VULNERABILITIES AND DESIGN CONSIDERATIONS FOR PAVEMENT INFRASTRUCTURE IN LIGHT OF CLIMATE CHANGE

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Paper prepared for presentation at the "Climate Change Considerations for Geotechnical and Pavement Materials Engineering" Session
Of the 2015 Conference of the Transportation Association of Canada
Charlottetown, PEI

Abstract

Although climate is directly linked to infrastructure deterioration, there is little research on potential impacts of climate change. Canadian estimates suggest increases in temperature of 2°C to 5°C and up to 10% precipitation over the next 45 years. Relatively little research has been completed to investigate the potential engineering impacts of climate change on infrastructure, and particularly roads and bridges. Potential impacts need to be addressed given the importance of road and bridge infrastructure on economic and social activity. More specifically, climate change can impact: thermal cracking, frost heave and thaw weakening, permafrost melting, permanent deformation associated with warm and cold temperatures, to name a few. Current and past engineering designs generally assume a static climate whose variability can be adequately determined from records of weather conditions, which normally span less than 30 years and often less than 10 years. The notion of anthropogenic climate change challenges this assumption and raises the possibility that the frequency, duration or severity of thermal cracking, rutting, frost heave and thaw weakening may be altered leading to premature deterioration.

General methods for assessing the potential impacts of climate change on various aspects of society, economy and environment have been developed over the past two decades, largely based on approaches rooted in applied climatology or the hazards and risk assessment literature. The leading international source of guidance on climate change impact assessment is the Intergovernmental Panel on Climate Change (IPCC). It is an organization that is responsible for periodic reviews of the scientific literature on aspects of climate change science, impacts and adaptation assessment, and emissions mitigation. Generally, maintenance, rehabilitation or reconstruction will be required earlier. The paper provides a brief introduction and background on climate change in general and the related predicted impacts on road infrastructure and associated structures, with primary focus on bridges. A summary of findings provides some more specific details and has been prepared using available public agency documents that were located from public sources.

Key words: Climate Change, Roads and Pavements, Mitigation, Deterioration

Introduction

Relatively little research has been completed to investigate the potential engineering impacts of climate change on infrastructure, and particularly roads and bridges [Tighe 2008, TAC 2013]. Potential impacts need to be addressed given the importance of road and bridge infrastructure on economic and social activity. More specifically, climate change can impact: thermal cracking, frost heave and thaw weakening, permafrost melting, permanent deformation associated with warm and cold temperatures, to name a few. Current and past engineering designs generally assume a static climate whose variability can be adequately determined from records of weather conditions which normally span less than 30 years and often less than 10 years. The notion of anthropogenic climate change challenges this assumption and raises the possibility that the frequency, duration or severity of thermal cracking, rutting, frost heave and thaw weakening may be altered leading to premature deterioration [Mills 2007].

Long-term performance of transportation infrastructure is climate change and the need to consider adaptation in pavement design and management to address its impact [TAC 2013]. Given the size and length of Canada's road network, it is expected that climate change will impact the design, construction and maintenance of our transportation infrastructure. The impact of climate change and potential methods for adapting to climate change are being studied as part of the Government of Canada Climate Change Impacts and Adaptation Program managed by Natural Resources Canada [Mills 2007, Hayley 2007].

More frequent and intense rainfalls may lead to flooding and higher groundwater levels, which in turn may lead to erosion, slope instability and reduced pavement strength and bearing capacity of road structures. In northern Canada, warmer winters are resulting in loss of permafrost, and shortened seasons for ice and snow roads. Roads may be exposed to higher incidence of freeze-thaw cycling. This will accelerate pavement deterioration and increase maintenance costs. Increases in the ambient temperature may cause bituminous bound materials to become more susceptible to permanent deformation in the form of rutting. It is expected that climate change will impact the way roads are planned, designed, constructed, operated and maintained [PIARC 2010].

