintenance	x		2050	5.28	0.37	0	5.65	n/a	n/a	n/a	n/a	-	-	-	-
				Insurance Considerations	x		2080	5.28	0.42	0	5.70	n/a	n/a	n/a	n/a	-	-	-	-
				Policies and Procedures		x	Comments/Data Sufficiency:												
				Economics	x		Very intense snowfall events could cause blockages (**functionality**). - Additional crews may be required to clear accumulated snow once the event is over (**operations and maintenance, economics**). - Increased snowfall amounts in shorter periods of time increase the need for more resources for snow removal (**economics**).								
5		**Snow** Changed frequency (1-Day, ≥ 20 SWE)		Serviceability	x		frequency	L_E	L_C	L_O	L_T	C_E	C_M	C_A	C_T	V_R	Y/N	A_R	C_D
				Functionality	x		2020	0.0018	0.0001	0	0.001854	n/a	n/a	n/a	n/a	-	-	-	-
				Operations and Maintenance	x		2050	0.0018	0.0008	0	0.002565	n/a	n/a	n/a	n/a	-	-	-	-
				Insurance Considerations	x		2080	0.0018	0.0010	0	0.002763	n/a	n/a	n/a	n/a	-	-	-	-
				Policies and Procedures		x	Comments/Data Sufficiency:												
				Economics	x		Calculations of frequency are based on **20 mm SWE predicted values** because both the 10 mm SWE and 5 mm SWE predicted values showed a decreasing trend in events of those magnitudes. An increase in frequency of higher magnitude snow events and a decrease in frequency of lower magnitude snow events will be seen. - Increased frequency of larger snowfall events will increase the need for snow clearing resources and possibly the use of more versatile and larger capacity equipment (**economics, policies and procedures, operations and maintenance**).								
	Culverts	Frost (freeze-thaw cycles)	16-20	Positive trend identified															
	Ditches	Rainfall	20 - 24	Grouped with drainage															
	Bridges/ Structure	Rainfall	12 - 24	Grouped with drainage															
	Bridges/ Structure	Frost (freeze-thaw cycles)	14 - 16	Positive trend identified															

TABLE 13: INDICATOR ANALYSIS RESULTS (STEP 4)

No.	INFRASTRUCTURE	CLIMATE ELEMENTS & FACTORS	P_C Range	PERFORMANCE RESPONSE	NUMERICAL CALCULATION	ENGINEERING JUDGEMENT/ ASSUMPTIONS	Horizon	Calculation of Total Load (L_T): Existing Load L_E	Climate Change Load L_C	Other Load L_O	Total Load L_T (L_E+L_C+L_O)	Calculation of Total Capacity (C_T): Existing Capacity C_E	Maturing Capacity C_M	Additional Capacity C_A	Total Capacity C_T (C_E+C_M+C_A)	Vulnerability V_R = L_T/C_T	STEP 5 Y/N	Adaptive Capacity A_R = C_T/L_T	Capacity Deficit C_D = L_T - C_T
				Structural Integrity	x		°C	L_E	L_C	L_O	L_T	C_E	C_M	C_A	C_T	V_R	Y/N	A_R	C_D
				Serviceability	x		2020	31.95	1.95	0	33.90	40	n/a	n/a	40	0.85		1.18	-6.11
				Functionality		x	2050	31.95	3.69	0	35.64	40	n/a	n/a	40	0.89		1.12	-4.37
				Operations And Maintenance	x		2080	31.95	5.61	0	37.56	40	n/a	n/a	40	0.94		1.06	-2.44
				Emergency Response Risk		x	Comments/Data Sufficiency:												
				Insurance Considerations	x														
				Policies And Procedures		x													
				Economics	x														
6	**Road surfaces**- Surface treatment (LCB and Asphalt)	**High Temp** Change in extreme (annual max)	**12 - 24**	Environmental Effects		x	An increase in extreme high temperatures and increased duration of higher temperatures cause asphalt road surfaces to lose rigidity and deform under normal traffic loadings. - This deformation causes thinning of the road surface which leads to increased water intrusion and contributes to degradation of the road sub-base. - Bleeding of asphalt binding material onto the road surface reduces the binding ability of the materials in the pavement thereby reducing **structural integrity**. - Along with increased intensity of rainfall, there is an increased chance of harmful substances from the asphalt pavement being carried into the natural **environment**. - Grooves and ruts in the roadway surface can reduce response time of **emergency** vehicles. - More vehicle accidents can arise from the irregular pavement surface increasing **insurance considerations**. - **Policies and procedures** will need to be revisited for road design. - Increased **maintenance** and repairs (e.g. testing and patching) will be necessary.														
				Structural Integrity	x		Observed	2050											
				Functionality		x	days	days											
				Operations And Maintenance	x		> 35 °C: 0.27	3											
7		**High Temp** change in frequency and intensity as a rare event					> 30 °C: 5.4	12											
							Comments/Data Sufficiency:												
							More frequent (prolonged), intense, high temperature events will increase the incidence of ruts, grooves, and asphalt bleeding to the surface, affecting the **structural** performance, **functionality**, and **operations and maintenance** of the roadway. - Prolonged periods of temperature remaining above 30-35 °C may have a weakening effect on LCB and Asphalt surfaces even though it was designed and graded for above 40 °C. Higher temperatures of longer durations will mean an accelerated rate of wear on the roads meaning higher **maintenance** costs.												
	Road surfaces - Surface treatment (LCB and Asphalt)	Low temperatures	**16 - 18**	Positive trend identified															
			16 - 24	Serviceability	x		(mm/day)	L_E	L_C	L_O	L_T	C_E	C_M	C_A	C_T	V_R	Y/N	A_R	C_D
				Functionality		x	2020	8.84	0.49	0	9.33	n/a	n/a	n/a	n/a	-	-	-	-
				Operations and Maintenance	x		2050	8.84	0.80	0	9.64	n/a	n/a	n/a	n/a	-	-	-	-
				Policies and Procedures		x	2080	8.84	1.59	0	10.43	n/a	n/a	n/a	n/a	-	-	-	-
				Environmental Effects		x	Comments/Data Sufficiency:												
8		**Rainfall** Changed intensity (SDII)					High intensity rainfall events could cause surface ponding on roadways impeding regular traffic and **emergency response**. - **Procedures and policies** need to take into account increased rainfall intensity for design and maintenance.- **Environmental effects** could include increased washing away of contaminants from the road surface into the drainage systems and water courses.												
	Road surfaces - surface treatment (LCB and Asphalt)			Serviceability	x		frequency	L_E	L_C	L_O	L_T	C_E	C_M	C_A	C_T	V_R	Y/N	A_R	C_D
				Functionality		x	2020	0.0204	0.0052	0	0.0256	n/a	n/a	n/a	n/a	-	-	-	-
				Operations and Maintenance	x		2050	0.0204	0.0091	0	0.0295	n/a	n/a	n/a	n/a	-	-	-	-
				Policies and Procedures		x	2080	0.0204	0.0219	0	0.0423	n/a	n/a	n/a	n/a	-	-	-	-
				Environmental Effects		x	Comments/Data Sufficiency:												
9		**Rainfall** Changed frequency (>10mm, 1 Day)					Calculations are based on prediced rainfall events of **greater than 10 mm.** More frequent flooding/high intensity rainfall results in more frequent washing of harmful materials into watercourses.												
	Road surfaces (LCB, Asphalt and Gravel), Sidewalks and Curbs		**16 - 42**	Serviceability	x		(mm/snow day)	L_E	L_C	L_O	L_T	C_E	C_M	C_A	C_T	V_R	Y/N	A_R	C_D
				Functionality		x	2020	5.28	0.16	0	5.44	n/a	n/a	n/a	n/a	-	-	-	-
				Operations And Maintenance	x		2050	5.28	0.37	0	5.65	n/a	n/a	n/a	n/a	-	-	-	-
				Emergency Response Risk		x	2080	5.28	0.42	0	5.70	n/a	n/a	n/a	n/a	-	-	-	-
				Insurance Considerations	x		Comments/Data Sufficiency:												
				Policies And Procedures		x	Very intense snowfall events (e.g.. white outs) will greatly impede snow clearing efforts (**serviceability**) and prevent user traffic (**functionality**). - Additional crews may be required to clear accumulated snow once the event is over (**operations and maintenance, economics**). - Adequate **emergency response** becomes extremely difficult or impossible. - Increased accidents and personal injury may result in increased **insurance considerations**. - Increased snowfall amounts in shorter periods of time increase the need for more resources for snow removal (**economics**). - A change in **policies and procedures** with respect to school and business closures may be affected (**economics**). - Restricted access to sidewalks forces pedestrians to walk along the sides of roadways, increasing risk of personal injury by traffic (**public safety**).												
10		**Snow** Changed Intensity (SDII)		Public Health and Safety		x													

TABLE 13: INDICATOR ANALYSIS RESULTS (STEP 4)

No.	INFRASTRUCTURE	CLIMATE ELEMENTS & FACTORS	P_C Range	PERFORMANCE RESPONSE	NUMERICAL CALCULATION	ENGINEERING JUDGEMENT/ ASSUMPTIONS	Horizon	Calculation of Total Load (L_T)				Calculation of Total Capacity (C_T)				Vulnerability V_R	STEP 5	Adaptive Capacity A_R	Capacity Deficit C_D
								Existing Load L_E	Climate Change Load L_C	Other Load L_O	Total Load L_T (L_E+L_C+L_O)	Existing Capacity C_E	Maturing Capacity C_M	Additional Capacity C_A	Total Capacity C_T (C_E+C_M+C_A)	$V_R = L_T/C_T$	Y/N	$A_R = C_T/L_T$	$C_D = L_T - C_T$
11	**Road surfaces** (LCB, Asphalt and Gravel), Sidewalks and Curbs	**Snow** Changed freqency (1-Day, ≥ 20 SWE)		Functionality		x	frequency	L_E	L_C	L_O	L_T	C_E	C_M	C_A	C_T	V_R	Y/N	A_R	C_D
				Operations And Maintenance	x		2020	0.0018	0.0001	0	0.001854	n/a	n/a	n/a	n/a	-	-	-	-
				Emergency Response Risk		x	2050	0.0018	0.0008	0	0.002565	n/a	n/a	n/a	n/a	-	-	-	-
				Insurance Considerations	x		2080	0.0018	0.0010	0	0.002763	n/a	n/a	n/a	n/a	-	-	-	-
				Policies And Procedures		x	Comments/Data Sufficiency:												
				Economics	x		Calculations of frequency are based on **20 mm SWE predicted values** because both the 10 mm SWE and 5 mm SWE predicted values showed a decreasing trend in events of those magnitudes. An increase in frequency of higher magnitude snow events and a decrease in frequency of lower magnitude snow events will be seen. - Increased frequency of larger snowfall events will increase the need for snow clearing resources and possibly the use of more versatile and larger capacity equipment (**economics, policies and procedures, operations and maintenance**). - Travel will be postponed, there will be more days when people refrain from shopping and are unable to travel to work (**economics**). - Increased commute times will result in greater vehicular emissions, affecting air quality and increasing greenhouse gas emissions (**environmental**), also snowmelt on gravel surfaces may cause erosion. - Deeper snow on the sidewalks may force people to walk on roadways thereby increasing the risks of personal injury. - Deeper snow may impede emergency response more often. Snow clearing policies and associated costs may change. - Vehicle maintenance and repair costs will increase (economic).										
				Environmental Effects		x													
12		**Snow** Average Annual Total Amount		Operations and Maintenance	x		(mm SWE/year)	L_E	L_C	L_O	L_T	C_E	C_M	C_A	C_T	V_R	Y/N	A_R	C_D
							2020	248.53	-3.73	0	244.80	300	n/a	n/a	300	-66		1.23	-55.20
							2050	248.53	-8.70	0	239.83	300	n/a	n/a	300	-28		1.25	-60.17
							2080	248.53	-37.28	0	211.25	300	n/a	n/a	300	-6		1.42	-88.75
							Comments/Data Sufficiency:												
							Total average snowfall is predicted to decrease.												
							(annual $/lane km)	L_E	L_C	L_O	L_T	C_E	C_M	C_A	C_T	V_R	Y/N	A_R	C_D
							2020	312.85	-17.85	0	295.00	400	n/a	n/a	400	-17		1.36	-105.00
							2050	312.85	-22.85	0	290.00	400	n/a	n/a	400	-13		1.38	-110.00
							2080	312.85	-32.85	0	280.00	400	n/a	n/a	400	-9		1.43	-120.00
							Comments/Data Sufficiency:												
							Annual winter **maintenance** costs will decrease.												
	Road surfaces - LCB, Asphalt and Gravel	Ice accretion/storm	**18 - 24**	No data available															
	Road surfaces - LCB, Asphalt and Gravel	Frost (freeze-thaw cycles)	**20 - 28**	Positive trend identified															
13	**Gravel Road Surfaces and Boulevards/ Shoulders**	**Rainfall** Changed intensity (SDII)	**12 - 25**	Structural Integrity	x		(mm/day)	L_E	L_C	L_O	L_T	C_E	C_M	C_A	C_T	V_R	Y/N	A_R	C_D
				Serviceability		x	2020	8.84	0.49	0	9.33	n/a	n/a	n/a	n/a	-	-	-	-
				Functionality	x		2050	8.84	0.80	0	9.64	n/a	n/a	n/a	n/a	-	-	-	-
				Operations and Maintenance		x	2080	8.84	1.59	0	10.43	n/a	n/a	n/a	n/a	-	-	-	-
				Policies and Procedures		x	Comments/Data Sufficiency:												
				Environmental Effects		x	High intensity rainfall events may erode gravel surfaces causing ruts and small depressions, it may also contribute to the loosening of the gravel surface, and erosion and runoff of gravel (**functionality, environmental effects**). - Grading and other **maintenance** of the gravel roadway may be required more often. - The **functionality** of the gravel surface may be affected by intense rainfall if the gravel is loosened. - More intense rainfall events may require **policy** changes pertaining to the need for pavement of roads.										
14		**Rainfall** Changed frequency (>10mm, 1 Day)		Structural Integrity	x		frequency	L_E	L_C	L_O	L_T	C_E	C_M	C_A	C_T	V_R	Y/N	A_R	C_D
				Serviceability		x	2020	0.0602	0.01	0	0.069832	n/a	n/a	n/a	n/a	-	-	-	-
				Functionality	x		2050	0.0602	0.02	0	0.075551	n/a	n/a	n/a	n/a	-	-	-	-
				Operations and Maintenance	x		2080	0.0602	0.03	0	0.092106	n/a	n/a	n/a	n/a	-	-	-	-
				Policies and Procedures		x	Comments/Data Sufficiency:												
				Environmental Effects		x	Calculations are based on predicted rainfall events of **greater than 10 mm.** More frequent, heavy rainfall events will result in more damage to gravel surfaces within the regula **maintenance** cycles, increasing the frequency of maintenance required. - It may diminish driving conditions, possibly making it impassable for some vehicles (**functionality, emergency response risk**).										

