Evaluation of Climate Impacts on Jointed Plain Concrete Pavement Structures

Authors:

Mohammad Shafiee, PhD (Corresponding Author)
Research Officer, National Research Council Canada
(email) Mohammad.Shafiee@nrc-cnrc.gc.ca

Omran Maadani, PhD
Research Officer, National Research Council Canada
(email) Omran.Maadani@nrc-cnrc.gc.ca

Hamidreza Shirkhani, PhD
Research Officer, National Research Council Canada
(email) Hamidreza.Shirkhani@nrc-cnrc.gc.ca

Address:

National Research Council Canada,

Building M-20, 1200 Montreal Road,

Ottawa, Ontario, K1A 0R6, Canada.

ABSTRACT

Canadian pavement infrastructures, now more than ever, face risks associated with the potential impacts of climate and extreme weather events. Canada has experienced and continues to experience a number of changes to environmental variables affecting the performance of pavements, including temperature, precipitation, sea level rise, flooding, and extreme weather events. Therefore, road agencies and public are increasingly concerned with climate resiliency of pavement infrastructures which were not intended to accommodate intense environmental conditions due to climate change. While much has been written about the general behavior of flexible pavements in response to climate change, yet there has been relatively scant investigation of the rigid pavement climate resiliency and sustainability. This paper primarily focuses on the vulnerability and long-term performance of Jointed Plain Concrete Pavement (JPCP) Structures from Mechanistic-Empirical Pavement Design Guide (MEPDG) perspective. In this paper, climatic data obtained from the latest Canadian Regional Climate Model (CanRCM4) were used. Simulation results from incorporating the projected climate data into AASHTOWare Pavement ME Design software showed that the magnitude of impacts and the degree of vulnerability arising from climate change was inconsistent between different performance indicators. Also, sensitivity analysis of the MEPDG distress models to multiple climatic factors revealed different trends of variation depending on climate variable.

Introduction

Rigid pavements account for an important part of Canadian infrastructure assets and play a major role in national transportation system. In the context of climate change, new and ageing rigid pavements in Canada are very likely to face multiple climate change-related impacts such as more frequent and lengthy extreme hot days, higher precipitation, more flooding and sea level rise (1). This will require the process of adapting road and pavement infrastructure to climate change by designing new roads and rehabilitating existing roads to withstand the projected climate loads. Traditionally, rigid pavement design has relied on the assumption of stationary climate conditions where available static data provided adequate roadmaps for future designs. However, the use of historical climate data for pavement design without consideration for impact of climate change can lead to unreliable designs. As a result, different design situations may occur under future climate scenarios where increase or decrease in air temperature, solar radiation, relative humidity, wind speed and precipitation will affect the construction and serviceability of new or reconstructed JPCP roads.

Performance of rigid pavements is significantly associated with environmental conditions. It is widely recognized that transitory temperature and moisture gradients in the Portland Cement Concrete (PCC) can cause curling and warping in the slabs, respectively. Transitory temperature differences from top to bottom of the PCC slab can induce upward or downward curling which leads to development of critical tensile stresses in conjunction with traffic loading. Besides, variations in ambient relative humidity can generate warping in PCC due to transitory moisture changes in the slab. Apart from the abovementioned transitory changes, temperature gradient at the time of hardening along with differential PCC shrinkage can produce permanent curl/warp in the slabs. Hence, both transient and permanent changes are crucial in calculating joint opening and closing as well as fatigue damage accumulation of JPCPs. While modeling the interaction between climatic factors, pavement materials and traffic loading is a complex process, the well-known Mechanistic-Empirical Pavement Design Guide (MEPDG) and the accompanying AASHTOWare Pavement ME Design software is currently the most robust and comprehensive method for simulating pavement performance. In particular, MEPDG's Enhanced Integrated Climate Model (EICM), which is a one-dimensional coupled heat and moisture flow program, allows for direct incorporation of climatic factors in the design procedure (2).

In a study conducted in the U.S. on the potential impact of climate change on the performance of Jointed Plain Concrete Pavement (JPCP) and Continuously Reinforced

Concrete Pavement (CRCP) and in the states of Delaware, New Jersey and Connecticut, it was concluded that incorporating climate change effects into the mechanistic-empirical based pavement design is a robust and effective adaptation strategy. By focusing on important performance indicators such as International Roughness Index (IRI), joint faulting and transverse cracking for JPCP sections and IRI and punchouts for CRCP sections, it was found that different emission models and climate change variability can significantly influence the pavement deterioration behavior (3). Another research on evaluating the vulnerability of rigid pavements to climate change in the UK suggested that higher temperatures can induce compression failures at joints and warping of the concrete, while more prolonged and intense precipitation results in surface damage during paving and increased potential of water infiltration through cracks (4).