The potential impacts of climate change need to be addressed given the importance of road infrastructure on economic and social activity [Tighe 2008]. Currently there are a few agencies that are considering aspects of climate change and sustainability. Table 1 shows the percentages of agencies, from the 2010 survey completed for the Transportation Association of Canada Pavement Asset Design and Management Guide regarding the potential impacts of climate change on infrastructure. In addition, TAC has published two documents, *Climate Change Checklist for TAC Committees and Transportation Association of Canada Climate Change Task Force: Guidance Document for Committees,* which provide a reference for agencies evaluating climate change impacts and implementation strategies and suggests fundamental questions to consider about how climate change relates to infrastructure [TAC 2011a, TAC 2011b, TAC 2013].

Table 1 Percentage of agencies evaluating climate change [Tighe 2010]

Agency	Percentage
Cities	21%
Federal/Provincial/Territorial	71%
Other Agencies	38%

The focus on sustainability and climate change is relatively recent and practitioners do not have adequate templates to follow and thus, are frequently struggling on where to start in addressing these issues. The complexity of addressing so many criteria is difficult and there is no clear and concise agreed upon criteria for assessing the effectiveness of sustainable actions or the impact of climate change [PIEVC 2011, FHWA 2011]. Key related issues include:

- Establishing objectives,
- Use of technologies,
- Processes, and
- Adaption

General methods for assessing the potential impacts of climate change on various aspects of society, economy and environment have been developed over the past two decades, largely based on approaches rooted in applied climatology or the hazards and risk assessment literature [Kates, 1985; Burton et al., 1993; Bruce et al., 2001]. The leading international source of guidance on climate change impact assessment is the Intergovernmental Panel on Climate Change (IPCC), an organization that is responsible for periodic reviews of the scientific literature on aspects of climate change science, impacts and adaptation assessment, and emissions mitigation [IPCC, 2001, 2007]. Canada's road infrastructure has an estimated value of $150 billion (TAC 2013).

This infrastructure enables transportation of people and resources which is a major source of our economic prosperity. It is generally accepted that climate impacts pavement performance, however, in the past it has been difficult to quantify this impact. Earlier design methods accounted for climate by categorizing into a broad climatic region (i.e. wet-freeze, wet-no freeze, dry-freeze, dry-no freeze.) In general, the temperature is increasing due to an increase in greenhouse gases in the atmosphere. For the majority of Canada, the average temperature is estimated to increase by 2^oC to 5^oC and the average precipitation is estimated to increase from 0-10% over the 45 year period from 1995-2040 (Environment Canada 2005).

Paper Scope and Objectives

This paper investigates the impact of climate change on roads, associated infrastructure within Canada, and proposes opportunities for future mitigation strategies.

Road Impacts

As with other forms of infrastructure, the fundamental concern related to a changing climate in road and pavement design and management is the potential for premature design failure. Current and past designs generally assume a static climate. The increase in temperatures and associated precipitation bring challenges and raise the possibility that the frequency, duration or severity of thermal cracking, wash outs due to flooding, rutting, frost heave and thaw weakening may be altered leading to premature deterioration [Mills 2007].

Analysis of deterioration-relevant climate indicators at 17 sites, located in Southern Canada suggests that, over the next 50 years, low temperature cracking will become less problematic; structures will freeze later and thaw earlier with correspondingly shorter freeze season lengths; and higher extreme in-service pavement temperatures will raise the potential for rutting [Mills 2007]. Further evidence from this study indicated that that permanent rutting on asphalt roads, cracking such as longitudinal, and alligator issues would be exacerbated by climate change with transverse cracking becoming less of a problem. In general, maintenance, rehabilitation or reconstruction will be required earlier in the design life [Mills 2007].

In Northern Canada, Snow Roads provide transportation routes. There are several examples of areas where the roads and pipelines have been disturbed by thawing permafrost. In addition, snow roads have been important for Oil and Gas Extraction and the Forestry Industry. With the thawing of the permafrost, alternative methods for bringing supplies in will be required in some communities. It has also been shown that the permafrost has warmed and the depth of the layers of thaws each year is increasing. In short, it is expected that permafrost will shift several hundred kilometres this century [GM 2007]. In addition, Hayley and McGregor [Hayley 2007] noted that Winter and Ice Roads are used extensively in Canada to resupply remote communities and to support resource development. In particular, the Tibbitt to Contwoyto Winter Roads in the Northwest Territories supports the diamond mine industry and current climate change has already affected the operation and initiated the need to shorten operating season [Hayley 2007].