TABLE 13: INDICATOR ANALYSIS RESULTS (STEP 4)

No.	INFRASTRUCTURE	CLIMATE ELEMENTS & FACTORS	P_C Range	PERFORMANCE RESPONSE	NUMERICAL CALCULATION	ENGINEERING JUDGEMENT/ ASSUMPTIONS	Horizon	Calculation of Total Load (L_T)				Calculation of Total Capacity (C_T)				Vulnerability V_R	STEP 5	Adaptive Capacity A_R	Capacity Deficit C_D
								Existing Load L_E	Climate Change Load L_C	Other Load L_O	Total Load L_T (L_E+L_C+L_O)	Existing Capacity C_E	Maturing Capacity C_M	Additional Capacity C_A	Total Capacity C_T (C_E+C_M+C_A)	V_R = L_T/C_T	Y/N	A_R = C_T/L_T	C_D = L_T - C_T
	Road Sub-Base	Frost (freeze-thaw cycles)	**14 - 30**	Positive trend identified															
			12 - 16	Structural Integrity	x		(mm/day)	L_E	L_C	L_O	L_T	C_E	C_M	C_A	C_T	V_R	Y/N	A_R	C_D
				Serviceability	x		2020	8.84	0.4862	0	9.3262	n/a	n/a	n/a	n/a	-	-	-	-
				Operations and Maintenance	x		2050	8.84	0.7956	0	9.6356	n/a	n/a	n/a	n/a	-	-	-	-
				Emergency Response Risks		x	2080	8.84	1.5912	0	10.4312	n/a	n/a	n/a	n/a	-	-	-	-
				Insurance Considerations	x		Comments/Data Sufficiency:												
				Policies and Procedures		x													
				Economics	x														
				Public Health and Safety		x													
				Environmental Effects		x													
15		**Rainfall** Changed intensity (SDII)					An increase in rainfall intensity may cause a loss of **structural** materials. - **Emergency** repairs of an embankment during high intensity events may be more difficult and dangerous. - Erosion control devises, including vegetation, may need to be installed and **maintained**. - **Emergency** preparedness planning should consider the possibility of high intensity events causing materials to be washed onto roadways. - Washouts, and falling rock and soil material, can result in vehicle accidents and personal injury affecting **insurance considerations**. - **Policies and procedure changes** affecting design and **maintenance** of embankments/cuts may be necessary (e.g.. decreased embankment slopes, greater use of slope stability devices), this will increase construction and maintenance costs (**economics**). - More material may be washed into nearby watercourses increasing sediment concentrations (**environmental effect**).										
				Structural Integrity	x		frequency	L_E	L_C	L_O	L_T	C_E	C_M	C_A	C_T	V_R	Y/N	A_R	C_D
				Serviceability	x		2020	0.0602	0.0096	0	0.0698	n/a	n/a	n/a	n/a	-	-	-	-
				Operations and Maintenance	x		2050	0.0602	0.0154	0	0.0756	n/a	n/a	n/a	n/a	-	-	-	-
				Emergency Response Risks		x	2080	0.0602	0.0319	0	0.0921	n/a	n/a	n/a	n/a	-	-	-	-
				Insurance Considerations	x		Comments/Data Sufficiency:												
				Policies and Procedures		x													
				Economics	x														
				Public Health and Safety		x													
				Environmental Effects		x													
16		**Rainfall** Changed frequency (>10mm, 1 Day)					Calculations are based on predicted frequency of events **greater than 10 mm of rainfall**. - More frequent, large rainfall events may decrease the service life of the embankment or cut. - A loss of material during these large events my increase, therefore requiring more repair work after the event (**operations and maintenance**). - **Emergency** preparedness planning should include allowances for the road closures (**policies and procedures**). - More material may be washed into nearby watercourses, increasing sediment loading and deposition (**environmental effects**).										
	Embankments/ Cuts			Structural Integrity	x			L_E	L_C	L_O	L_T	C_E	C_M	C_A	C_T	V_R	Y/N	A_R	C_D
				Operations and Maintenance	x		2020	48.32	2.66	0	50.98	n/a	n/a	n/a	n/a	-	-	-	-
				Emergency Response Risks		x	2050	48.32	5.07	0	53.39	n/a	n/a	n/a	n/a	-	-	-	-
				Insurance Considerations	x		2080	48.32	11.60	0	59.92	n/a	n/a	n/a	n/a	-	-	-	-
				Policies and Procedures		x	Comments/Data Sufficiency:												
				Economics	x														
				Public Health and Safety		x													
				Environmental Effects		x													
17		**Rainfall** Change in extremes (magnitude) (1 day, annual max)					Calculations are based on **predicted maximum rainfall over a 1 day period**. - Upstream ponding on an embankment, or the effect of backwater on an embankment may affect its **structural integrity**. - The possibility of embankment washouts due to high water levels may become an issue. - **Emergency** plans have to consider the possibility of washouts occurring within the roadway system. Damage to highway embankments and cuts may require additional **maintenance**.										
				Structural Integrity	x		(mm)	L_E	L_C	L_O	L_T	C_E	C_M	C_A	C_T	V_R	Y/N	A_R	C_D
							2020	690.58	75.96	0	766.54	n/a	n/a	n/a	n/a	-	-	-	-
							2050	690.58	117.40	0	807.98	n/a	n/a	n/a	n/a	-	-	-	-
							2080	690.58	231.34	0	921.92	n/a	n/a	n/a	n/a	-	-	-	-
18		**Rainfall** Change in annual mean (annual average total)					Comments/Data Sufficiency:												
							Calculations based on predicted mean annual rainfall. - Change in mean rainfall amounts over time may begin to affect the geotechnical properties of the embankment or the slopes along cuts.												

TABLE 13: INDICATOR ANALYSIS RESULTS (STEP 4)

No.	INFRASTRUCTURE	CLIMATE ELEMENTS & FACTORS	P_C Range	PERFORMANCE RESPONSE	NUMERICAL CALCULATION	ENGINEERING JUDGEMENT/ ASSUMPTIONS	Horizon	Calculation of Total Load (L_T)				Calculation of Total Capacity (C_T)				Vulnerability V_R	STEP 5	Adaptive Capacity A_R	Capacity Deficit C_D
								Existing Load L_E	Climate Change Load L_C	Other Load L_O	Total Load L_T (L_E+L_C+L_O)	Existing Capacity C_E	Maturing Capacity C_M	Additional Capacity C_A	Total Capacity C_T (C_E+C_M+C_A)	$V_R = L_T/C_T$	Y/N	$A_R = C_T/L_T$	$C_D = L_T - C_T$
	Curb	Frost (freeze-thaw cycles)	15 - 28	Positive trend identified															
	Sidewalk	Ice accretion/storm	20 - 25	No data available															
	Sidewalk	Frost (freeze-thaw cycles)	15 - 28	Positive trend identified															
	Traffic Signals	Wind	12 - 24	No trend identified															
	Street Lights	Wind	12 - 24	No trend identified															
	Utility Poles	Wind	12 - 28	No trend identified															
	Utility Poles	Ice accretion/ storm	12 - 28	No data available															
	Municipal Signage	Wind	12 - 21	No trend identified															
	Maintenance Holes	Frost (freeze-thaw cycles)	14 - 20	Positive trend identified															
	Administration/ Personnel	Ice accretion/ storm	25 - 30	Not Infrastructure															
	Administration/ Personnel	Rainfall	12 - 20	Not Infrastructure															
	Administration/ Personnel	Snowfall	12 - 30	Not Infrastructure															
	Administration/ Personnel	Wind	12	Not Infrastructure															
	Administration/ Personnel	Frost (Freeze/Thaw Cycles)	16 - 21	Not Infrastructure															
	Maintenance (Markings, Crack Sealing, etc…)	Rainfall	12 - 16	Not infrastructure															
	Winter Maintenance	Rainfall	12 - 16	Not infrastructure															
	Winter Maintenance	Snowfall	24 - 30	Not infrastructure															
	Winter Maintenance	Wind	20	Not infrastructure															
	Winter Maintenance	Ice accretion/ storm	15 - 30	Not infrastructure															
	Winter Maintenance	Frost (freeze-thaw cycles)	20 - 28	Not infrastructure															
	Record Keeping	Frost (freeze-thaw cycles)	18 - 28	Not infrastructure															
	Record Keeping	Snowfall	16 - 25	Not infrastructure															
	Trees	Wind	12 - 21	No trend identified															
	Trees	Ice accretion/storm	12 - 21	No data available															

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Edited by MML, February 28, 2008

No Data Available
Positive Trend
Not Infrastructure
No Trend
Grouped

The evaluation criteria was simplified from the original five (5) evaluation methods as highlighted by the protocol since the data used to calculate the loads and capacities was not sufficiently detailed to allow the nuanced distinctions inherent to the five (5) original method criteria. Therefore, the performance responses were evaluated based on two (2) only, namely, numerical calculation and/or engineering/professional judgement.

5.1. Load Calculations

The load calculations for the five (5) remaining CII were based on climate indices for rain, snow and high temperature. The rain and high temperature indices load calculations were straight forward as changes in these indices directly translated into changes in the load on the infrastructure components. The same was true for the calculation of climate change loads associated with the snow indices with one exception, however, the CII for average annual total snow climate factor with the road surfaces such as LCB, asphalt, gravel sidewalks and curbs. For this CII, the climate change load was expressed as the annual winter maintenance cost (as dollars per lane - km). This cost can be considered an aggregate value for different road classes and infrastructure types.

5.2. Capacity Calculations

The capacity calculations that were implemented during this study were hindered by a number of factors, specifically; the City of Greater Sudbury's drainage infrastructure could not be properly evaluated because of the limited available detail regarding the type, size, location, age and conveyance capacity of the drainage infrastructure. As the rainfall – drainage infrastructure interaction predicted for the Greater Sudbury area is potentially large enough to affect a large number of performance responses including structural integrity, we strongly recommend that a database of the drainage infrastructure including conveyance capacity and design flows be developed immediately for all drainage sub-components of the infrastructure. Once completed, current hydraulic engineering design standards based on historic climate event data, will be adjusted in order to address the changes in climatic trends.

Similarly with the capacities of the infrastructure components and performance responses affected by the snowfall intensity and frequency climate factors, could not be calculated because of the lack of current drainage capacity data. Although the City of Greater Sudbury has the equipment, personnel and procedures to deal with heavy snowfall events, an increase in the number of severe snowstorms is not expected to result in a vulnerability. However, no

information was available to allow us to quantify this “gut feel”. There is a potential reduction in annual winter maintenance costs associated with road surfaces, sidewalks and curbs resulting from the predicted reduction in annual total snowfall.

Although the capacity calculations for road surfaces (LCB and asphalt) associated with the high temperature climate factors did not indicate a vulnerability, we caution that the adaptive capacity predicted for the 2080 horizon is uncomfortably small, meaning the climate factors used to predict the load on surfaces should be considered indicators rather than absolute predictors. Specifically, the softening of the bituminous binder in LCB and asphalt road surfaces is a function of temperature magnitude, temperature duration and solar exposure. Furthermore, the interpretation of load and capacity calculations is further complicated by the non-linear response of the road surfaces to increased temperatures, in addition to non-linear response to operations & maintenance requirements and service life of road surfaces to softening of the road surfaces due to increased temperatures.

The capacity of embankments/cuts infrastructure could not be properly evaluated, since quantifiable data on the sub-component does not currently exist. Knowing the number and type of embankment, soil/rock types, embankment geometry, local groundwater conditions and embankment loads would have simplified attempt at qualifying the calculations. However, the vulnerability changes in the rainfall and groundwater conditions are not expected to be sufficiently large enough to affect the performance responses identified for this CII.

5.3. Vulnerability Calculations

The intent of the protocol is to compare total loads of the infrastructure to total capacity. Specifically, in the event the load calculation exceeds the capacity calculation for the same sub-component, then a vulnerability is considered to exist. Considering the data availability difficulties were encountered in the calculations of both loads and capacities (as discussed above), the existence of vulnerabilities was therefore most often determined using engineering judgement/assumptions rather than numerical analysis. The results are presented in the comments/data sufficiency sections of Table 13.

Although the information presented in Table 13 does not identify any vulnerability, the CII associated with ice accretion (ice storms) should be noted as a potentially significant “blind spot” in the evaluation process. Furthermore, ice related potential climate events were identified as

being potentially significant, and the evaluation of these potential climate events may yet result in the identification of significant infrastructure vulnerability.

5.4. Adaptive Capacity/Capacity Deficit Calculations

As previously mentioned, in the event where vulnerability assessments were performed using numerical calculations, no vulnerabilities or capacity deficits were identified. However, based on engineering judgement and assumptions, vulnerabilities may still exist for the infrastructure components that could be impacted by rainfall or ice accretion based climate events. It is suspected that the vulnerabilities resulting from rainfall – drainage infrastructure interactions can be accommodated by either the existing adaptive capacities of the drainage infrastructure or minor remedial actions such as the construction of improvements to the hydraulic efficiency of existing culverts, the integration of the minor and major drainage systems and retrofitting of existing bridge openings. Additional study is recommended to quantify the suspected vulnerabilities of the drainage infrastructure, and the potential climate change loads associated with ice accretion or ice storm events.

6.0 STEP 5 – RECOMMENDATIONS

6.1. Limitations

The future climate change scenarios that were provided by Ouranos are subject to a number of limitations. As stated in Section 4 of the Ouranos Report:

“Climate scenario production was limited to the use of only 2 simulations. Furthermore, these simulations were produced by the same regional Climate model (CRCM 4.1.1), driven by two runs of the same GCM (CGCM 3) and the same GHG emissions scenario (SRES A2). In short, the predicted changes cover only a small portion of the spectrum or envelop of changes that would be produced via the use of multiple SRES scenarios and multiple driving models or even multiple RCMs.

These limitations are considered acceptable for the purposes of this sensitivity analyses and study. However, it is recommended that any policy-making activities be based on an expanded version of the present case study.

6.2. Vulnerability Recommendations

Recommendations related to the vulnerability of the infrastructures that were assessed are presented in Table 14. This table organized the recommendations by infrastructure component, climate element (or index), climate factor and finally performance response. These recommendations are intended to address the various performance responses ranked as having a priority of either: none, low, medium or high. The following numbers of recommendations were identified for each of the above priorities.

- High priority 0 recommendations.
- Medium priority 8 recommendations related to the effects of rainfall on drainage infrastructure and gravel road surfaces.
- Low priority 67 recommendations.
- No priority (none) 29 recommendations.

These recommendations are grouped into four (4) categories (as per the protocol) consisting of: remedial action is required, management action is required, no further action is required or additional study /or the acquisition of more data is required. The following recommendations were associated with each of the above categories.

- Remedial action 10 recommendations - 3 related to the effects of rainfall on drainage infrastructure, 1 related to the effects of high temperatures on road surfaces (LCB and asphalt), 3 related to the effects of rainfall on gravel surfaced roads and 3 related to the effects of rainfall on embankments/cuts).

- Management action 48 recommendations - 17 related to the effects of rain on drainage infrastructure, 9 related to the effects of snow on road surfaces, 8 related to the effects of high temperatures on road surfaces (LCB and asphalt), 6 related to the effects of rain on gravel road surfaces, and 8 related to the effects of rain on embankments/cuts.