In the current version of AASHTOWare Pavement ME Design (ver. 2.5.4), project specific climatic factors rely on historical data available from North American Regional Reanalysis (NARR) and Modern-Era Retrospective Analysis for Research and Applications (MERRA) databases. The recent report of the Intergovernmental Panel on Climate Change (5), as well as the Fourth National Climate Assessment Report (6) by the U.S. Global Change Research Program and Canada’s Climate Change Report (7) indicated that the global emissions of carbon dioxide from human activity has resulted in global warming and changing climate. Therefore, the historical climatic data cannot represent the future climatic conditions anymore. In light of climate change and this new reality, current study aims at investigating relative change, rather than absolute change, of pavement performance from baseline under future climate change scenarios.

Methodology

All analysis in this study were performed using the latest version of the AASHTOWare Pavement ME Design 2.5.4. Table 1 shows the embedded distress models in the MEPDG to predict the JPCP performance using the software. In this study, five cities including Montreal, Ottawa, Saskatoon, Toronto and Winnipeg which are mainly located in central Canada and prairies were selected for this analysis. Initially, the current practice which uses archived climatic data was followed to evaluate the impact of climate data source on the key rigid pavement performance indicators namely as IRI, mean joint faulting and transverse cracking. Secondly, to understand the implications of climate variations on the performance indicators, a series of sensitivity analysis were carried out. Finally, the impact of projected change in climate was assessed using Canadian Regional Climate Model (CanRCM4).

Table 1- JPCP Distress Prediction Models (2)

Distress	MEPDG Prediction Model
Faulting	$Fault_m = \sum_{i=1}^{m} \Delta Fault_i$ $\Delta Fault_i = C_{34} \times (FAULTMAX_{i-1} - Fault_{i-1})^2 \times DE_i$ $FAULTMAX_i = FAULTMAX_0 + C_7 \times \sum_{j=1}^{m} DE_j \times \log(1 + C_5 \times 5^{EROD})^{C_6}$ $FAULTMAX_0 = C_{12}\delta_{curling} \times \left[\log(1 + C_5 \times 5^{EROD}) \times \log\frac{P_{200} \times WetDays}{P_s}\right]^{C_6}$ $Fault_m$ = mean joint faulting at the end of month m, in. $\Delta Fault_i$ = incremental change (monthly) in mean transverse joint faulting during month i, in. $FAULTMAX_i$ = maximum mean transverse joint faulting for month i, in. $FAULTMAX_0$ = initial maximum mean transverse joint faulting, in. EROD = base/subbase erodibility factor. DE_i = differential deformation energy accumulated during month i. $\delta_{curling}$ = maximum mean monthly slab corner upward deflection PCC due to temperature curling and moisture warping. P_S=overburden on subgrade, lb. P_{200}=percent subgrade material passing #200 sieve. WetDays=average annual number of wet days (greater than 0.1 in rainfall). C_1, C_2, C_3, C_4, C_5, C_6, C_7, C_{12}, C_{34} = calibration coefficients.
Cracking	$CRK = \frac{100}{1 + C_4\ FD^{C_5}}$ $FD = \sum \frac{n_{i,j,k,l,m,n}}{N_{i,j,k,l,m,n}}$ $\log N_{i,j,k,l,m,n} = C_1 (\frac{MR_i}{\sigma_{i,j,k,l,m,n}})^{C_2}$ CRK = predicted amount of bottom-up or top-down cracking (fraction). FD = Fatigue damage. σi,j,k,l,m,n = Applied stress at condition i, j, k, l, m, n $n_{i,j,k,l,m,n}$ = Applied number of load applications at condition i, j, k, l, m, n. $N_{i,j,k,l,m,n}$ = Allowable number of load applications at condition i, j, k, l, m, n. C_1, C_2, C_3, C_4, C_5= calibration coefficients.
IRI	$IRI = IRI_I + C_1 \times CRK + C_2 \times SPALL + C_3 \times TFAULT + C_4 \times SF$ $SF = AGE\ (1 + 0.5556 * FI)\ (1 + P_{200}) * 10^{-6}$ $SPALL = \left[\frac{AGE}{AGE + 0.01}\right]\left[\frac{100}{1 + 1.005^{-12\ AGE+SCF}}\right]$ $SCF = -1400 + 350\ AIR\%\ (0.5 + PREFORM) + 3.4\ f'c \times 0.4 - 0.2\ (FTCYC \times AGE) + 43\ h_{PCC} - 536\ WC\_Ratio$ IRI = predicted IRI, in/mi. IRII = initial smoothness measured as IRI, in/mi. CRK = percent slabs with transverse cracks (all severities). SPALL = percentage of joints with spalling (medium and high severities). TFAULT =total joint faulting cumulated per mi, in. SF= Site Factor SCF= Scaling Factor AIR% = PCC air content, percent. AGE = time since construction, years PREFORM =1 if preformed sealant is present; 0 if not. f'c = PCC compressive strength, psi. FTCYC=average annual number of freeze-thaw cycles. h_{PCC} = PCC slab thickness, in. WC_Ratio =PCC water/cement ratio. C_1, C_2, C_3, C_4 = calibration coefficients.