Additional rainfall, resulting in flooding and lane closures is also a potential engineering vulnerability. For example, in New Brunswick [GNB 2005], road closures due to flooding are posted on their website. This has been occurring, as there are many areas of the province that are low-lying and susceptible to flooding. The provincial department of transportation makes every effort to sign or barricade roads where there is risk to motorists. However, water levels can increase quickly, and drivers are warned to use appropriate caution whenever they encounter water over the road. Similar examples of road closures and washouts can be found across Canada.

Another key point is the change in the timing and duration of Seasonal Load Restrictions (SLR) and Winter Weight Premiums (WWP), which are applied to many roads located in Canada. Application of seasonal load restrictions to certain parts of the highway network can lead to lost productivity and a substantial impact on the economy.

Once these restrictions are in place, the payload of certain heavy vehicles must be reduced [Tighe 2006].

One of the largest challenges particularly in Northern regions of Canada, is to design and monitor roads concisely to mitigate damage caused by seasonal effects. This is a complex problem as many of the roads are gravel or surface treated and there is limited funding available for the construction and maintenance of these facilities. Thus, it is vital that these roads are protected, particularly during the vulnerable spring thaw period. In order to properly protect these facilities, it is necessary to monitor them in a coordinated manner which utilizes both temperature and pavement data [Tighe 2006, Baiz 2008]. The use of real time data is essential and may lead to the need to instrument many sections of road to closely monitor the conditions so that roads can be adequately identified and that potential damage due to overloading during weakened conditions can be avoided. Instrumentation may include Road Weather Information Systems (RWIS), thermister strings, strain gauges, moisture probes, etc. [Tighe 2006]. There are several current initiatives on-going in Ontario, Quebec, Manitoba, New Brunswick and British Columbia to better understand the relationship between pavement strength and thaw weakening.

For road authorities that manage much of the primary paved road network in Canada, the key adaptation issues will not simply focus on how to deal with potential impacts, but rather when to modify current design and maintenance practices to accommodate these changed conditions. The basis for such decisions often falls back to an assessment of relative costs (between status quo and various designs or interventions) borne by the public, road users and, to the extent permitted in contractual agreements, by private sector construction and maintenance providers [GNB 2005, AIT 2007]. Many agencies do employ some form of Pavement Management and this will assist in tracking vulnerabilities and in-service performance.

Bridge and Associated Infrastructure Impacts

Many of the situations described above in the previous section have relevance to bridges and will not be repeated in this section. Low-lying roadways and the associated structures are at risk of flooding from intense rainfall events. The intense rainfall provides a big concern as it results in culverts and bridges that might be vulnerable. For example, in the City of Toronto, there are 34 culverts and 70 bridges that may be vulnerable under intense rainfall conditions [CAP 2006]. Similar statistics would be expected for various other cities, municipalities and provincial and territorial transportation agencies.

An increase in precipitation would also cause an increase in soil moisture, resulting in slope instability and possibly an increase in landslides, which could put some bridges and culverts out of service. Other indirect impacts would affect other sectors as well, such as agriculture, oil, and gas, which in the long term will also affect the demand, timing and location for freight transportation [AIT 2007].

There is some uncertainty and variation in the climate change model results about future rain and snowfall levels on the prairies. A number of models show that rain and snow will not be sufficient to compensate for the warmer temperatures. The associated increase in evaporation rates in Saskatchewan being drier on average in both the south and north. Drier conditions will likely increase the frequency of droughts. This could potentially affect bridge and culvert life cycle performance. An additional concern is that summer rainfall may tend to occur as intense storms or 'cloud bursts' with increased risk of flooding and storm damage [SHI 2007].

The Ontario Ministry of Transportation (MTO) has examined the impact of climate change on structures. The purpose of the study [Coulibaly 2006] was to investigate the potential impact of climate change on highway drainage infrastructure including bridges, culverts, storm sewers and stormwater management facilities. The research used models that predict the climate change in terms of precipitation and water flow and the associated impact on different catchments areas [MTO 2006].