TABLE 14: RECOMMENDATIONS FOR DIFFERENT INFRASTRUCTURE-CLIMATE FACTOR RESPONSE COMBINATIONS

INFRASTRUCTURE	CLIMATE ELEMENT	CLIMATE FACTORS	PERFORMANCE RESPONSE	PRIORITY FOR ACTION	RECOMMENDATION	COMMENTS ON THE RECOMMENDATION
Drainage (Bridges/Structures, Storm sewer systems, Catch Basins, Culverts, and Ditches)	Rainfall	Changed intensity	Structural Integrity	Medium	Additional Study Required	Review design criteria with respect to structural sizing and capability to handle debris.
			Functionality	Medium	Additional Study Required	High intensity rainfall events could overload drainage infrastructure. A database of existing drainage infrastructure could be prepared. This would allow for the capacity of drainage infrastructure to be assessed by comparing design values to physical size of the infrastructure, and by comparing the original design criteria against design criteria revised to account for climatic change.
			Serviceability, Operations And Maintenance	Medium	Remedial Action	More intense storms may result in more littoral debris being carried to drainage systems, thereby increasing the need for remedial action, that is the clearing of debris from catch basins and culvert inlets.
			Emergency Response Risks	Low	Management Action	Surface ponding on roadway surfaces could impede emergency response. Emergency response centres should be made aware of impassable roads. Alternate routes for emergency vehicles to use could be developed from onsite investigation or as output from a transportation model for the city. Alternate emergency response modes (e.g. vehicle type) could be considered.
			Insurance Considerations	Low	Management Action	Overloading of drainage systems could result in overland flow that affects public property, increasing the risk of insurance claims. Insurance needs should be periodically reviewed.
			Policies and Procedures	Medium	Management Action	Design criteria as provided in municipal specifications and design codes may have to be changed. New information in the form of I-D-F curves and runoff coefficients that account for climate change may have to be provided. This information should be updated every five to ten years as new information becomes available.
			Economics	Medium	Management Action	With respect to the infrastructure owner, higher intensity events may require additional funds for staff or consulting services to review and update information on drainage infrastructure and on the vulnerability of that infrastructure to climatic change. In the broader sense, high intensity rainfall events increases the chances of ponding on the highways that increase minor traffic delays (loss work productivity) and the number of traffic accidents (more money for vehicles repair shops, increased medical costs). These are considerations that would need to be considered in traffic/ transportation studies and in stormwater management planning. The possibility of more intense rainfall events may require additional capability for stormwater conveyance and this from now onwards should be considered in preparing municipal budgets for road and street drainage (new and replacement).
			Public Health and Safety	Low	Management Action	Public health can be affected during intense rainfall events that result in surcharging of combined sewers. Storm water interceptors for onsite stormwater collection, treatment or disposal should be considered for all large paved surfaces. Stormwater management practices with respect to water quality need to be reviewed and by-laws concerning contaminant discharge into storm sewer system strictly enforced.
				Low	Management Action	In populated areas public safety could become an issue when unexpectedly high flows and velocities in confined channels and culverts take place. Consider whether access or culvert grating could increase public risk.
			Environmental Effects	Low	Management Action	Environmental effects could include increased erosion (carrying sediments and contaminants to watercourses) and increased washing away of contaminants from the road surface into the drainage systems and water courses. at construction sites, the time that bare soil is exposed to intense rainfall events should be kept short, with vegetation or soil erosion measures enacted soon after the land is cleared and during the construction. The City's by-laws and specifications concerning construction activities should be reviewed and amended if necessary.
		Changed frequency	Functionality	Medium	Remedial Action	As the frequency increases, the existing capacity to convey flow decreases, reducing the functionality. A structure designed based on the probability of past event occurrence (a specific return period) will have less capacity if the frequency of the events of a given magnitude increases. In some cases, where culvert structures appear to be undersized or lacking the capacity to handle increased flows, entrance conditions may have to be modified or a flow-relief culvert installed to increase flow conveyance.
			Operations and Maintenance	Medium	Remedial Action	An increased frequency of larger precipitation events may impact operations and maintenance. The need for diligence in maintaining clear flow paths will increase. Inspection should be carried out following major rainfall events, and remedial action taken as necessary..
			Emergency Response Risks	Medium	Management Action	Flood events could occur more often, requiring a higher degree of emergency preparedness and more frequent emergency response. Emergency response planning should be reviewed and updated every few years.
			Insurance Considerations	Low	Management Action	More water related damages may occur to public and private properties affecting insurance considerations. Insurance coverage should be reviewed and updated every few years. Private landowners should be encouraged to purchase insurance that covers damage to property from surface runoff.
			Policies and Procedures	Low	Management Action	An increased frequency of larger precipitation events may impact policies and procedures in order to mitigate any effects on the other Performance Responses. Design specifications and codes would have to be reviewed such that information is appropriate for changing hydro-climatic conditions. Flood-plain delineation may change and policies and procedures may have to be modified with respect to development in flood prone areas.
			Economics	Low	Management Action	More municipal funds may have to be dedicated to increasing maintenance and emergency responses, or providing additional drainage capacity.
			Public Health and Safety	Low	Additional Study Required	The effect of ponding and flooding on public safety should be reviewed.
			Environmental Effects	Low	Management Action	More frequent flooding/high intensity rainfall results in more frequent washing of harmful materials into watercourses. Non-source pollution may be lessened by a decision to reduce the application of treated sand and highway de-icers to the lowest amount necessary for winter highway use.
		Changed in extremes (magnitudes)	Structural Integrity	Low	Additional Study Required	Greater rainfall results in greater drainage flows, increased runoff, and higher chances of flooding. Bridges are at increased risk due to elevated water surfaces moving more quickly carrying ice and debris that impact the structural elements of the bridge. Additional study may be required to identify specific existing structures where the waterway opening may be insufficient to handle the passage of more ice and debris at elevated water levels. That level of information was unavailable when performing this study.
			Functionality	Low	Additional Study Required	Greater flows could carry more debris causing blockages to drainage infrastructure, increasing the chance that the design capacity of the drainage system would be exceeded (Functionality). Where the problems persists, measures could be enacted to reduce the debris flow, to catch debris before it enters the drainage system, or to increase the capacity of the drainage systems. In some cases, this would require only remedial action in the field, but in other cases, it may require further study.
			Operations And Maintenance	Low	Management Action	Higher magnitude events can result in a need for more maintenance. Maintenance activities may have to be periodically reviewed as hydroclimatic conditions change.
			Emergency Response Risks	None	No Further Action.	Higher magnitude events can result in slower emergency response due to ponding or flooding.
			Insurance Considerations	None	No Further Action.	Higher magnitude events can result in greater and more extensive damage thereby increasing insurance costs.
			Policies and Procedures	Medium	Management Action	Design criteria for bridges, culverts, and drainage infrastructure should be reviewed and changed as appropriate to account for changing hydro-climatic conditions..
			Economics	Low	Management Action	Additional municipal funds may be required to upgrade existing drainage infrastructure, to increase drainage capacity, or to purchase/ design/ construct larger structures in the future compared to the past.
			Public Health and Safety	Low	Management Action	Higher magnitude events can result in greater risks to public safety from drowning and flooding. Public information activities related to public safety should be reviewed periodically.
			Environmental Effects	Low	Management Action	Higher magnitude events can carry more sediment and debris which may have some environmental impacts. Contaminant and sediment monitoring may have to be adjusted to get a truer indication of annual or seasonal loadings. Normal environmental management practices should suffice.
Road surfaces (LCB, Asphalt and Gravel) and Sidewalks	Snow	Changed Intensity (1 Day Amount)	Serviceability	None	No Further Action.	Very intense snowfall events (e.g., white outs) will greatly impede snow clearing efforts (serviceability).
			Functionality	None	No Further Action.	Very intense snowfall events (e.g., white outs) will prevent user traffic (functionality).
			Operations And Maintenance	Low	Management Action	Additional crews may be required to clear accumulated snow once the event is over (operations and maintenance,
			Emergency Response Risk	None	No Further Action.	Adequate emergency response becomes extremely difficult or impossible.
			Insurance Considerations	Low	Management Action	The infrastructure owner may consider insurance needs with respect to snow removal crews and equipment. Increased accidents and personal injury also may result in increased insurance claims and premiums. This adjustment would be made over time based on actuarial practices.
			Policies And Procedures	Low	Management Action	Procedures and priorities concerning snow removal and policies concerning road closures may have to be changed. A change in policies and procedures with respect to school and business closures may be necessary.
			Economics	Low	Management Action	Snow removal budgets may have to be increased. Increased snowfall amounts in shorter periods of time increase the need for more resources for snow removal (economics).
			Public Health and Safety	Low	Management Action	Restricted access to sidewalks forces pedestrians to walk along the sides of roadways, increasing risk of personal injury by traffic (public safety). Public safety activities such as announcements could be made to drivers to drive more slowly and to watch for pedestrians on the roadway during major snowfall events.
		Changed frequency (1-DAY)	Functionality	None	No Further Action.	Climate change projections are for an increase in frequency of higher magnitude snow events and a decrease in frequency of lower magnitude snow events will be seen. Increased frequency of larger snowfall events could increase the number of days that a highway, street or road remains impassable to certain vehicles. The inconvenience associated with reduced functionality of the road has to be weighed against the costs of snow clearing (see Economics).
			Operations And Maintenance	Low	Management Action	Climate change projections are for an increase in frequency of higher magnitude snow events and a decrease in frequency of lower magnitude snow events. Increased frequency of larger snowfall events will increase the need for snow clearing resources and possibly the use of more versatile and larger capacity equipment.
			Emergency Response Risk	Low	Management Action	Deeper snow may impede emergency response more often. The provision of emergency services during major snowfall events should be periodically reviewed, as the climate changes.
			Policies And Procedures	Low	Management Action	Snow clearing policies and procedures should change in response to changing climatic conditions.
			Economics	Low	Management Action	The possible use of more versatile equipment (which could be used for other purposes during the longer period between snowfall events) and larger capacity equipment and need for more resources to remove a greater amount of snow following a major event, would alter budgets for snow clearing and disposal. In a broader context of the community, travel will be postponed, there will be more days when people refrain from shopping and are unable to travel to work. Vehicle maintenance and repair costs could increase.
			Environmental Effects	None	No Further Action.	Increased commute times will result in greater vehicular emissions, affecting air quality and increasing greenhouse gas emissions. Snowmelt runoff from gravel surfaces may carry gravel into nearby watercourses.

TABLE 14: RECOMMENDATIONS FOR DIFFERENT INFRASTRUCTURE-CLIMATE FACTOR RESPONSE COMBINATIONS

INFRASTRUCTURE	CLIMATE ELEMENT	CLIMATE FACTORS	PERFORMANCE RESPONSE	PRIORITY FOR ACTION	RECOMMENDATION	COMMENTS ON THE RECOMMENDATION
Road surfaces- Surface treatment (LCB and Asphalt)	High temperatures	Change in extreme (magnitude)	Structural Integrity	Low	Management Action	An increase in extreme high temperatures and increased duration of higher temperatures could result in asphalt road surfaces losing rigidity and deforming under normal traffic loadings. This deformation would result in thinning of the road surface which leads to increased water intrusion and contributes to degradation of the road sub-base. Bleeding of asphalt binding material onto the road surface reduces the binding ability of the materials in the pavement thereby reducing structural integrity. On the other hand, the pavement surface likely would deteriorate over time and. catastrophic failure of the pavement surface would not occur. Structural integrity would have an effect on pavement repair, maintenance and replacement schedules and costs. The infrastructure owner would have to consider shorter service lives during highway planning (design, maintenance and operations).
			Functionality	Low	Management Action	Poor driving surfaces may result in slower traffic flow and restrictions on the use of specific roads by heavier vehicles that could further damage the driving surface. Traffic controls (e.g. speed limits, weight restrictions) may have to be reviewed periodically.
			Operations And Maintenance	Low	Management Action	Increased maintenance and repairs (e.g.. testing and patching) will be necessary. The capability to undertake the maintenance work (equipment, staffing) has to be reviewed.
			Emergency Response Risk	Low	Management Action	Grooves and ruts in the roadway surface can reduce the response times of emergency vehicles. This should be taken into account when decisions are made concerning the purchase of emergency vehicles (type of vehicle, number of vehicles), and is dependent in part upon decisions made with respect to pavement replacement and highway/ street maintenance and repairs. If a pavement surface has deteriorated greatly, operational considerations could include the use of alternate routes or different types of emergency response.
			Insurance Considerations	None	No Further Action.	More vehicle accidents can arise from the irregular pavement surface increasing insurance claims. An adjustment in insurance premiums would follow. From the standpoint of the infrastructure owner, this could affect the insurance costs for maintenance vehicles.
			Policies And Procedures	Low	Management Action	Road design standards need to be revised, including revised guidelines with respect in paving materials (e.g., changes in asphalt mix design to accommodate higher temperature extremes) and more emphasis on quality control during construction.
			Economics	Low	Management Action	The maintenance and paving budgets of the infrastructure owner would have to be increased to take into account the increased need for highway patching and repairs and the need for replacement due to the potentially shorter service life of pavement.
			Environmental Effects	Low	Management Action	Along with increased intensity of rainfall, a change in extreme high temperature could increase the potential for harmful substances from the asphalt pavement being carried into the natural environment. Stormwater management could be reviewed and changed if necessary to lessen the potential. In paved areas such as parking lots, grease and oil separators could be used.
		Change in frequency and intensity as a rare event	Structural Integrity	Low	Management Action	More frequent (prolonged), intense, high temperature events will increase the incidence of ruts, grooves, and asphalt bleeding to the surface, affecting the structural performance of the roadway. The service life would decrease, thereby requiring repaving at shorter time intervals than present. The infrastructure owner would have to consider shorter the effects of shorter service lives on highway planning and operations.
			Functionality	Low	Management Action	More frequent (prolonged), intense, high temperature events will increase the incidence of ruts, grooves, and asphalt bleeding to the surface, affecting the functionality of the roadway. Traffic controls (e.g. speed limits, weight restrictions) may have to be reviewed periodically.
			Operations And Maintenance	Low	Remedial Action	More frequent (prolonged), intense, high temperature events will increase the incidence of ruts, grooves, and asphalt bleeding to the surface, affecting the need for more frequent need to repair the roadway.
	Low temperatures	Change in magnitude	Structural Integrity, Operations and Maintenance	None	No Further Action	Positive trend identified (higher average of low daily temperatures) such that vulnerability to climate effects would lessen.
	Rain	Change in intensity	All applicable.	None	No Further Action	Increased rainfall intensity will only have a minor effect on wear of the pavement surface. Any effect due to the differences in rainfall intensities due to climate change are assumed to be negligible.
		Change in frequency	All applicable.	None	No Further Action	Increased rainfall frequency of rainfall will an insignificant effect on wear of the pavement surface. Any effect due to climate change is assumed to be negligible.
		Change in extremes (magnitude)	All applicable.	None	No Further Action	Increased rainfall amounts would not have a significant effect on wear of the pavement surface. Any effect due to climate change is assumed to be negligible.
	Ice accretion/ storm	All applicable.	All applicable.	Low	Additional Study Required.	Insufficient information exists by which to evaluate icing of highway surfaces. The loading depends upon the likelihood of several climate elements occurring concurrently. It is assumed that the vulnerability of highway surfaces would not greatly increase, but this should be re-assessed during the next vulnerability assessment.
	Frost (freeze-thaw cycles)	Changed frequency	All applicable.	None	No Further Action	Positive trend identified such that vulnerability to free-thaw cycles effects lessens.
Road surfaces - gravel	Low Temperatures	All applicable.	All applicable.	None	No Further Action	Positive trend identified (higher average of low daily temperatures) such that vulnerability to climate effects lessens.
	Rain	Changed intensity (1-DAY, SDII)	Structural Integrity	Medium	Remedial Action	High intensity rainfall events may erode gravel surfaces causing ruts and small depressions, it may also contribute to the loosening of the gravel surface, and erosion and runoff of gravel . Inspection of gravel roads should be carried out following intense storm events and grading and other maintenance work performed when required.
			Functionality	Low	Management Action	High intensity rainfall events may erode gravel surfaces causing ruts and small depressions thereby affecting traffic. Road closures (when possible) could be considered until maintenance work is completed. his would be a temporary effect on travel access, travel times, and convenience.
			Operations and Maintenance	Low	Management Action	Grading and other maintenance of the gravel roadway may be required more often. Allocation of resources (money, equipment, and equipment operators) might be modified as time passes to take this into account.
			Policies and Procedures	Low	Management Action	More intense rainfall events may require policy changes pertaining to the need for pavement of roads.
			Environmental Effects	Low	Remedial Action	High intensity rainfall events may erode gravel surfaces causing runoff of gravel into watercourses. Ensure that erosion control devices are placed along gravel roads to provide a reasonable level of protection to the environment.
		Changed frequency	Functionality	Low	Management Action	More frequent, heavy rainfall events may diminish driving conditions, possibly making roads and streets impassable for some vehicles. Highway features may need to be modified to facilitate greater travel capability during more frequent heavy rainfall events.
			Operations and Maintenance	Low	Remedial Action	More frequent, heavy rainfall events will result in more damage to gravel surfaces within the regular maintenance cycles, increasing the frequency of maintenance required.
			Policies and Procedures	Low	Management Action	Design standards have to be reviewed and updated to account for more frequent, heavy rainfall events. This may require a change in policy such a change in the criterion used to decide whether a gravel roads should be paved.
			Environmental Effects	Low	Management Action	More frequent heavy rainfall amounts may result in overland flow conditions that wash more gravel and absorbed contaminants from the road surface into watercourses. This may require a change in monitoring practices to better allow for determination of sediment and contaminant loading during a specified period of time.
	Ice accretion/ storm	Changed frequency and variability	All applicable.	Low	Additional Study Required	No information currently available by which to assess the changes in effect of ice accretion on gravel roadways. The vulnerability also relates to highway conditions.
	Frost (freeze-thaw cycles)	Changed frequency	Functionality	None	No Further Action	No information currently is available by which to assess quantitatively the specific effect of freeze-thaw effects on gravel roads in the area of interest. Since the number of freeze-thaw cycles is expected to decrease, no further action is required with respect to climate change impact. Routine maintenance should continue.
			Operations And Maintenance	None	No Further Action	No information currently is available by which to assess quantitatively the specific effect of freeze-thaw effects on gravel roads in the area of interest. Since the number of freeze-thaw cycles is expected to decrease, no further action is required with respect to climate change impact. Routine maintenance should continue.
Road Sub-Base	Frost (freeze-thaw cycles)	Changed frequency	Structural Integrity	None	No Further Action	Since the number of freeze-thaw cycles is expected to decrease, there should be less potential for detrimental climate-change loadings that would affect the structural integrity of the subbase. Vulnerability of a subbase to freeze-thaw cycles should decrease. Therefore, no further action is required.
Embankments/ Cuts	Rainfall	Changed intensity	Structural Integrity	Low	Management Action	An increase in rainfall intensity may cause a loss of structural materials. An inspection program may need to be established.
			Serviceability	None	No Further Action	Emergency repairs of an embankment during high intensity events may be more difficult and dangerous.
			Operations and Maintenance	Medium	Remedial Action	Erosion control devises, including vegetation, may need to be installed and maintained.
			Emergency Response Risks	Medium	Management Action	Emergency preparedness planning should be modified so that they consider the possibility of high intensity events causing materials to be washed onto roadways.
			Insurance Considerations	Low	No Further Action	Washouts, and falling rock and soil material, can result in vehicle accidents and personal injury affecting insurance considerations. Nevertheless, an increased number or severity of washouts due to climate change may not be a major consideration with respect to insurance needs. For both the infrastructure owner and user, insurance premiums would adjust over time to reflect a perception by the insurance companies of increased risk.
			Policies and Procedures	Low	Management Action	Modification of design codes and standards, and maintenance guidelines and procedures may be necessary (e.g.. decreased embankment slopes, greater use of slope stability devices).
			Economics	Low	Management Action	The infrastructure owner may have to consider increased construction and maintenance costs.
			Environmental Effects	Medium	No Further Action	More material may be washed into nearby watercourses increasing sediment concentrations (environmental effect). The environmental damage would be minimized by good embankment construction, design and maintenance, as would be reflected in modified design codes, municipal construction guidelines and maintenance procedures. Separate environmental action with respect to the non-point loss of materials from embankments and cuts during more intense rainfall events that may occur as a result of changing climatic conditions does not seem justified beyond that which is currently done.