The CanRCM4, developed by the Canadian Centre for Climate Modelling and Analysis (8) is used in this study to project the required climatic data. The output of CanRCM4 under RCP8.5 scenario was utilized as the latest global GHG emissions trend is following this emission scenario which can reveal the potential risks associated with continuing the current ‘business as usual’ rate of emission. The mean hourly temperatures, wind speed, total cloud fraction, precipitation, and specific humidity of CanRCM4 output are used as the climatic data needed for this study.

A four-lane unreinforced cast-in-place JPCP with doweled transverse joints and tied shoulders was considered for this analysis. Figure 1 shows the cross section of the pavement structure featuring a slab on granular base. Table 2 also depicts the properties of the pavement materials as well as the design parameters used in this study. These values were mainly selected from Ontario Ministry of Transportation Guidelines (9). Besides, the initial two-way Average Annual Daily Truck Traffic (AADTT) was assumed equal to 6,000 corresponding to a major arterial roadway located in an urban setting. It is however important to note that the abovementioned conditions are typical for Level-3 (default) analysis. The pavement design life was chosen to be 25 years for the purpose of this study. Besides, the initial IRI was chosen as 1.5 m/km.

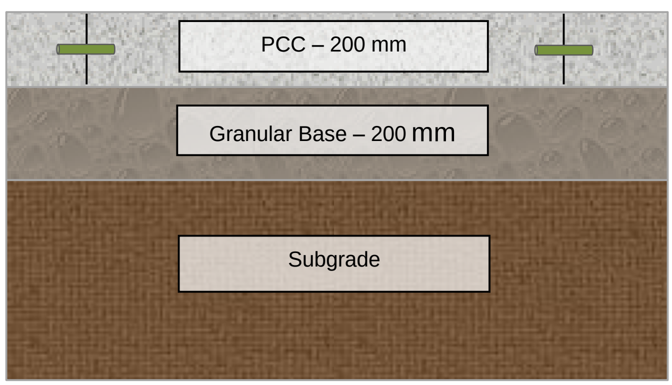


Figure1- JPCP structure selected for MEPDG performance analysis

Table 2- Material Properties and Design Parameters (9)

Parameter	Value
PCC	
Cement Type	GU (Type 1)
Cementitious Material Content (kg/m^3)	335
Water/Cement Ratio	0.45
Aggregate Type	Limestone
Mix Unit Weight (kg/m^3)	2320
Poisson's Ratio	0.2
28-Day Modulus of Rupture (MPa)	5.6
Elastic Modulus (GPa)	29.6
Coefficient of Thermal Expansion (mm/mm/ºC ×10^{-6})	7.8
Thermal Conductivity (watt/meter-Kelvin)	2.16
Heat Capacity (Joule/kg-Kelvin)	1172
Granular Base	
Resilient Modulus (MPa)	250
Subgrade	
Soil Type	ML
Resilient Modulus (MPa)	40
Structural Design	
Dowel Spacing (mm)	300
Dowel Diameter (mm)	32
Joint Spacing (m)	4.5
Tied Shoulders	Tied with long term LTE of 70%
Permanent Curl/Warp Effective Temperature Difference (ºC)	-5.6