The MTO study relates the predicted Global Change Models (GCM's) temperature and precipitation predictions to local precipitation data. To determine estimates of local and regional values of future daily precipitation and variability, this study used data from eight rainfall stations to represent typical southern and northern Ontario regions. Four stations were in the Grand River watershed and the other four rainfall stations were located in the Kenora/Rainy River watershed [MTO 2010].

To show how much, how long and how often precipitation occurs in the two test regions, rainfall intensity-duration-frequency (IDF) curves were derived using the GCMs and daily precipitation data from the rainfall stations. To detect rainfall trends, IDF curves were developed for four time periods, the present, 2020, 2050 and 2100 [MTO 2010].

The IDF curves showed changes in precipitation intensity, suggesting that by 2050 and 2100 a 24% and 35% increase in heavy, and more frequent, rainfall events can be expected. All correlations showed these increasing trends, except for the 2020s when there was a decrease [MTO 2010]. In short, the findings indicated that existing highway drainage infrastructure may be significantly affected by climate change. The study predicts that, by 2050, highway drainage systems designed to accommodate storms that occur once in 10 years may only be able to accommodate storms that occur once in 5-years. Larger highway drainage systems designed for a once in 50-year storm period might only be able to accommodate a once in 20-year storm period.

From an engineering design perspective, it suggests that design flow rates (the estimated runoff flow rates) may need to be increased leading to larger bridges, culverts, storm sewers and stormwater management ponds to maintain the level of service provided today and to avoid potential constricted water flow and possible future flooding events [MTO 2010].

While this research provides some insight into the potential impact of climate change on highway drainage infrastructure based on a limited number of sites and a short period of rainfall record, more research is required to fully understand future climate effects on rainfall and flow rates before considering modifications to highway drainage design standards [MTO 2006].

Overall, from this search there are many questions that need to be addressed including: how will climate change impact the transportation sector, can these changes be handled by current design drainage systems and standards, and ultimately what needs to be done today to ensure future performance of structures in light of climate [MTO 2010].

Summary of Findings

Adaptation to the impacts of climate change will require long-term planning and several changes to the transportation sector. Current discussion, policy and programmes related to climate change generally focus on mitigation; however it will be important to integrate adaptation and mitigation efforts into design, construction and maintenance. Planning for new infrastructure will require modification in engineering design to ensure the new roads and bridges can withstand the change in length and frequency of weather events, as well as hydrological changes [AIT 2007].

The safety margin for building codes will have to be adjusted to allow for greater variability in weather and account for a wider range of extremes. Careful monitoring of weather information systems will also be important. There is also a need to monitor, and possibly map, areas vulnerable to receding permafrost, flooding or landslides. The transportation sector will also need to be prepared for any changes to maintenance costs [AIT 2007, MTO 2010].

Further research is required to determine what specific impacts climate change will have on a regional scale. Local research is also needed to determine the capacity of specific systems (for example, drainage systems) to deal with these impacts. Research could also determine the options available to transportation policy makers in dealing with the impacts of climate change.

In addition, NWTDOT are working with Engineers Canada on the vulnerability study and have offered a “test area” which includes a section of highway, which is undergoing significant permafrost issues [McLeod 2008].

Summary of Findings Road and Pavement Infrastructure

The most detailed efforts found in the area of roads were studies carried out by Mills et al [Mills 2007] as part of the Government of Canada Climate Change Impacts and Adaptation Program managed by Natural Resources Canada and Hayley et al [Hayley 2007] which was presented at the PIARC meetings in Paris 2007. This first study focused primarily on Southern Canada while the latter study focuses on Northern Canada with specific emphasis on Permafrost, Ice and Seasonally Frozen areas.

This Mills et al [Mills 2007] study involved using two sets of case studies to examine and investigate the generalized impacts of climate change. Two climate change scenarios were adopted for analysis in the current study: one based on the A2x emission experiment from the Canadian Centre for Climate Modelling and Analysis Coupled Global Climate Model 2 (CGCM2A2x), the other from the B21 experiment run through the Hadley Climate Model 3 (HadCM3B21). The specifications of the CGCM2 and HadCM3 climate models, and performance in relation to other internationally recognized models, are also well documented elsewhere [Flato et al., 2000; Flato and Boer, 2001; Gordon et al., 2000; CMIP, 2001].