TABLE 14: RECOMMENDATIONS FOR DIFFERENT INFRASTRUCTURE-CLIMATE FACTOR RESPONSE COMBINATIONS

INFRASTRUCTURE	CLIMATE ELEMENT	CLIMATE FACTORS	PERFORMANCE RESPONSE	PRIORITY FOR ACTION	RECOMMENDATION	COMMENTS ON THE RECOMMENDATION
		Changed frequency	Structural Integrity	Medium	Management Action	More frequent, large rainfall events may decrease the service life of the embankment or cut. This should be an asset management consideration.
			Operations and Maintenance	Low	Remedial Action	A loss of material during these large events my increase, therefore requiring more repair work after the event.
			Policies and Procedures	Low	Management Action	Emergency preparedness planning should include allowances for road closures.
			Environmental Effects	None	No Further Action.	More material may be washed into nearby watercourses, increasing sediment loading and deposition..
		Change in extremes (magnitudes)	Structural Integrity	Low	Management Action	Upstream ponding on an embankment, or the effect of backwater on an embankment may affect its structural integrity. The possibility of embankment washouts due to high water levels may become an issue.
			Operations and Maintenance	Low	Remedial Action	Damage to highway embankments and cuts may require additional maintenance. Additional erosion control devices may be necessary. The amount of change in rainfall amounts will unlikely necessitate a major departure from current practices.
			Policies and Procedures	Low		Emergency plans have to consider the possibility of washouts occurring within the roadway system.
		Change in mean value	Structural Integrity	Low	Management Action	Change in mean rainfall amounts over time may begin to affect the geotechnical properties of the embankment or the slopes along cuts. For large slopes or embankments where there are concerns over potential slope instability and public safety, a decision may be made to install soil moisture and movement monitoring equipment or to undertake regular surveys as a way to quantify any movement as a means of assessing possible loss of slope integrity (embankment failure, slippage, landslide).
	Frost (freeze-thaw cycles)	All applicable.	All applicable.	None	No Further Action	Embankment/ cut slope stability concerns with respect to freeze-thaw cycles would still have to be considered, but positive trend identified such that vulnerability to free-thaw cycles would be reduced over time. Therefore, there would be no need for further action as a result of potential climate change impacts.
	Groundwater table	Change in mean value	Structural Integrity	Low	Additional Study Required.	Monitoring of groundwater levels and/or periodic surveys of slope deformation or movement is recommended at large embankments and slopes around cuts where slope stability concerns exist and where there is a risk to public safety.
Curb	Ice accretion/ storm	All applicable.	All applicable.	Low	Additional Study Required	No information currently available by which to assess the changes in effect of ice accretion on sidewalks.
	Frost (freeze-thaw cycles)	All applicable.	Structural Integrity	None	No Further Action	No information is currently available by which to assess the specific effect of freeze-thaw effects on curbs, but low impact is expected based on judgement and the fact that the number of freeze-thaw cycles is expected to decrease. With respect to climate change impact, no further action is required. Routine maintenance should continue, with deteriorated curbs repaired.
Sidewalk (for snow effects on sidewalks see above)	Ice accretion/ storm	All applicable.	All applicable.	Low	Additional Study Required	No information is currently available by which to assess the specific effect of freeze-thaw effects on sidewalks, but based upon current climate change projections the number of freeze-thaw cycles is expected to decrease. Therefore, with respect to climate change impacts, additional study is required. Routine maintenance should continue, with deteriorated sidewalks repaired.
	Frost (freeze-thaw cycles)	All applicable.	Structural Integrity	Low	Remedial Action	Sidewalk repair or replacement as necessary.
Traffic signals	Wind	All applicable.	All applicable.	None	No Further Action	No trend identified. Climate effects projected to remain the same.
	Ice accretion/ storm	All applicable.	All applicable.	Low	Additional Study Required.	No information currently available by which to assess the effect of ice accretion on traffic signals. A study could be carried out if needed in the future.
Street lights	Wind	All applicable.	All applicable.	None	No Further Action	No trend identified. Climate effects projected to remain the same.
Utility poles	Wind	All applicable.	All applicable.	None	No Further Action	No trend identified. Climate effects projected to remain the same.
	Ice accretion/ storm	All applicable.	Operations And Maintenance	Low	Additional Study Required.	No information currently available by which to assess the effect of ice accretion on traffic signals. A study could be carried out if needed in the future.
Municipal Signage	Wind	All applicable.	All applicable.	None	No Further Action	No trend identified. Climate effects projected to remain the same.
Maintenance Holes	Frost (freeze-thaw cycles)	All applicable.	All applicable.	None	No Further Action	Positive trend identified such that vulnerability to free-thaw cycles effects lessens.
Underground utilities	Frost (freeze-thaw cycles)	All applicable.	All applicable.	None	No Further Action	Positive trend identified such that vulnerability to free-thaw cycles effects lessens.
Administration/ Personnel	Ice accretion/ storm	All applicable.	Operations And Maintenance	Low	Additional Study Required	No information currently available by which to assess the effect of ice accretion on administration and personnel. This could be part of a study on the response to ice storms if a specific study was carried out in the future.
Record Keeping	Frost (freeze-thaw cycles)	All applicable.	Operations And Maintenance	None	No Further Action	No information currently available. Practices would probably change as conditions change.
Trees	Wind	All applicable.	Insurance Considerations	None	No Further Action	No trend identified. Climate effects projected to remain the same.
	Ice accretion/ storm	All applicable.	Environmental Effects	Low	Additional Study Required	Insufficient information currently available.

- No further action 34 recommendations.

- Additional study 12 recommendations - 5 related to the effects of rain on drainage infrastructure, 1 related to the effects of groundwater on embankments/cuts, and 6 related to the effects of ice accretion/ice storms on various infrastructures.

In summary, the recommendations were developed as a result of the application of the PIEVC protocol specifically, medium priority recommendations and recommendations that call for remedial action and/or additional study focus on the stormwater management aspects of drainage infrastructure and unpaved roads, the effects of high temperature on paved roads, the effects of rainfall (groundwater) on embankments/cuts and the further evaluation of the potential vulnerabilities related to the effects of ice accretion on roads & associated infrastructure.

Specific recommendations, in order of decreasing importance, are as follows:

1. Develop a database containing hydraulic information for all of the culverts within the City of Greater Sudbury. It is our understanding that a database containing structural information already exists for large culverts/bridges greater than 3 meters. The addition of hydraulic and possibly environmental information would allow this combined database to be used as a planning and optimization tool. This database would incorporate the combined maintenance and replacement of the structure and the associated driving surface, flood risk analyses, stormwater management, the identification of potential limits to development due to lack of hydraulic capacity, environmental management and HADD compensation. In short, the lack of data available for the City of Greater Sudbury's infrastructure, specifically, drainage related infrastructure, can be considered a vulnerability in itself.

2. Perform a capacity evaluation of the minor and major drainage systems within the City of Greater Sudbury.

3. Perform impact assessments of the functionality and environmental effects associated with increased rainfall intensity and frequency on gravel-surfaced roads. Together with the previous recommendations are intended to address the unknowns associated with the capacities of drainage infrastructure and unpaved roads identified during the study.

4. The lack of reliable information related to potential increases in ice accretion / ice storms. It will be necessary to perform a risk and criticality assessment of the various infrastructures, design standards, and operations & maintenance procedures that are potentially impacted by this event. The assessment should focus on drastic impacts of ice, snow, the re-freezing of ponded water and slush as it impacts on the functionality of sidewalks. This information will then be a priority that is assigned to the winter maintenance of sidewalks in particular.

5. Evaluate the possibility as well as the costs associated with changing the asphalt mixes used in the City of Greater Sudbury. The new standard would be initiated in order to accommodate higher temperatures. The use of modified asphalt mixes will allow the gradual development of additional adaptive capacity for the high temperature – paved road interactions during regular road rehabilitation and reconstruction. Alternatively, the use of trees to provide shade on low-speed roads (local and collector roads) and reduce the urban “heat island: effect” could also be considered.

6. Perform sensitivity analyses on the slope stability of large and “high risk” embankments/cuts within the City of Greater Sudbury in response to increased groundwater levels.

7.0 CONCLUSIONS

Based on the information presented above and the insights gained during the application of the PIEVC protocol to the vulnerability assessment of roads and associated structures within the City of Greater Sudbury, the following conclusions were reached.

1. The roads and associated structures within the City of Greater Sudbury generally are robust and do not appear to have any major vulnerabilities to the predicted effects of climate change, with the exception of the drainage infrastructure vulnerability to the predicted changes in rainfall events as presented below.

2. The assessment revealed the drainage infrastructure (culverts, bridges, ditches, catch basins and storm sewers) to have potentially major vulnerabilities to the predicted increases in the severity and frequency of rainfall events associated with climate change. These vulnerabilities are expected to consist of the surcharging and flooding of the drainage infrastructure, with likely impacts on all performance responses (including

structural integrity, functionality, and operations & maintenance). It was however not possible to quantify this vulnerability due to the lack of hydraulic information for the existing drainage infrastructure within the City of Greater Sudbury.

3. The assessment revealed gravel-surfaced roads to have moderate vulnerabilities to the predicted increases in the severity and frequency of rainfall events associated with climate change. These vulnerabilities are expected to consist of washouts and rutting of gravel-surfaced roads, with likely impacts on the functionality, operations & maintenance, and environmental performance responses.

4. The assessment revealed the asphalt-surfaced roads to have minor vulnerabilities to the predicted increases in temperatures associated with climate change. These vulnerabilities are expected to consist of increased softening and rutting of asphalt surfaces, with likely impacts on the durability and operations & maintenance performance responses. This minor vulnerability should be couched in the knowledge that the relatively short service life of roads (approximately 30 years) will allow the adjustment of asphalt mix designs to accommodate the predicted future temperature increases as the existing inventory of roads is replaced and as new roads are constructed.

5. The assessment revealed the embankments and road cuts to have minor vulnerabilities to the predicted increases in groundwater table fluctuations associated with climate change. These vulnerabilities are expected to consist of minor increases in the destabilizing forces on embankments and road cuts, with potential impacts on the structural integrity performance responses.

6. Due to a lack of climate prediction data, the assessment was unable to demonstrate (neither qualitatively nor quantitatively) a vulnerability to the potential increases in the frequency and severity of ice accretion/ice storms associated with climate change. However, as this inability is due to a lack of data and in light of the potentially severe vulnerabilities associated with ice on roads and associated structures, a risk and critically assessment should be performed to evaluate the various infrastructures, design standards, and operations & maintenance procedures that are potentially impacted by ice accretion/ice storms.

APPENDIX A2-1

Ouranos Climate Change Report

Climate change in Canada
Climate scenarios for the public infrastructure vulnerability assessment

Sudbury Roads and Associated infrastructure case study

Produced for the *Public Infrastructure Engineering Vulnerability Committee* (PIEVC)

By Ouranos

January 2008

Ouranos, a research consortium on regional climatology and adaptation to climate change, is a joint initiative of the Government of Québec, Hydro-Québec, and the Meteorological Service of Canada with the participation of UQAM, Université Laval, McGill University, and the INRS. Valorisation Recherche Québec collaborated on the establishment and financing of Ouranos. The opinions and results presented in this publication are the sole responsibility of Ouranos and do not reflect in any way those of the aforementioned organizations.

Report prepared by:

Travis Logan
Specialist – Climate change scenarios

Caroline Larrivée
Specialist – Climate change and infrastructure

Diane Chaumont
Coordinator – Climate Change Scenarios

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1. Introduction

The Canadian Council of Professional Engineers set up the Public Infrastructure Engineering Vulnerability Committee (PIEVC) to examine the vulnerability of public infrastructure to climate change across the nation. A series of case studies serve to assess infrastructure vulnerability with the protocol proposed in Phase 1 of the PIEVC initiative and provide feedback on the state of different categories of infrastructure throughout the country. The current study is located in the Sudbury region (Ontario) and focuses on roads and associated infrastructure.

The draft engineering protocol requires information on a variety of climatic elements to use as input towards estimating the vulnerability of infrastructure to climate change. Estimates of climatic elements enable numerical estimations of the exposure of the infrastructure and help identify which changes in climatic conditions will have the most impact on its vulnerability.

In order to provide coherent and equivalent results for all of the pilot projects, the vulnerability analyses must be based on plausible and comparable scenarios of climate change for the various regions of the country. Ouranos has been mandated to provide this data.

This report provides historical climate data and climate change scenarios for the Sudbury region on the vulnerability of the City's roads and associated infrastructure.

The data provided in this report is intended for the use of this case study only and should not be used for any other purpose because the results are specific to the characteristics of this project (location, timeframe, etc.).

2. Methodology

2.1. Selection of weather stations

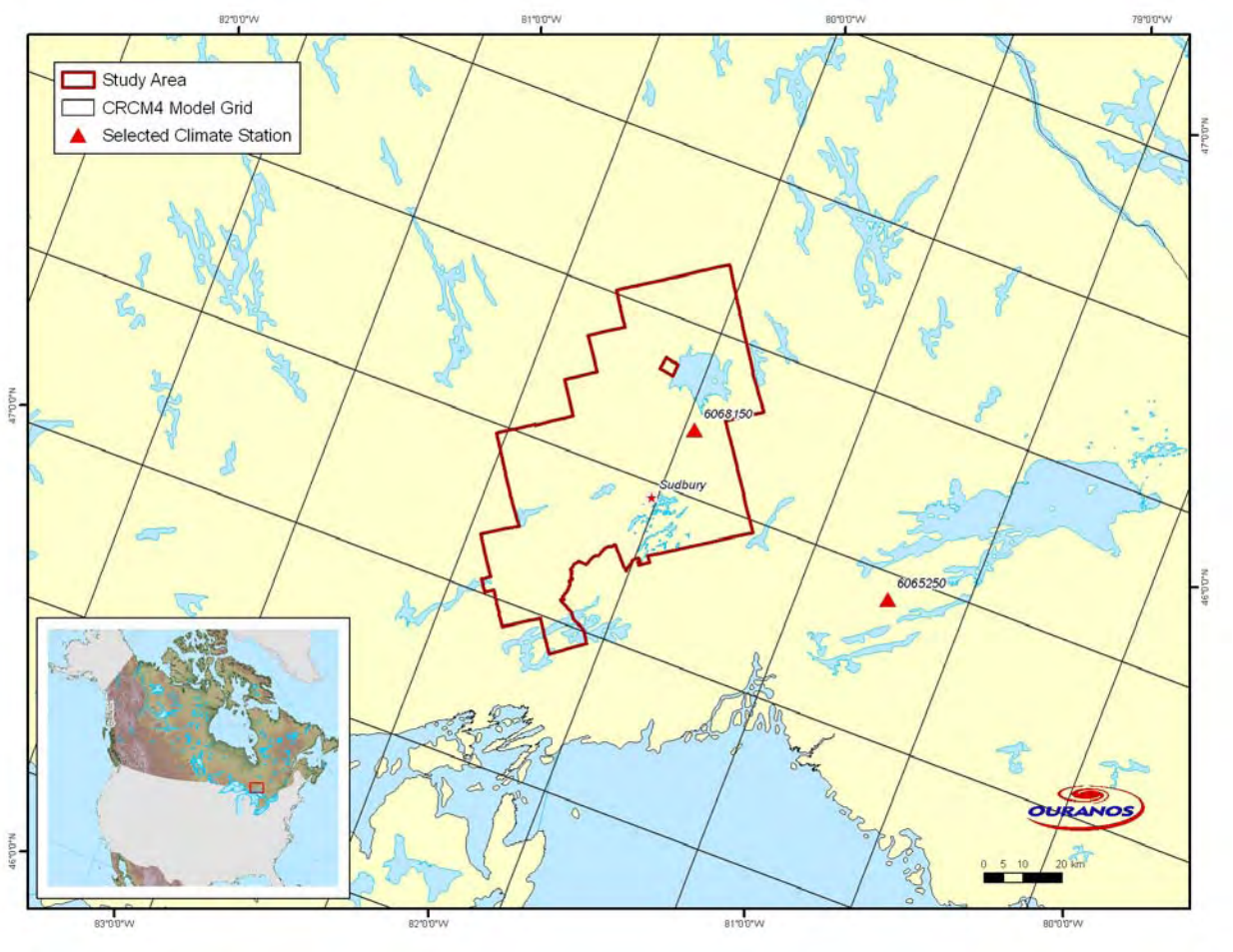
Observed weather station data was obtained from Environment Canada's national archives for the area of interest. Archived data were screened in order to select stations deemed to have a sufficiently long/complete record. Selection criteria included: a data series minimum length of 20 years, with less than 10% missing data and a final year being no earlier than 1995. A summary of the selected stations is presented in Table 2.1. The distribution of the stations within the study region is shown in Figure 2.1.