Results and Analysis

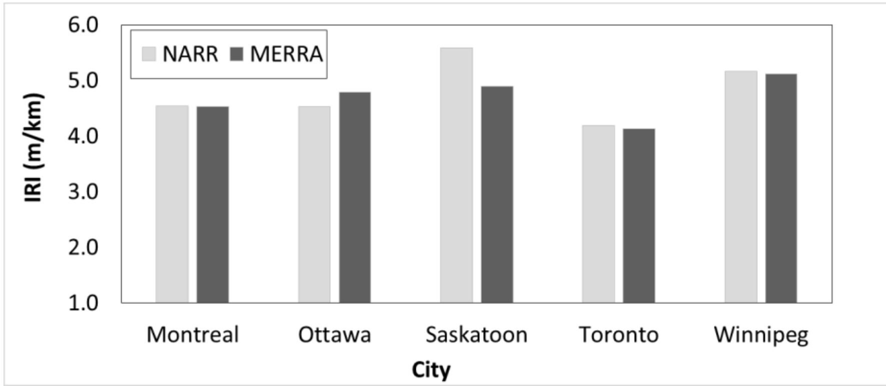
Effect of Climate Dataset Selection

Currently, climate dataset in the Pavement ME AASHTOWare is defined by pavement type. Hence, NARR and MERRA datasets should be used when running rigid and flexible pavement designs, respectively. However, there are plans to adopt MERRA for rigid pavement design in the future when the performance models are recalibrated. NARR was developed by National Oceanic and Atmospheric Administration (NOAA) to model a long-term overview of weather over North America (10). On the other hand, MERRA, produced by the National Aeronautical and Space Administration (NASA), integrates numerical models with variety of satellite-measured data in order to generate temporally and spatially consistent synthesis of climate variables (11). To quantitatively evaluate embedded climate sources in the software and determine the extent to which different climate data sources may affect the predicted performance, rigid pavement simulations were carried out using both datasets. Table 3 shows the selected weather stations from two datasets

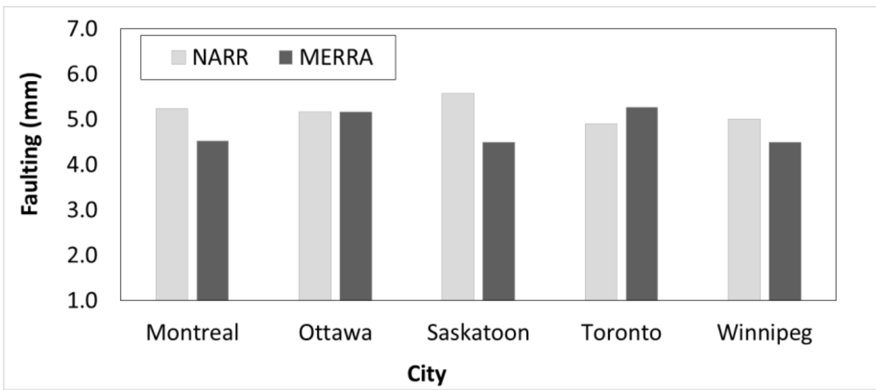
Table 3- Selected Climate Station

City	**Station ID**	
	NARR	MERRA
Montreal, QC	94792	155654
Ottawa, ON	04772	148194
Saskatoon, SK	25015	157942
Toronto, ON	94791	150504
Winnipeg, MB	14996	150507

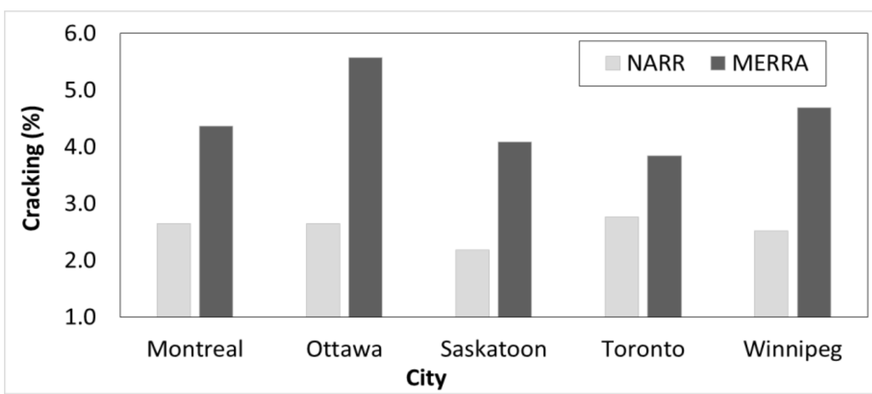
Figure 2 shows the impact of selecting different climate datasets on JPCP simulation under default calibration parameters. The comparison between predicted performance indicators showed that the transverse cracking was consistently higher in case of MERRA dataset. This is in line with findings reported by Durham et al. (11) that the MERRA- predicted distresses are often relatively higher than the ones predicted via other climate data resources including NARR. Besides, disagreements between climatic data from different sources were reflected in predicted faulting and IRI values. For example, in cities such as Toronto, Vancouver and Calgary, both faulting and IRI were higher when using MERRA.