Raw scenario surface temperature (minimum, maximum, mean) and precipitation (total) data for each model and experiment were obtained through the Canadian Climate Scenarios Network [CCSN, 2005]. Monthly data were available for baseline (1961-1990) and three future 30-year temporal windows centred on the 2020s, 2050s, and 2080s. Given that the average design life of pavement infrastructure is about 20-30 years, only the 2050s scenarios were examined in the current study.

The data consisted of output for climate model grid cells, each of which spans 2.5 (HadCM3) to 3.75 (CGCM2) degrees latitude and 3.75 (both models) degrees longitude (i.e., over 100,000 km2). Each site was assigned to the model grid cell in which it was located, except when the cell was designated as ‘water’ in the model specifications; in these cases, the nearest ‘land’ cell was used. Scatter plots of potential changes in annual and seasonal mean temperature and precipitation were prepared to indicate the position or severity of the CGCM2A2x and HadCM3B21 experiment results relative to other Atmosphere and Ocean General Circulation Models (AOGCM) scenarios for each site. Examples of annual scatter plots for the most northern (Edmonton) and southern (Windsor) study sites [Mills 2007].

In general, the CGCM2A2x and HadCM3B21 scenarios are average and conservative, respectively, when compared to other AOGCMs and experiments. Results for both are contingent on the realization of mid-century changes in climate derived from the CGCM2A2x and HadCM3B21 global climate modeling experiments. These scenarios are moderate compared to those from other models [Mills 2007].

The analysis involved applying the newly developed Mechanistic-Empirical Pavement Design Guide (MEPDG) to assess the impact of pavement structure, material characteristics, traffic loads, and changes in climate on incremental and terminal pavement deterioration and performance [ARA 2004]. Evidence from the six Canadian sites that were examined in that study was not as universal as that revealed through the first set of case studies but nonetheless suggested that rutting (asphalt, base and subbase layers) and cracking (longitudinal and alligator) issues will be exacerbated by climate change with transverse cracking becoming less of a problem on Southern Canadian roads due to warmer temperatures.

In general, maintenance, rehabilitation or reconstruction will be required earlier in the design life as there would be more distresses and they would be appearing earlier in the pavement life. The effect of climate change was found to be modest, both in absolute terms and relative to variability in pavement structure and baseline traffic loads [Mills 2007, Tighe 2008]. Note, this study was only evaluating Southern Canadian roads and it would be expected that changes would be more dramatic for Northern Ontario roads depending on their climatic conditions.

Pavement engineers, with assistance from government and academic climate change experts, should be encouraged to develop a protocol or guide for considering potential climate change in the development and evaluation of future designs and maintenance programs. Incorporating other climate-related road infrastructure issues, for instance those associated with concrete pavements, surface-treated roads, airfields, bridges and culverts, would also be beneficial [Mills 2007].

At a minimum, long time series of historic climatic and road weather observations—ideally greater than 30 years in the case of climate—should be incorporated into analyses of pavement deterioration and applicability of Seasonal Load Restrictions (SLRs) and Winter Weight Premiums (WWPs) or assignment of performance graded materials. Pavement design procedures that result in a higher resistance to deformation, longer service lives, and satisfactory surface characteristics are needed to satisfy the increased demand in road usage. The expected performance and service life of pavements are decreased by distresses such as rutting, fatigue, and low temperature cracking, distresses caused by increased axle loads, traffic volume, environmental conditions, and construction and design errors [Mills 2007].

There are many different consequences to climate change, and each has an impact on the pavement and road infrastructure. Severe weather events, including flooding and freezing rain, are predicted to increase with climate change. Both these occurrences would cause safety hazards for the transportation sector, and flooding could potentially cause the loss of some infrastructure. The delays caused by these occurrences would also have social and economic impacts on the transportation sector AIT 2007, Mills 2007].