***NB – after selection criteria were applied only a single climate station remained (Sudbury Airport) within the study area (Sudbury municipal boundaries) – see Figure 2.1. However, it was deemed prudent, wherever possible, to include a second station (some variables were unavailable) in order to include some variability in the calculation of average observed climatic indices. As such, the Monetville station (ID 6065250) was included in the analysis for variables with sufficient data.*

Table 2.1 Selected Environment Canada station data for variables of Temperature, Precipitation, Snow and Wind
(Selection was based on the criteria of a minimum record length of 20 years and a maximum of 10% missing data, and final year no earlier than 1995).

	Climatic Variables					
ID	TMAX	TMIN	SNOWFALL	RAINFALL	SNOWGROUND	Wind
6068150	yes	yes	yes	yes	yes	yes
6065250	yes	yes	yes	yes (NB -daily only)	no	no

Figure 2.1 Canadian Regional Climate Model (CRCM4) grid and location of selected climate stations within the study area.



2.2. Choice of climate model

Impacts and adaptation projects should, in a best-case scenario, be based on projections of multiple climatic simulations in order to ensure that uncertainty of future climate projections is fully explored and incorporated in decision-making processes. Furthermore, in a regional context, such as the current PIEVC pilot project, downscaling of coarse resolution Global Circulation Model (GCM) output is desirable. Regional climate modeling employing the commonly termed approach of dynamical downscaling is one area of expertise covered by the Ouranos consortium and its research partners. Ouranos has contributed to the development of the Canadian Regional Climate Model (CRCM; Caya and Laprise, 1999) which, like other regional climate models (RCMs), uses principles of conservation on energy, mass and movement to generate temporal series of *physically coherent climatic variables*. Developed using the same physical principles as GCMs, RCMs concentrate on a portion of the globe and allow production of simulations at higher spatial resolution (approximately 45km for the CRCM compared to the several hundred seen with typical GCMs). Dynamical downscaling can have a particular advantage in simulating meso-scale weather events when compared with global models. As such, extreme events (particularly precipitation events) are typically

better reproduced by regional modeling efforts. Plummer *et al*. (2006) showed that general observed patterns of precipitation and temperature are relatively well reproduced over North America by the CRCM (version 3.7.1). Regional comparison of CRCM precipitation output (again version 3.7.1) and corresponding intensity duration frequency curves showed favourable results versus observed values for southern Quebec (Mailhot *et al*. 2007). Mailhot *et al*. also state that there is good indication that CRCM results are statistically consistent with observations in terms of extreme rainfall estimates.

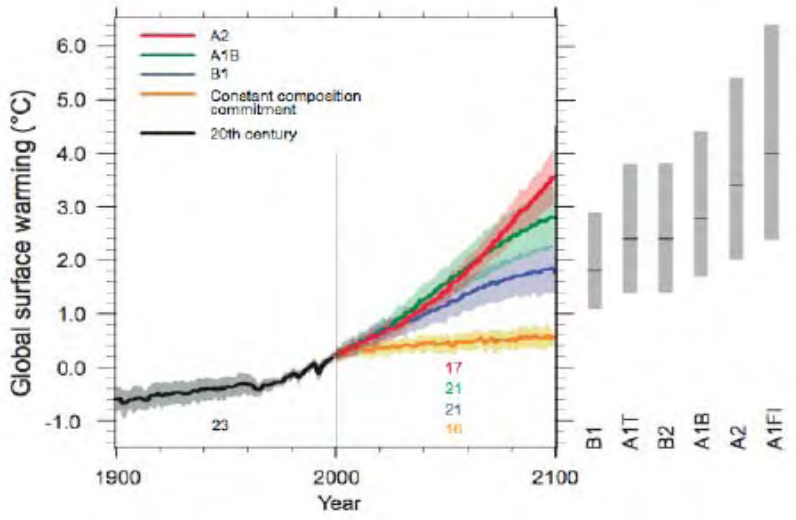
In general the majority of CRCM simulations produced by Ouranos for impacts and adaptation purposes focus on the future period of 2041-2070 (termed horizon 2050). However, due to increasing demand for climatic scenarios for different future periods a small number of continuous simulations have been produced for the period 1961-2100. Two of these simulations have been selected for use in this case study. The simulations were produced using the CRCM, version 4.1.1 (Music and Caya, 2007; Brochu and Laprise, 2007). This selection was based on the advantages of having increased spatial resolution (compared to GCMs), the availability of continuous future daily series for the period 1961-2100 (the future horizons of interest in the pilot study being horizons 2020, 2050 and 2080). The choice was also due to the time constraints imposed for completion of the project.

NB - it is important to note that, due to the restricted number of simulations, caution is required in the interpretation of any modeling effort or analysis based on the scenarios provided. Use of only 2 simulations is sufficient for sensitivity analyses but lacks the robustness provided by the use of a large ensemble of simulations (recommended for decision-making or policy planning; see Conclusions - section 4 of this report).

The two simulations (CRCM 4.1.1 ACU; CRCM4.1.1 ADC) were carried out for a domain centred over Québec and covering an area of approximately 5,050 km by 4,000 km with a horizontal grid-size mesh of 45 km (true at 60 degrees north latitude) for the period 1961-2100. The simulations were driven at their boundaries by atmospheric fields taken from simulation output of the 4th and 5th members of the third generation coupled Canadian Global Climate Model (CGCM3). Both global and regional simulations were performed using the IPCC SRES A2 greenhouse gas (GHG) and aerosol projected evolution[1]. Figure 2.2 shows the simulated mean global temperature evolution according to the multiple GCM output grouped under various SRES different scenarios. It is interesting to note that the emissions scenarios diverge very little before approximately 2050.

[1] "The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing population. Economic development is primarily regionally oriented and per capita economic growth and technological change more fragmented and slower than other storylines." (Nakicenovic *et al*., 2000)

Figure 2.2 Mean global temperature evolution according to the multiple GCM output grouped under various SRES different scenarios.



2.3. Climate model simulations and time periods

A total of 6 CRCM grid cells fell within the study area boundaries (see Figure 2.1). Corresponding grid cell data from the two CRCM 4.1.1 simulations described in section 2.2 (ACU and ADC) were extracted and used to calculate the climate indices listed in section 2.4. Future changes in indices were determined for three future periods or horizons: **horizon 2020** (2011 – 2040); **horizon 2050** (2041-2070); and **horizon 2080** (2071-2100) with respect to the present period (**1961-1990**).

Changes (or deltas) in indices are calculated as either the difference or ratio between simulated future conditions and simulated present day conditions. Deltas can then be applied to calculated observed values either through addition (difference) or multiplication (ratio).

2.4. Description of climate indices

The choice and priority of climate indices was made in consultation with the client in terms of project needs as well as in terms of the limitations of the climate model simulations. Calculated indices were chosen from those having been known and used in the climate literature in the past.

Temperature indices

a. Monthly average maximum temperature (Monthly AVG TMAX):
   - Average daily maximum temperature for a given month over the time period

b. Monthly average minimum temperature (Monthly AVG TMIN):

- *Average daily minimum temperature for a given month over the time period*

c. Average annual daily maximum temperature (annual_max):

$$annual_\max = \left(\sum_{i=1}^{I} (t\max 365i) \right) / I$$

Calculated as the sum of $t\max 365i$ for years *i* through I divided by the number of years. Where $t\max 365i$ is the highest daily temperature for a given year *i*

d. Average annual daily minimum temperature (annual_min):

$$annual_\min = \left(\sum_{i=1}^{I} (t\min 365i) \right) / I$$

Calculated as the sum of $t\min 365i$ for years *i* through I divided by the number of years. Where $t\min 365i$ is the lowest daily temperature for a given year *i*

Rain indices

Rain indices refer in all cases to precipitation in **liquid form*

a. Rainfall Frequency 6 hour (6h_frequency)
   - *cutoff values of 5, 10 and 20 mm*
   - *frequency of events that are greater than cutoff(s)*

b. Rainfall Frequency 1 day (1day_frequency)
   - *cutoff values of 5, 10 and 20 mm*
   - *frequency of events that are greater than cutoff(s)*

c. Yearly Max. Rainfall (annual_max_rain):

   - *average maximum yearly rainfall event for 1, 2 and 5-day periods*

$$annual_\max_rain = \left(\sum_{i=1}^{I} (rain365ix) \right) / I$$

Calculated as the sum of $rain365ix$ for years *i* through I divided by the number of years. Where $rain365ix$ is the highest rainfall amount for a given year *i summed over period of x days.*

d. Average total annual / seasonal rainfall (Avg_total_rain)
   - *average sum of liquid precip for the year and 4 seasons (DJF, MAM, JJA, SON)*

e. Simple Daily Intensity Index (SDII)
   - *mean rainfall amount per wet day (wet day > 1mm)*

f. Drought : Average maximum annual dryspell length (Avg_max_dryspell
- *average yearly maximum number of consecutive 'no rain days' (< 1mm) for the season April 1 – Oct 31st*

$$Avg_MAX_dryspell = \left(\sum_{i=1}^{I} (dSPELLi) \right) / I$$

Calculated as the sum of $dSPELLi$ for years *i* through I divided by the number of years. Where $dSPELLi$ is the maximum dryspell length for a given year *i.*

g. Wetspell: Average maximum annual wetspell length (Avg_max_wetspell)
- *average yearly maximum number of consecutive 'rain days' (> 1 mm) for the season April 1 – Oct 31st*

$$Avg_MAX_wetspell = \left(\sum_{i=1}^{I} (wSPELLi) \right) / I$$

Calculated as the sum of $wSPELLi$ for years *i* through I divided by the number of years. Where $wSPELLi$ is the maximum wetspell length for a given year *i.*

Snow indices

**Snow index values in mm indicate values of Snow Water Equivalent (SWE) in all cases.*
***Observed snowfall values from EC stations had units of cm of snow and were converted to SWE using an assumed conversion ratio of 10:1 (i.e. 10 mm of fresh snow = 1mm SWE)*

a. Snowfall Frequency 1 day (1day_frequency)
- *cutoff values of 5, 10 and 20 mm*
- *frequency of events that are greater than cutoff(s)*

b. Yearly Max. Snowfall (annual_max_snow):
- *average maximum yearly rainfall event for 1, 2 and 5-day periods*

$$annual_\max_snow = \left(\sum_{i=1}^{I} (snow365ix) \right) / I$$

Calculated as the sum of $snow365ix$ for years *i* through I divided by the number of years. Where $snow365ix$ is the highest rainfall amount for a given year *i summed over period of x days.*

c. Average Total annual / seasonal rainfall (Avg_total)

- average sum of solid precipitation for the year and 4 seasons (DJF, MAM, JJA, SON)

d. Simple Daily Intensity Index (SDII)
- mean snowfall amount per wet day (wet day > 1mm)

e. Rain on snow events
- occurrence defined as presence liquid precipitation > 1mm combined with presence of snow on ground (> 0)
- cutoff values of 1, 5 and 10 mm
- frequency of events that are greater that cutoff(s) over 1-day period

Wind indices

**Wind index values in m/s indicate values of average wind speed over a 6h period.*
***NB – A 6hour timestep was used as this is the minimum timestep available for analysis for the CRCM4 data.*

a. Monthly average 6h Windspeed (Monthly AVG WIND6h):
- Average 6h windspeed for a given month over the time period

b. Yearly Max. 6hour Wind (*Avg annual MAX6h*):

- average maximum yearly 6h Wind

$$Avg_annual_MAX6h = \left(\sum_{i=1}^{I} (wind365i) \right) / I$$

Calculated as the sum of $wind365i$ for years *i* through *I* divided by the number of years. Where $wind365i$ is the highest 6h mean windspeed for a given year *i.*

Frost indices

a. Frost Season (fr_seas_dys)
-Average annual max length in days that the 30 day moving average of daily average temperature remains consecutively below 0 degrees celsius

b. Freeze Thaw Cycles (frz_thw_freq)
- Frequency of days where tmax > 0 degrees C and tmin < 0 degrees C

2.5. Regionalization of climate indices

Climate indices listed in section 3.1 were calculated for each climate station and each RCM grid cell individually. A regional value for each index is then determined by taking the average of all stations (grid points) within the study area. These regional values are presented in the results section of this report.

3. Results

3.1 Climate scenarios for Temperature, Rain, Snow, Wind and Frost indices

TEMPERATURE indices

TEMPERATURE : Monthly AVG TMAX							
Month	*Observed (°C)*	*Future Change ACU*			*Future Change ADC*		
		2020 *(°C)*	***2050*** *(°C)*	***2080*** *(°C)*	***2020*** *(°C)*	***2050*** *(°C)*	***2080*** *(°C)*
January	-7.62	0.32	2.71	4.80	2.00	4.51	6.09
February	-5.42	1.83	3.86	5.29	2.87	5.43	5.47
March	0.42	1.47	2.90	4.53	2.66	2.20	4.49
April	8.95	1.13	2.48	3.83	1.52	1.68	2.80
May	16.98	1.56	2.38	4.69	1.56	3.43	5.90
June	22.22	1.48	3.25	4.76	1.53	2.91	4.39
July	24.91	1.39	3.29	5.29	2.82	3.50	6.25
August	23.37	1.96	3.58	6.34	1.67	3.15	5.33
September	18.09	0.93	2.99	5.67	2.00	3.71	5.32
October	10.93	1.48	3.00	4.96	2.38	3.23	5.60
November	2.95	1.29	1.98	2.92	1.52	2.63	4.04
December	-4.17	1.57	2.99	4.22	3.00	3.90	4.65

TEMPERATURE : Monthly AVG TMIN

Month	*Observed (°C)*	*Future Change ACU*			*Future Change ADC*		
		2020 *(°C)*	***2050*** *(°C)*	***2080*** *(°C)*	***2020*** *(°C)*	***2050*** *(°C)*	***2080*** *(°C)*
January	-18.13	1.37	3.89	7.25	2.62	5.54	7.96
February	-16.45	2.67	4.66	7.08	3.41	6.17	7.21
March	-10.42	2.19	4.22	6.27	2.43	3.29	5.85
April	-1.90	1.94	3.86	5.86	2.02	2.74	4.68
May	4.76	1.96	3.53	5.61	1.98	3.96	6.31
June	10.07	1.50	3.26	4.71	1.55	2.95	4.25
July	12.88	1.62	3.11	4.79	2.18	3.04	5.10
August	11.91	2.15	3.40	5.48	1.68	3.12	4.69
September	7.51	1.13	2.71	5.02	1.96	3.45	5.15
October	1.93	1.39	2.53	5.00	2.36	3.01	5.45
November	-4.34	1.86	2.27	3.78	1.87	3.15	4.60
December	-13.10	2.21	3.70	6.00	4.03	5.65	6.75

TEMPERATURE : annual max /annual min

Month	*Observed (°C)*	*Future Change ACU*			*Future Change ADC*		
		2020 *(°C)*	***2050*** *(°C)*	***2080*** *(°C)*	***2020*** *(°C)*	***2050*** *(°C)*	***2080*** *(°C)*
annual maximum	31.95	1.96	3.53	5.61	1.93	3.84	5.61
annual minimum	-34.54	2.31	3.44	7.87	2.49	5.80	7.69