If temperatures close to water's freezing point become more common in Canada, the resulting increase in frequency of the freeze-thaw cycle will likely cause pavement deterioration. In addition, with increased heat and drought, this will cause permanent deformation in the form of rutting. The drought conditions could also lead to an increase in forest fires. This would affect both roads and bridges by resulting in closures of certain routes and the loss of some infrastructure [AIT 2007].

Warmer winters may also be associated with a decrease in the amount of snow clearing required, as well as a change in the mix of sand and salt used on the roads. Warmer winters could also mean a decrease in the length of time where seasonal roads are available, and a change in permafrost location. This would have a negative impact on communities and industries using these temporary roads. However, there could eventually be all-season roads in some areas. The subsidence of the ground due to melting permafrost could also affect pipelines and adjacent roadways. An increase in temperatures could also mean a change in the timing and duration of seasonal weight limits for the trucking industry [AIT 2007].

Climate change will also potentially cause an increase in precipitation, which would contribute to flooding. For example a storm on August 19, 2005 washed out a portion of Finch Avenue in Toronto. It seems apparent that this type of event is expected to become more frequent in the next 50 years [CAP 2006].

An increase in precipitation would also cause an increase in soil moisture, resulting in slope instability and possibly an increase in landslides. Other indirect impacts would affect other sectors as well, such as agriculture and oil and gas, which in the long term will also affect the demand, timing and location for freight transportation [AIT 2007].

In terms of northern Canada, Hayley and McGregor [Hayley 2007] identified several challenges, which are currently being faces in Northern Canada. In areas where roads are over permafrost terrain, the thin surface "active" layer thaws each summer.

Summary of Findings Bridges and Associated Structures

Many of the situations described above in the previous section have relevance to bridges and will not be repeated in this section. Low-lying roadways and the associated structures are at risk of flooding from intense rainfall events. The intense rainfall provides a big concern as it results in culverts and bridges that might be vulnerable. For example, in the City of Toronto, there are 34 culverts and 70 bridges that may be vulnerable under intense rainfall conditions [CAP 2006]. Similar statistics would be expected for various other cities, municipalities and provincial and territorial transportation agencies.

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Overall, from this search there are many questions that need to be addressed including: how will climate change impact the transportation sector, can these changes be handled by current design drainage systems and standards, and ultimately what needs to be done today to ensure future performance of structures in light of climate [MTO 2006].

Conclusions

As with other forms of infrastructure, the fundamental concern related to a changing climate in design and management is the potential for premature design failure. Current and past designs generally assume a static climate whose variability can be adequately determined from records of weather conditions, which normally span less than 30 years and often less than 10 years. The notion of anthropogenic climate change challenges this assumption and raises the possibility that the frequency, duration or severity of thermal cracking, rutting, frost heave and thaw weakening may be altered leading to premature deterioration as indicated by trends in one or more of the performance indicators described earlier.

For road authorities that manage much of the primary paved road network in Canada, the key adaptation issues will surround not how to deal with potential affects but rather when to modify current design and maintenance practices. The basis for such decisions often falls back to an assessment of relative costs (between status quo and various designs or interventions) borne by the public, road users and, to the extent permitted in contractual agreements, by private sector construction and maintenance providers. The addition of climate change scenarios to typical 20+ year design evaluations into the LCCA process could be readily used to support future decisions. Regardless of future climate change, the reliability of such design evaluations could be improved by considering longer time series of climatic data to capture more variability.

Recommendations for Future Research

Incorporating other climate-related road infrastructure issues, for instance those associated with concrete pavements, surface-treated roads, airfields, bridges and culverts, would also be beneficial. At a minimum, long time series of historic climatic and road weather observations, ideally, greater than 30 years in the case of climate should be incorporated into analysis of pavement deterioration and applied to update Seasonal Load Restrictions and Winter Weight Premiums or assignment of performance graded materials.

Acknowledgements

The author gratefully acknowledge the funding of Engineers Canada, Public Infrastructure Engineering Vulnerability Committee (PIEVC) Secretariat, the Climate Change Action Fund under Project A812 and the partnership with Environment Canada and the Adaptation and Impacts Research Group, Meteorological Services of Canada.

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