RAIN indices

RAIN : 6h_Frequency

cutoff (mm)	*Observed (frequency)*	*Future Change ACU*			*Future Change ADC*		
		2020 *(ratio)*	***2050*** *(ratio)*	***2080*** *(ratio)*	***2020*** *(ratio)*	***2050*** *(ratio)*	***2080*** *(ratio)*
5	0.0235	1.07	1.24	1.45	1.25	1.30	1.60
10	0.0095	1.21	1.39	1.82	1.34	1.49	2.01
20	0.0020	1.40	1.99	2.44	1.85	2.17	3.95

RAIN : 1day_Frequency

cutoff (mm)	*Observed (frequency)*	*Future Change ACU*			*Future Change ADC*		
		2020 *(ratio)*	***2050*** *(ratio)*	***2080*** *(ratio)*	***2020*** *(ratio)*	***2050*** *(ratio)*	***2080*** *(ratio)*
5	0.1118	1.10	1.20	1.30	1.13	1.17	1.30
10	0.0602	1.11	1.24	1.49	1.21	1.27	1.57
20	0.0204	1.14	1.35	1.95	1.37	1.54	2.20

RAIN: Avg_Max_rain

period (days)	*Observed (mm)*	*Future Change ACU*			*Future Change ADC*		
		2020 *(ratio)*	***2050*** *(ratio)*	***2080*** *(ratio)*	***2020*** *(ratio)*	***2050*** *(ratio)*	***2080*** *(ratio)*
1	48.32	1.05	1.09	1.17	1.06	1.12	1.31
2	57.06	1.09	1.11	1.27	1.11	1.13	1.34
5	70.61	1.12	1.14	1.26	1.07	1.13	1.27

RAIN : Avg_total_rain

Total rain	*Observed (mm)*	*Future Change ACU*			*Future Change ADC*		
		2020 *(ratio)*	***2050*** *(ratio)*	***2080*** *(ratio)*	***2020*** *(ratio)*	***2050*** *(ratio)*	***2080*** *(ratio)*
Annual	690.58	1.09	1.18	1.34	1.13	1.16	1.33
DJF	39.71	1.65	2.20	3.33	1.71	1.94	2.99
MAM	155.98	1.14	1.37	1.66	1.28	1.30	1.57
JJA	244.75	1.04	1.05	0.97	1.03	1.00	0.96
SON	241.09	1.04	1.08	1.30	1.06	1.17	1.42

RAIN : Simple Daily Intensity Index (SDII)

Observed (mm/day)	*Future Change ACU*			*Future Change ADC*		
	2020 *(ratio)*	***2050*** *(ratio)*	***2080*** *(ratio)*	***2020*** *(ratio)*	***2050*** *(ratio)*	***2080*** *(ratio)*
8.84	1.03	1.07	1.14	1.08	1.11	1.22

RAIN : Dry spells / Wet_spells

	Observed (days)	*Future Change ACU*			*Future Change ADC*		
		2020 *(days)*	***2050*** *(days)*	***2080*** *(days)*	***2020*** *(days)*	***2050*** *(days)*	***2080*** *(days)*
Avg MAX Dryspell	14.74	0.66	-0.09	-0.30	0.83	0.44	1.38
Avg MAX Wetspell	4.74	-0.42	-0.21	0.07	0.66	-0.06	0.15

SNOW indices

SNOW : 1day_Frequency

SWE cutoff (mm)	*Observed (frequency)*	*Future Change ACU*			*Future Change ADC*		
		2020 *(ratio)*	***2050*** *(ratio)*	***2080*** *(ratio)*	***2020*** *(ratio)*	***2050*** *(ratio)*	***2080*** *(ratio)*
5	0.0446	0.95	0.98	0.78	0.95	0.87	0.83
10	0.0149	0.98	1.09	0.76	1.00	0.78	0.89
20	0.0018	1.27	2.18	1.59	0.79	0.67	1.48

SNOW`: Annual_Max_snow

period (days)	*Observed (mm)*	*Future Change ACU*			*Future Change ADC*		
		2020 *(ratio)*	***2050*** *(ratio)*	***2080*** *(ratio)*	***2020*** *(ratio)*	***2050*** *(ratio)*	***2080*** *(ratio)*
1	23.36	1.05	1.28	1.12	0.98	0.89	1.05
2	29.51	0.98	1.25	1.03	1.04	0.96	1.08
5	39.13	0.96	1.15	0.94	1.02	0.94	1.02

SNOW : Avg_total_snow

Total snowfall (SWE) (mm)	*Observed (mm)*	*Future Change ACU*			*Future Change ADC*		
		2020 *(ratio)*	***2050*** *(ratio)*	***2080*** *(ratio)*	***2020*** *(ratio)*	***2050*** *(ratio)*	***2080*** *(ratio)*
Annual	248.53	0.91	0.90	0.75	0.93	0.85	0.80
DJF	166.98	1.06	1.03	0.95	0.98	0.98	1.03
MAM	49.88	0.81	0.77	0.60	1.06	0.88	0.64
JJA	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SON	34.93	0.59	0.73	0.41	0.59	0.38	0.37

SNOW : Simple Daily Intensity Index (SDII)

Observed (mm/day)	*Future Change ACU*			*Future Change ADC*		
	2020 *(ratio)*	***2050*** *(ratio)*	***2080*** *(ratio)*	***2020*** *(ratio)*	***2050*** *(ratio)*	***2080*** *(ratio)*
5.28	1.04	1.14	1.08	1.02	1.00	1.08

SNOW : Rain_on_Snow_events

Rain cutoff (mm)	*Observed (frequency)*	*Future Change ACU*			*Future Change ADC*		
		2020 *(ratio)*	***2050*** *(ratio)*	***2080*** *(ratio)*	***2020*** *(ratio)*	***2050*** *(ratio)*	***2080*** *(ratio)*
1	0.0251	0.99	1.07	1.12	1.01	0.97	1.05
5	0.0131	1.12	1.18	1.30	1.15	1.13	1.24
10	0.0062	1.12	1.22	1.52	1.42	1.38	1.64

WIND indices

WIND : Monthly AVG WIND6h

Month	*Observed (km/h)*	*Future Change ACU*			*Future Change ADC*		
		2020 *(ratio)*	***2050*** *(ratio)*	***2080*** *(ratio)*	***2020*** *(ratio)*	***2050*** *(ratio)*	***2080*** *(ratio)*
January	17.89	0.97	0.99	1.04	1.02	1.09	1.09
February	18.32	1.02	0.97	1.06	1.05	1.07	1.04
March	18.33	0.98	1.04	1.04	1.05	1.04	1.03
April	18.70	1.05	1.04	1.05	1.00	0.98	1.03
May	17.62	1.01	1.03	1.04	1.06	1.05	1.05
June	16.43	0.98	0.99	0.97	0.97	0.98	0.98
July	15.01	0.98	0.96	0.95	1.00	1.01	1.02
August	14.71	0.98	0.95	0.96	1.00	0.98	0.95
September	16.16	0.98	0.97	0.94	0.98	0.98	0.96
October	17.36	0.98	1.01	1.02	1.00	1.03	1.00
November	18.32	1.04	1.06	1.09	0.98	0.97	1.04
December	17.52	1.00	1.02	1.03	1.06	1.01	1.05

WIND : AVG Annual MAX WIND6h						
Observed (km/h)	*Future Change ACU*			*Future Change ADC*		
	2020 *(ratio)*	***2050*** *(ratio)*	***2080*** *(ratio)*	***2020*** *(ratio)*	***2050*** *(ratio)*	***2080*** *(ratio)*
53.47	0.996	1.024	1.012	1.002	1.004	1.001

FROST INDICES

FROST SEASON LENGTH : fr_seas_dys						
Observed (days)	*Future Change ACU*			*Future Change ADC*		
	2020 *(days)*	***2050*** *(days)*	***2080*** *(days)*	***2020*** *(days)*	***2050*** *(days)*	***2080*** *(days)*
133.73	-9.72	-22.19	-34.93	-21.13	-24.98	-31.95

FREEZE THAW EVENTS: fr_thw_freq						
Observed (frequency)	*Future Change ACU*			*Future Change ADC*		
	2020 *(ratio)*	***2050*** *(ratio)*	***2080*** *(ratio)*	***2020*** *(ratio)*	***2050*** *(ratio)*	***2080*** *(ratio)*
0.20	0.94	0.93	0.87	0.98	0.96	0.87

3.2 Literature review for other climate indices

While climate scenarios for temperature changes and changes in precipitation patterns are quite reliable, there is far greater uncertainty linked to projections for relatively small-scale or very localized atmospheric phenomena. Most authors agree that GHG concentrations do have an effect on these events; however, it remains difficult to find reliable projections that indicate future trends of intensity, direction or frequency for events such as storms, intense winds or other extreme events (Maarten, 2006). Climate scenarios are therefore difficult to produce for certain very localized events (wind gusts, tornadoes, thunderstorms) or events where processes are complex and depend on a number of factors (hurricanes, ice storms). The observed data is insufficient to validate the model outputs for these events.

Moreover, any seemingly apparent trend stemming from the observed data must be interpreted carefully as an increase could result from a combination of factors such as:

- increased weather station coverage
- improved quality of the data collected
- changes in land use (and corresponding increases in damage claims).

Consequently, among the list of climate elements that were requested for the Sudbury case study, it is not possible to provide sound numerical climate scenarios that could be used for the infrastructure vulnerability assessment. The following is the list of climate variables that fall under this category with a review of the literature explaining possible changes.

WIND (hurricanes, tornadoes, thunderstorms, winds gusts)

According to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2007), it is “more likely than not” that the observed trend of hurricane intensification since the 1970s is linked to human-induced greenhouse gas emissions. The report also claims that “it is likely that future tropical cyclones (typhoons and hurricanes) will become more intense, with larger peak wind speeds and more heavy precipitation associated with ongoing increases of tropical sea surface temperatures.” However, there is no clear trend in terms of the frequency of tropical cyclones. Although some authors claim that there has been an increase in the frequency of hurricanes, namely in the North Atlantic (Holland *et al.* 2007, Webster *et al.* 2005), there remains much debate as to the possible mechanisms explaining this.

Results from some model simulations suggest that the atmosphere over mid-latitude land areas could become more unstable in the future, suggesting that an increase in convective activity is quite probable (Balling *et al.* 2003). However, researchers have been unable to identify significant increases in overall severe storm activity as measured in the magnitude and/or frequency of thunderstorms, hail events, tornadoes, hurricanes, and winter storm activity in North America. Increasing trends in damages caused by these events seem to be more closely linked to changes in demography and land use (Balling *et al.* 2003)

ICE (ice build-up, ice accretion, freezing rain)

Ice build-up, caused by melting blocks of ice that accumulate and obstruct water ways or pile up around infrastructure components, can be triggered by:
- rapid melt events when there is a significant accumulation of snow and ice
- heavy precipitation events in spring when there is still a cover of ice
- heavy rain on snow events

Warmer average temperatures throughout the year (see climate scenarios in section 3.1) suggest that the length and severity of the cold season will decrease. However, depending on precipitation patterns, this could mean either an increase or decrease in river or lake ice build-up, because of the nature of the precipitation as well as the intensity of the events that cause ice build-up.

Very few studies have been conducted on the possible impacts of climate change on freezing rain events and ice storms. A study conducted over northern and eastern Ontario (Cheng *et al.* 2007) suggests that freezing rain events could move further north as the boundary between snowfall and rainfall shifts northward. However, as the temperatures increase in the Fall and Spring (beginning and end of the winter season), freezing rain events could decrease since precipitation falling as freezing rain could fall as liquid rain under warmer conditions. At present, it remains unknown how climate change could affect the frequency and severity of freezing rain events and ice storms (Irland, 2000, Cheng *et al.* 2007).

SNOW (rapid melt events)

Variations and trends in temperature significantly influence snow covered areas, namely by determining whether precipitation falls as snow or rain and determining snowmelt (IPCC, 2007). However rapid snowmelt events are difficult to predict because they depend on a number of factors, including:
- temperature and precipitation conditions at the time of the melt
- total amount of snow on the ground

Because these events occur as the result of a combination of factors and can be very localized (in both time and space), it is difficult to establish reliable scenarios of change in future climate conditions. Moreover, the inherent variability of the climate makes it difficult to predict whether this type of event will occur more frequently or more intensely, as a change in only one of the determining factors can determine whether rapid snowmelt will happen or not.

Nevertheless, it is recognized that changes in average temperature will impact precipitation and wind patterns and influence the change in probability distributions of many atmospheric processes. Indeed, a warmer atmosphere increases the chances for convective activity. This is already the case in warmer regions of the world during warmer seasons (Balling *et al.* 2003). This will impact the frequency, intensity, duration and direction of extreme events such as tornadoes, hailstorms, thunderstorms. However, it remains difficult to determine quantitatively precisely how these events will change.

Climate change will also influence the variability of the climate, including inter-annual events such as El Nino. However, climate scenarios on this type of climate phenomenon or event have not yet been developed.

To assess the vulnerability of infrastructure to changes in these parameters where numerical scenarios are not reliable, it can be useful to conduct “what if” scenarios, using a plausible factor of change to add to historical trend data and local knowledge of climate events. These sensitivity analyses help to determine at what threshold the infrastructure can become vulnerable to climatic events and estimate the likelihood of such events happening based on the physics of climate change and on local observations of climate events.

4 Conclusion

The case studies carried out within the PIEVC initiative to assess infrastructure vulnerability to climate change using the protocol developed in Phase 1 of the initiative require plausible and reliable climate scenarios based on similar methodologies in order to compare the relative vulnerability of various infrastructures throughout the country.

This report provides historical climate data and climate change scenarios for the Sudbury region case study on the vulnerability of the City's roads and associated infrastructure.

Prudence is required in the interpretation of analyses based on the future scenarios provided. Climate scenario production was limited to the use of only 2 simulations. Furthermore, these simulations were produced by the same regional climate model (CRCM 4.1.1), driven by two runs of the same GCM (CGCM3) and the same GHG emissions scenario (SRES A2). In short, the predicted changes cover only a small portion of the spectrum or envelope of changes that would be produced via the use of multiple SRES scenarios and multiple driving models (or even multiple RCMs). **As such, it is recommended that any decision or policy making activities be based on an expanded version of the present case study.**

At present, large ensemble analyses using strictly RCM output are not possible over North America. However, Ouranos continues to produce RCM simulations, and is also actively involved in the North American Regional Climate Change Assessment Program (NARCCAP http://www.narccap.ucar.edu/), an international program that will serve the high resolution climate scenario needs of the United States, Canada, and northern Mexico, using regional climate model, coupled global climate model, and time-slice experiments. The needs of the PIEVC (i.e. simulations with a fine spatial resolution, and inclusion of a number of extreme indices) would be best addressed using an ensemble of multiple RCM driven by multiple pilot GCMs such as will be produced with NARCCAP project This approach would allow a large inclusion of possible futures and thus better cover the envelope of uncertainty. Further research continues to be needed in climate modeling and climate scenarios in order to provide reliable data for climate change vulnerability and impacts assessments.

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APPENDIX A3-1

Vulnerability Assessment Matrix Results (Step 3)

APPENDIX A3-1 - TABLE 11
SAMPLE VULNERABILITY ASSESSMENT MATRIX
STEP 3

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Infrastructure Components	Performance Criteria	Potential Climate Event																														Recommendations/Comments
		High Temp				Low Temp				Precip. As Rain				Precip. As Snow				Wind				Ice Accretion (Ice Storm)				Hail				Frost (Freeze/Thaw Cycles)				Ground Water Table				
		Y/N	S_C	S_R	P_C	Y/N	S_C	S_R	P_C	Y/N	S_C	S_R	P_C	Y/N	S_C	S_R	P_C	Y/N	S_C	S_R	P_C	Y/N	S_C	S_R	P_C	Y/N	S_C	S_R	P_C	Y/N	S_C	S_R	P_C	Y/N	S_C	S_R	P_C	
Arterial																																					
Surface - Asphalt																																					
Curb																																					
Sidewalk																																					
Traffic Signals																																					
Street Lighting																																					
Utility/Poles																																					
Boulevards and Shoulders																																					
Interlock Pavers																																					
Bikepaths																																					
Embankments/Cuts																																					
Bridge/Structures																																					
Municipal Signage																																					
Road Sub-Base																																					
Storm Sewer Systems																																					
Catch Basins																																					
Culverts																																					
Ditches																																					
Distribution Systems																																					
Collection Systems																																					
Maintenance Holes																																					
Underground Utilities																																					
Administration/Personel																																					
Maintenance (Markings, Crack Sealing																																					
Winter Maintenance																																					
Records																																					
Collector																																					
Surface - Asphalt																																					
Curb																																					
Sidewalk																																					
Traffic Signals																																					
Street Lighting																																					
Utility/Poles																																					
Boulevards and Shoulders																																					
Embankments/Cuts																																					
Bridge/Structures																																					
Municipal Signage																																					
Road Sub-Base																																					
Storm Sewer Systems																																					
Catch Basins																																					
Culverts																																					
Ditches																																					
Distribution Systems																																					
Collection Systems																																					
Maintenance Holes																																					
Underground Utilities																																					
Administration/Personel																																					

APPENDIX A3-1 - TABLE 11
SAMPLE VULNERABILITY ASSESSMENT MATRIX
STEP 3

DENNIS CONSULTANTS
CIVIL ENGINEERS
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Infrastructure Components	Performance Criteria	Potential Climate Event																														Recommendations/Comments
		High Temp				Low Temp				Precip. As Rain				Precip. As Snow				Wind				Ice Accretion (Ice Storm)				Hail				Frost (Freeze/Thaw Cycles)				Ground Water Table				
		Y/N	S_C	S_R	P_C	Y/N	S_C	S_R	P_C	Y/N	S_C	S_R	P_C	Y/N	S_C	S_R	P_C	Y/N	S_C	S_R	P_C	Y/N	S_C	S_R	P_C	Y/N	S_C	S_R	P_C	Y/N	S_C	S_R	P_C	Y/N	S_C	S_R	P_C	
Maintenance (Markings, Crack Sealing																																				
Winter Maintenance																																				
Records																																				
Local - Urban																																				
Surface - Asphalt																																				
Curb																																				
Sidewalk																																				
Traffic Signals																																				
Street Lighting																																				
Utility/Poles																																				
Boulevards and Shoulders																																				
Interlock Pavers																																				
Bikepaths																																				
Embankments/Cuts																																				
Bridge/Structures																																				
Municipal Signage																																				
Road Sub-Base																																				
Storm Sewer Systems																																				
Catch Basins																																				
Culverts																																				
Ditches																																				
Distribution Systems																																				
Collection Systems																																				
Maintenance Holes																																				
Underground Utilities																																				
Administration/Personel																																				
Maintenance (Markings, Crack Sealing																																				
Winter Maintenance																																				
Records																																				
Local - Rural																																				
Surface - Asphalt																																				
Surface - Surface Treatment																																				
Surface - Gravel																																				
Utility/Poles																																				
Boulevards and Shoulders																																				
Embankments/Cuts																																				
Bridge/Structures																																				
Municipal Signage																																				
Road Sub-Base																																				
Culverts																																				
Ditches																																				
Administration/Personel																																				
Maintenance (Markings, Crack Sealing																																				
Winter Maintenance																																				
Records																																				

APPENDIX A3-1 - TABLE 12A
VULNERABILITY ASSESSMENT MATRIX WORKSHOP RESULTS
STEP 3

P_C Results - Between 12 and 36 - Potentials
36 and over - Vulnerability to Step 5

DENNIS CONSULTANTS
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Infrastructure Components	Performance Criteria	Potential Climate Event																														Recommendations/Comments
		High Temp				Low Temp				Precip. As Rain				Precip. As Snow				Wind				Ice Accretion (Ice Storm)				Hail				Frost (Freeze/Thaw Cycles)				Ground Water Table				
		Y/N	S_C	S_R	P_C	Y/N	S_C	S_R	P_C	Y/N	S_C	S_R	P_C	Y/N	S_C	S_R	P_C	Y/N	S_C	S_R	P_C	Y/N	S_C	S_R	P_C	Y/N	S_C	S_R	P_C	Y/N	S_C	S_R	P_C	
Arterial																																		
Surface - Asphalt	Structural Integrity, Serviceability, Functionality, Operations & Maintenance, Emergency Response Risk, Insurance Considerations, Policies & Procedures, Economics, Public Health & Safety, Environmental Effects	Y	6	4	24	Y	6	3	18	Y	4	4	16	Y	4	4	16	N				Y	4	6	24	N				Y	7	4	28	Y	2	3	6	
Curb	Structural Integrity, Serviceability, Functionality, Operations & Maintenance, Policies & Procedures	N				N				N				Y	2	3	6	N				Y	6	4	24	N				Y	7	4	28	N				
Sidewalk	Structural Integrity, Serviceability, Functionality, Operations & Maintenance, Insurance Considerations, Policies & Procedures, Public Health & Safety, Environmental Effects	N				N				N				Y	3	4	12	N				Y	5	5	25	N				Y	7	4	28	N				
Traffic Signals	Structural Integrity, Serviceability, Functionality, Operations & Maintenance, Emergency Response Risk, Insurance Considerations, Public Health & Safety	N				N				N				N				Y	4	6	24	Y	5	5	25	N				N				N				Wind Data
Street Lighting	Structural Integrity, Serviceability, Functionality, Operations & Maintenance, Public Health & Safety	N				N				N				N				Y	4	6	24	N				N				N				N				
Utility/Poles	Structural Integrity, Serviceability, Functionality, Operations & Maintenance, Emergency Response Risk, Insurance Considerations, Policies & Procedures, Economics, Public Health & Safety, Environmental Effects	N				N				N				N				Y	4	7	28	Y	4	7	28	N				N				N				
Boulevards/Shoulders Interlock Pavers	Structural Integrity, Serviceability, Functionality, Operations & Maintenance, Emergency Response Risk, Insurance Considerations, Policies & Procedures, Economics, Public Health & Safety	N				N				N				N				N				N				N				Y	7	1	7	N				
Bikepaths	Structural Integrity, Functionality, Operations & Maintenance, Insurance Considerations, Public Health & Safety	Y	6	2	12	N				Y	3	2	6	N				N				N				N				Y	7	1	7	N				
Embankments/Cuts	Structural Integrity, Serviceability, Functionality, Operations & Maintenance, Emergency Response Risk, Insurance Considerations, Policies & Procedures, Economics, Public Health & Safety, Environmental Effects	N				N				Y	4	4	16	N				N				N				N				Y	7	2	14	Y	2	7	14	
Bridge/Structures	Structural Integrity, Serviceability, Functionality, Operations & Maintenance, Emergency Response Risk, Insurance Considerations, Policies & Procedures, Economics, Public Health & Safety, Environmental Effects	N				N				Y	6	2	12	N				N				Y	6	5	30	N				Y	7	2	14	N				
Municipal Signage	Structural Integrity, Serviceability, Functionality, Operations & Maintenance, Emergency Response Risk, Insurance Considerations, Policies & Procedures, Public Health & Safety	N				N				N				N				Y	3	7	21	N				N				N				N				
Road Sub-Base	Structural Integrity, Serviceability, Functionality, Operations & Maintenance, Emergency Response Risk, Insurance Considerations, Policies & Procedures, Economics, Public Health & Safety, Environmental Effects	N				N				N				N				N				N				N				Y	7	2	14	Y	2	5	10	
Storm Sewer Systems	Structural Integrity, Serviceability, Functionality, Operations & Maintenance, Emergency Response Risk, Insurance Considerations, Policies & Procedures, Economics, Public Health & Safety, Environmental Effects	N				N				Y	7	5	35	N				N				N				N				Y	7	1	7	Y	2	2	4	
Catch Basins	Structural Integrity, Serviceability, Functionality, Operations & Maintenance, Emergency Response Risk, Insurance Considerations, Policies & Procedures, Public Health & Safety, Environmental Effects	N				N				Y	7	5	35	N				N				N				N				Y	7	4	28	Y	2	2	4	
Culverts	Structural Integrity, Serviceability, Functionality, Operations & Maintenance, Emergency Response Risk, Insurance Considerations, Policies & Procedures, Economics, Public Health & Safety, Environmental Effects	N				N				Y	7	5	35	N				N				N				N				N				Y	2	2	4	
Ditches	Structural Integrity, Serviceability, Functionality, Operations & Maintenance, Policies & Procedures, Economics, Public Health & Safety, Environmental Effects	Y	4	3	12	N				Y	4	6	24	N				N				N				N				N				N				
Distribution Systems	Structural Integrity, Serviceability, Functionality, Operations & Maintenance, Emergency Response Risk, Insurance Considerations, Policies & Procedures, Economics, Public Health & Safety, Environmental Effects	N				N				N				N				N				N				N				Y	7	5	35	N				
Maintenance Holes	Structural Integrity, Serviceability, Functionality, Operations & Maintenance, Insurance Considerations, Public Health & Safety, Environmental Effects	N				N				Y	6	1	6	N				N				N				N				Y	7	2	14	N				
Underground Utilities	Serviceability, Policies & Procedures, Economics, Public Health & Safety	N				N				Y	2	3	6	N				N				N				N				Y	7	2	14	Y	2	2	4	
Administration/Personel	Serviceability, Functionality, Operations & Maintenance, Emergency Response Risk, Policies & Procedures, Economics, Public Health & Safety	N				N				Y	4	3	12	N				Y	3	3	9	Y	5	5	25	Y	3	3	9	N				N				
Maintenance (Markings, Crack Sealing	Serviceability, Functionality, Operations & Maintenance, Policies & Procedures, Economics, Public Health & Safety	Y	4	5	20	N				Y	4	3	12	N				N				N				N				N				N				
Winter Maintenance	Serviceability, Functionality, Operations & Maintenance, Emergency Response Risk, Insurance Considerations, Policies & Procedures, Economics, Public Health & Safety, Environmental Effects	N				N				Y	4	4	16	Y	3	3	9	Y	3	3	9	Y	6	5	30	N				Y	7	4	28	N				
Records	Operations & Maintenance, Insurance Considerations, Policies & Procedures, Economics	N				N				Y	4	2	8	N				Y	3	3	9	Y	3	3	9	N				Y	7	4	28	N				
Trees/Forestry	Structural Integrity, Operations & Maintenance, Emergency Response Risk, Insurance Considerations, Policies & Procedures, Public Health & Safety, Environmental Effects	Y	5	2	10	N				Y	5	2	10	N				Y	3	7	21	Y	3	7	21	Y	3	2	6	N				Y	2	5	10	
Guiderails	Structural Integrity, Serviceability, Functionality, Operations & Maintenance, Insurance Considerations, Public Health & Safety.	N				N				N				N				N				Y	6	2	12	N				N				N				

APPENDIX A3-1 - TABLE 12A
VULNERABILITY ASSESSMENT MATRIX WORKSHOP RESULTS
STEP 3

P_C Results - Between 12 and 36 - Potentials
36 and over - Vulnerability to Step 5

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Infrastructure Components	Performance Criteria	Potential Climate Event																														Recommendations/Comments
		High Temp				Low Temp				Precip. As Rain				Precip. As Snow				Wind				Ice Accretion (Ice Storm)				Hail				Frost (Freeze/Thaw Cycles)				Ground Water Table				
		Y/N	S_C	S_R	P_C	Y/N	S_C	S_R	P_C	Y/N	S_C	S_R	P_C	Y/N	S_C	S_R	P_C	Y/N	S_C	S_R	P_C	Y/N	S_C	S_R	P_C	Y/N	S_C	S_R	P_C	Y/N	S_C	S_R	P_C	Y/N	S_C	S_R	P_C	
Collector																																						
Surface - Asphalt	Structural Integrity, Serviceability, Functionality, Operations & Maintenance, Emergency Response Risk, Insurance Considerations, Policies & Procedures, Economics, Public Health & Safety, Environmental Effects	Y	4	4	16	Y	4	4	16	Y	4	5	20	Y	4	4	16	N				Y	3	6	18	Y	3	5	15	Y	5	5	25	N				Assume and Reviewed as "conc"
Curb	Structural Integrity, Serviceability, Functionality, Operations & Maintenance, Policies & Procedures	N				N				N				N				N				N				N				Y	4	5	20	N				
Sidewalk	Structural Integrity, Serviceability, Functionality, Operations & Maintenance, Insurance Considerations, Policies & Procedures, Public Health & Safety, Environmental Effects	N				N				N				Y	5	5	25	N				Y	4	5	20	N				Y	4	5	20	N				
Traffic Signals	Structural Integrity, Serviceability, Functionality, Operations & Maintenance, Emergency Response Risk, Insurance Considerations, Public Health & Safety	N				N				N				N				Y	3	3	9	Y	3	3	9	N				N				N				
Street Lighting	Structural Integrity, Serviceability, Functionality, Operations & Maintenance, Public Health & Safety	N				N				N				N				Y	3	3	9	Y	3	3	9	N				N				N				
Utility/Poles	Structural Integrity, Serviceability, Functionality, Operations & Maintenance, Emergency Response Risk, Insurance Considerations, Policies & Procedures, Economics, Public Health & Safety, Environmental Effects	N				N				N				N				Y	3	3	9	Y	3	4	12	N				N				N				
Boulevards and Shoulders	Structural Integrity, Serviceability, Functionality, Operations & Maintenance, Emergency Response Risk, Insurance Considerations, Policies & Procedures, Economics, Public Health & Safety	Y	2	2	4	N				Y	3	4	12	N				N				N				N				Y	3	4	12	N				
Embankments/Cuts	Structural Integrity, Serviceability, Functionality, Operations & Maintenance, Emergency Response Risk, Insurance Considerations, Policies & Procedures, Economics, Public Health & Safety, Environmental Effects	N				N				Y	3	4	12	N				N				N				N				Y	3	3	9	N				
Bridge/Structures	Structural Integrity, Serviceability, Functionality, Operations & Maintenance, Emergency Response Risk, Insurance Considerations, Policies & Procedures, Economics, Public Health & Safety, Environmental Effects	N				N				Y	4	6	24	N				N				N				N				Y	4	4	16	N				
Municipal Signage	Structural Integrity, Serviceability, Functionality, Operations & Maintenance, Emergency Response Risk, Insurance Considerations, Policies & Procedures, Public Health & Safety	Y	1	1	1	N				N				N				Y	3	3	9	N				N				N				N				
Road Sub-Base	Structural Integrity, Serviceability, Functionality, Operations & Maintenance, Emergency Response Risk, Insurance Considerations, Policies & Procedures, Economics, Public Health & Safety, Environmental Effects	N				N				Y	4	4	16	N				N				N				N				Y	6	5	30	Y	3	3	9	
Storm Sewer Systems	Structural Integrity, Serviceability, Functionality, Operations & Maintenance, Emergency Response Risk, Insurance Considerations, Policies & Procedures, Economics, Public Health & Safety, Environmental Effects	N				N				Y	6	5	30					N				N				N				N				Y	3	3	9	
Catch Basins	Structural Integrity, Serviceability, Functionality, Operations & Maintenance, Emergency Response Risk, Insurance Considerations, Policies & Procedures, Public Health & Safety, Environmental Effects	N				N				Y	5	5	25	N				N				N				N				N				N				
Culverts	Structural Integrity, Serviceability, Functionality, Operations & Maintenance, Emergency Response Risk, Insurance Considerations, Policies & Procedures, Economics, Public Health & Safety, Environmental Effects	N				N				Y	5	6	30	N				N				N				N				Y	4	4	16	N				
Ditches	Structural Integrity, Serviceability, Functionality, Operations & Maintenance, Policies & Procedures, Economics, Public Health & Safety, Environmental Effects	N				N				Y	3	3	9	N				N				N				N				Y	2	3	6	Y	2	2	4	
Distribution Systems	Structural Integrity, Serviceability, Functionality, Operations & Maintenance, Emergency Response Risk, Insurance Considerations, Policies & Procedures, Economics, Public Health & Safety, Environmental Effects	N				Y	5	5	25	N				N				N				N				N				Y	4	5	20	N				
Maintenance Holes	Structural Integrity, Serviceability, Functionality, Operations & Maintenance, Insurance Considerations, Public Health & Safety, Environmental Effects	N				Y	2	2	4	N				N				N				N				N				Y	4	4	16	N				
Underground Utilities	Serviceability, Policies & Procedures, Economics, Public Health & Safety	N				N				N				N				N				N				N				Y	3	2	6	N				
Administration/Personel	Serviceability, Functionality, Operations & Maintenance, Emergency Response Risk, Policies & Procedures, Economics, Public Health & Safety	N				N				Y	4	4	16	Y	6	5	30	Y	3	4	12	Y	6	5	30	Y	3	2	6	Y	4	4	16	N				
Maintenance (Markings, Crack Sealing	Serviceability, Functionality, Operations & Maintenance, Policies & Procedures, Economics, Public Health & Safety	Y	3	3	9	Y	4	2	8	N				N				N				N				N				N				N				"Summer"
Winter Maintenance	Serviceability, Functionality, Operations & Maintenance, Emergency Response Risk, Insurance Considerations, Policies & Procedures, Economics, Public Health & Safety, Environmental Effects	Y	4	3	12	Y	4	4	16	N				Y	6	5	30	N				Y	8	3	24	N				Y	5	4	20	N				
Records	Operations & Maintenance, Insurance Considerations, Policies & Procedures, Economics	N																																				???? No response
Trees/Forestry	Structural Integrity, Operations & Maintenance, Emergency Response Risk, Insurance Considerations, Policies & Procedures, Public Health & Safety, Environmental Effects	N				N				N				N				Y	4	4	16	Y	4	4	16	N				N				N				
Guiderails	Structural Integrity, Serviceability, Functionality, Operations & Maintenance, Insurance Considerations, Public Health & Safety.	N				N				N				N				N				N				N				N				N				

GROUP 2 OF 4

APPENDIX A3-1 - TABLE 12A
VULNERABILITY ASSESSMENT MATRIX WORKSHOP RESULTS
STEP 3

P_C Results - Between 12 and 36 - Potentials
36 and over - Vulnerability to Step 5

DENNIS CONSULTANTS
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Infrastructure Components	Performance Criteria	Potential Climate Event																														Recommendations/Comments
		High Temp				Low Temp				Precip. As Rain				Precip. As Snow				Wind				Ice Accretion (Ice Storm)				Hail				Frost (Freeze/Thaw Cycles)				Ground Water Table				
		Y/N	S_C	S_R	P_C	Y/N	S_C	S_R	P_C	Y/N	S_C	S_R	P_C	Y/N	S_C	S_R	P_C	Y/N	S_C	S_R	P_C	Y/N	S_C	S_R	P_C	Y/N	S_C	S_R	P_C	Y/N	S_C	S_R	P_C	
Local - Urban																																
Surface - Asphalt	Structural Integrity, Serviceability, Functionality, Operations & Maintenance, Emergency Response Risk, Insurance Considerations, Policies & Procedures, Economics, Public Health & Safety, Environmental Effects	Y	2	6	12	N				Y	6	4	24	Y	7	4	28	N				Y	3	6	18	Y	2	5	10	Y	5	5	25	N				
Curb	Structural Integrity, Serviceability, Functionality, Operations & Maintenance, Policies & Procedures	N				N				N				N				N				N				N				Y	5	3	15	N				
Sidewalk	Structural Integrity, Serviceability, Functionality, Operations & Maintenance, Insurance Considerations, Policies & Procedures, Public Health & Safety, Environmental Effects	N				N				N				Y	7	6	42	N				Y	3	7	21	Y	2	5	10	Y	5	3	15	N				
Traffic Signals	Structural Integrity, Serviceability, Functionality, Operations & Maintenance, Emergency Response Risk, Insurance Considerations, Public Health & Safety	N				N				N				Y	2	6	12	Y	3	4	12	Y	1	6	6	N				Y	5	2	10	N				
Street Lighting	Structural Integrity, Serviceability, Functionality, Operations & Maintenance, Public Health & Safety	N				N				N				N				Y	3	4	12	Y	1	6	6	N				N				N				
Utility/Poles	Structural Integrity, Serviceability, Functionality, Operations & Maintenance, Emergency Response Risk, Insurance Considerations, Policies & Procedures, Economics, Public Health & Safety, Environmental Effects	N				N				N				N				Y	3	4	12	Y	1	6	6	N				N				N				
Boulevards and Shoulders	Structural Integrity, Serviceability, Functionality, Operations & Maintenance, Emergency Response Risk, Insurance Considerations, Policies & Procedures, Economics, Public Health & Safety	N				N				Y	6	4	24	N				N				N				N				N				N				Designation curb/no shoulder
Embankments/Cuts	Structural Integrity, Serviceability, Functionality, Operations & Maintenance, Emergency Response Risk, Insurance Considerations, Policies & Procedures, Economics, Public Health & Safety, Environmental Effects	N				N				Y	2	1	2	N				N				N				N				N				N				
Bridge/Structures	Structural Integrity, Serviceability, Functionality, Operations & Maintenance, Emergency Response Risk, Insurance Considerations, Policies & Procedures, Economics, Public Health & Safety, Environmental Effects	N				N				Y	2	6	12	N				N				Y	2	4	8	N				N				N				
Municipal Signage	Structural Integrity, Serviceability, Functionality, Operations & Maintenance, Emergency Response Risk, Insurance Considerations, Policies & Procedures, Public Health & Safety	N				N				N				Y	4	3	12	Y	3	3	9	N				N				N				N				
Road Sub-Base	Structural Integrity, Serviceability, Functionality, Operations & Maintenance, Emergency Response Risk, Insurance Considerations, Policies & Procedures, Economics, Public Health & Safety, Environmental Effects	N				N				Y	3	5	15	N				N				N				N				Y	6	4	24	Y	1	6	6	
Storm Sewer Systems	Structural Integrity, Serviceability, Functionality, Operations & Maintenance, Emergency Response Risk, Insurance Considerations, Policies & Procedures, Economics, Public Health & Safety, Environmental Effects	N				N				Y	5	3	15	Y	3	4	12	N				Y	1	5	5	N				Y	6	4	24	N				
Catch Basins	Structural Integrity, Serviceability, Functionality, Operations & Maintenance, Emergency Response Risk, Insurance Considerations, Policies & Procedures, Public Health & Safety, Environmental Effects	N				N				Y	5	3	15	Y	3	4	12	N				Y	1	5	5	N				Y	5	2	10	N				
Culverts	Structural Integrity, Serviceability, Functionality, Operations & Maintenance, Emergency Response Risk, Insurance Considerations, Policies & Procedures, Economics, Public Health & Safety, Environmental Effects	N				N				Y	5	5	25	Y	3	4	12	N				N				N				Y	6	3	18	N				
Ditches	Structural Integrity, Serviceability, Functionality, Operations & Maintenance, Policies & Procedures, Economics, Public Health & Safety, Environmental Effects	N				N				Y	3	3	9	N				N				N				N				N				N				
Distribution Systems	Structural Integrity, Serviceability, Functionality, Operations & Maintenance, Emergency Response Risk, Insurance Considerations, Policies & Procedures, Economics, Public Health & Safety, Environmental Effects	N				N				N				N				N				N				N				Y	1	4	4	N				
Maintenance Holes	Structural Integrity, Serviceability, Functionality, Operations & Maintenance, Insurance Considerations, Public Health & Safety, Environmental Effects	N				N				Y	1	4	4	Y	5	2	10	N				N				N				Y	5	4	20	N				
Underground Utilities	Serviceability, Policies & Procedures, Economics, Public Health & Safety	N				N				N				N				N				N				N				Y	1	4	4	N				
Administration/Personel	Serviceability, Functionality, Operations & Maintenance, Emergency Response Risk, Policies & Procedures, Economics, Public Health & Safety	N				N				Y	5	4	20	Y	7	4	28	Y	2	6	12	Y	2	5	10	N				Y	7	3	21	N				
Maintenance (Markings, Crack Sealing	Serviceability, Functionality, Operations & Maintenance, Policies & Procedures, Economics, Public Health & Safety	N				N				Y	3	4	12					Y	3	5	15					Y	0	6	0					N				
Winter Maintenance	Serviceability, Functionality, Operations & Maintenance, Emergency Response Risk, Insurance Considerations, Policies & Procedures, Economics, Public Health & Safety, Environmental Effects	N				Y	3	3	9	Y	3	4	12	Y	6	5	30	Y	4	5	20	Y	3	5	15	N				Y	7	4	28	N				
Records	Operations & Maintenance, Insurance Considerations, Policies & Procedures, Economics	N				N				Y	3	4	12	Y	5	5	25	Y	2	4	8	Y	1	4	4	N				Y	6	3	18	N				
Trees/Foresty	Structural Integrity, Operations & Maintenance, Emergency Response Risk, Insurance Considerations, Policies & Procedures, Public Health & Safety, Environmental Effects	Y	1	2	2	N				N				Y	1	4	4	Y	3	4	12	Y	2	6	12	N				N				N				
Guiderails	Structural Integrity, Serviceability, Functionality, Operations & Maintenance, Insurance Considerations, Public Health & Safety.	N				N				N				N				N				N				N				Y	5	2	10	N				

APPENDIX A3-1 - TABLE 12A
VULNERABILITY ASSESSMENT MATRIX WORKSHOP RESULTS
STEP 3

P_C Results - Between 12 and 36 - Potentials
36 and over - Vulnerability to Step 5

DENNIS CONSULTANTS
CIVIL ENGINEERS
a division of R.V. Anderson Associates Limited

Infrastructure Components	Performance Criteria	Potential Climate Event																																Recommendations/Comments
		High Temp				Low Temp				Precip. As Rain				Precip. As Snow				Wind				Ice Accretion (Ice Storm)				Hail				Frost (Freeze/Thaw Cycles)				Ground Water Table				
		Y/N	S_C	S_R	P_C	Y/N	S_C	S_R	P_C	Y/N	S_C	S_R	P_C	Y/N	S_C	S_R	P_C	Y/N	S_C	S_R	P_C	Y/N	S_C	S_R	P_C	Y/N	S_C	S_R	P_C	Y/N	S_C	S_R	P_C	Y/N	S_C	S_R	P_C	
Local - Rural																																				
Surface - Asphalt	Structural Integrity, Serviceability, Functionality, Operations & Maintenance, Emergency Response Risk, Insurance Considerations, Policies & Procedures, Economics, Public Health & Safety, Environmental Effects	N				Y	3	3	9	N				Y	5	4	20	N				Y	3	5	15	N				Y	5	4	20	N				
Surface - Surface Treatment	Structural Integrity, Serviceability, Functionality, Operations & Maintenance, Emergency Response Risk, Policies & Procedures, Economics, Public Health & Safety, Environmental Effects	N				N				Y	2	3	6	Y	5	4	20	N				Y	3	5	15	N				Y	5	4	20	N				
Surface - Gravel	Structural Integrity, Serviceability, Functionality, Operations & Maintenance, Emergency Response Risk, Policies & Procedures, Economics, Public Health & Safety, Environmental Effects	N				N				Y	5	5	25	Y	5	4	20	Y	3	2	6	Y	3	5	15	N				Y	3	3	9	Y	3	2	6	
Utility/Poles	Structural Integrity, Serviceability, Functionality, Operations & Maintenance, Emergency Response Risk, Insurance Considerations, Policies & Procedures, Economics, Public Health & Safety, Environmental Effects	N				N				N				N				Y	2	6	12	Y	3	7	21	N				N				N				
Boulevards and Shoulders	Structural Integrity, Serviceability, Functionality, Operations & Maintenance, Emergency Response Risk, Insurance Considerations, Policies & Procedures, Economics, Public Health & Safety	N				N				Y	4	4	16	Y	5	4	20	N				Y	3	5	15	N				Y	3	3	9	Y	3	2	6	
Embankments/Cuts	Structural Integrity, Serviceability, Functionality, Operations & Maintenance, Emergency Response Risk, Insurance Considerations, Policies & Procedures, Economics, Public Health & Safety, Environmental Effects	N				N				Y	3	3	9	N				N				N				N				Y	3	3	9	Y	3	3	9	
Bridge/Structures	Structural Integrity, Serviceability, Functionality, Operations & Maintenance, Emergency Response Risk, Insurance Considerations, Policies & Procedures, Economics, Public Health & Safety, Environmental Effects	Y	3	4	12	Y	3	4	12	Y	4	4	16	N				Y	2	3	6	Y	1	2	2	N				Y	3	3	9	N				
Municipal Signage	Structural Integrity, Serviceability, Functionality, Operations & Maintenance, Emergency Response Risk, Insurance Considerations, Policies & Procedures, Public Health & Safety	N				N				N				Y	2	3	6	Y	4	3	12	Y	3	3	9	N				N				N				
Road Sub-Base	Structural Integrity, Serviceability, Functionality, Operations & Maintenance, Emergency Response Risk, Insurance Considerations, Policies & Procedures, Economics, Public Health & Safety, Environmental Effects	N				Y	4	3	12	Y	4	4	16	N				N				N				N				Y	4	4	16	Y	4	4	16	
Culverts	Structural Integrity, Serviceability, Functionality, Operations & Maintenance, Emergency Response Risk, Insurance Considerations, Policies & Procedures, Economics, Public Health & Safety, Environmental Effects	N				Y	3	4	12	Y	4	5	20	Y	4	5	20	N				Y	2	2	4	N				Y	4	5	20	Y	3	2	6	
Ditches	Structural Integrity, Serviceability, Functionality, Operations & Maintenance, Policies & Procedures, Economics, Public Health & Safety, Environmental Effects	N				N				Y	5	4	20	Y	5	4	20	N				N				N				Y	4	5	20	Y	3	3	9	
Administration/Personel	Serviceability, Functionality, Operations & Maintenance, Emergency Response Risk, Policies & Procedures, Economics, Public Health & Safety	N				N				Y	2	2	4	Y	3	4	12	Y	3	3	9	Y	3	5	15	N				Y	4	4	16	N				
Maintenance (Markings, Crack Sealing	Serviceability, Functionality, Operations & Maintenance, Policies & Procedures, Economics, Public Health & Safety	N				N				Y	4	4	16	N				Y	3	3	9	Y	3	3	9	N				Y	4	4	16	N				
Winter Maintenance	Serviceability, Functionality, Operations & Maintenance, Emergency Response Risk, Insurance Considerations, Policies & Procedures, Economics, Public Health & Safety, Environmental Effects	N				Y	2	3	6	N				Y	6	4	24	Y	5	4	20	Y	5	4	20	N				N				N				
Records	Operations & Maintenance, Insurance Considerations, Policies & Procedures, Economics	N				N				Y	3	3	9	Y	4	4	16	N				Y	3	3	9	N				Y	2	2	4	N				
Trees/Foresty	Structural Integrity, Operations & Maintenance, Emergency Response Risk, Insurance Considerations, Policies & Procedures, Public Health & Safety, Environmental Effects	N				N				N				Y	2	1	2	Y	3	4	12	Y	3	5	15	N				N				N				

GROUP 4 OF 4

APPENDIX A3-1 - TABLE 12B
COMBINED VULNERABILITY ASSESSMENT MATRIX
STEP 3

Pc Values

Pc Values

Infrastructure Component	High Temp				Low Temp				Rainfall				Snowfall				Wind				Ice Accretion (Ice Storm)				Frost (Freeze/Thaw Cycles)				Ground Water Table			
	Team 1	Team 2	Team 3	Team 4	Team 1	Team 2	Team 3	Team 4	Team 1	Team 2	Team 3	Team 4	Team 1	Team 2	Team 3	Team 4	Team 1	Team 2	Team 3	Team 4	Team 1	Team 2	Team 3	Team 4	Team 1	Team 2	Team 3	Team 4	Team 1	Team 2	Team 3	Team 4
Surface - Asphalt	24	16	12		18	16			16	20	24		16	16	28	20					24	18	18		28	25	25	20				
Surface - Surface Treatment																20												20				
Surface - Gravel												25				20																
Curb																					24				28	20	15					
Sidewalk													12	25	42						25	20	21		28	20	15					
Traffic Signals																	24		12		25											
Street Lighting															12		24		12													
Utility/Poles																	28		12	12	28	12										
Boulevards/Shoulders										12	24	16				20										12						
Bike paths	12																															
Embankments/Cuts									16	12															14				14			
Bridge/Structures				12				12	12	24	12	16									30				14	16						
Municipal Signage															12		21			12												
Road Sub-Base								12		16	15	16													14	30	24	16				16
Storm Sewer Systems									35	30	15				12												24					
Catch Basins									35	25	15				12										28							
Culverts								12	35	30	25	20			12	20										16	18	20				
Ditches	12								24			20				20												20				
Distribution Systems						25																			35	20						
Maintenance Holes																									14	16	20					
Underground Utilities															28										14							
Administration/Personnel									12	16	20			30		12		12	12		25	30				16	21	16				
Maintenance (Markings, Crack Sealing)	20								12		12	16							15									16				
Winter Maintenance		12				16			16		12			30	30	24			20	20	30	24	15		28	20	28					
Records											12				25	16									28		18					
Trees/Forestry																	21	16	12	12	21	16	12									
Guiderails																					12											

LEGEND

Team 1 - Arterial
Team 2 - Collector
Team 3 - Local/Urban
Team 4 - Local/Rural