(a)



(b)



(c)

Figure 2- Impact of climate source on predicted (a) IRI, (b) faulting and (c) cracking

Effect of Climate Characteristics

To quantify the impact of individual climatic factors on MEPDG-predicted pavement performance, a series of sensitivity analysis were carried out for the typical rigid pavement design by varying each climatic factor one at a time (OAT) against the available NARR data. For each selected city, a total of 24 scenarios were considered which generated 125 simulation runs overall including the reference cases. Table 4 shows the different cases which were repeated for each city in this study. It is worthwhile to state that the percent change for temperature was applied to the difference between hourly and average daily temperature.

Once the simulations were completed using customized climate data files, the resultant percentage change in IRI, joint faulting and cracking were then calculated and plotted as illustrated in Figure 3.

Table 4- Sensitivity Analysis Scenarios

Variable (hourly data)	Scenarios
Case 1-Temperature	-20, -15, -10, -5, 5, 10, 15 and 20 percent
Case 2 -Precipitation	5, 10, 15 and 20 percent
Case 3 -Humidity	-10, -5, 5 and 10 percent
Case 4 -Sunshine	-10, -5, 5 and 10 percent
Case 5 -Wind Speed	-10, -5, 5 and 10 percent

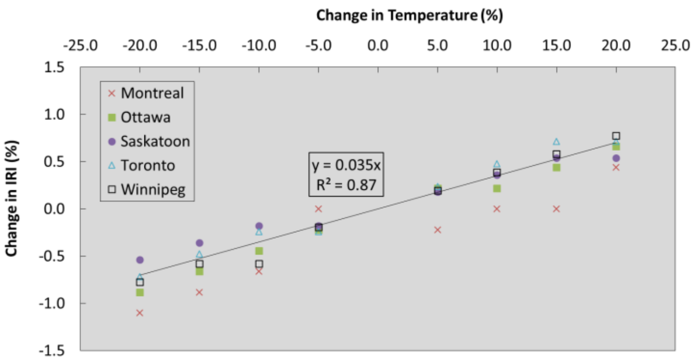
Comparisons of JPCP performance as predicted by Pavement ME AASHTOWare in case of different temperature scenarios showed that increase in the daily temperature range generally led to more performance issues as shown in Figure 3 (a), (b) and (c). Under different temperature scenarios, it was observed that predicted cracking fluctuated in a slightly wider range as opposed to IRI and faulting. This is also confirmed by results from Li et al. (3), who identified the sensitivity of JPCP slab cracking to average daily temperature range as very high. This is expected to occur as ambient temperature have a significant impact on temperature gradient from top to bottom of the slab and accordingly on the induced critical stresses during day (upward curling) and night (downward curling).

As depicted in Figure 3 (d), (e) and (f), increase in humidity levels mainly resulted in more faulting and IRI, while reduced the predicted cracking. In addition, the observed changes were more pronounced in case of faulting and cracking rather than IRI. It is worth noting that fluctuations in relative humidity can affect the transient moisture shrinkage in the top of the PCC slab; hence the amount of moisture warping in JPCP is consequently adjusted by the software.

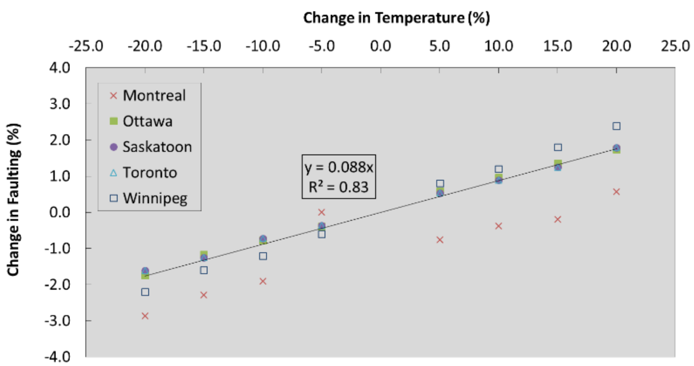
The percentage sunshine, as an input to the MEPDG, is known to influence the heat balance at the surface of the JPCP. By varying the percentage of sunshine, it was found that less cloud covers may negatively impact the three performance indicators as shown in Figure 3 (g), (h) and (i). Analysis showed that predicted-IRI was less influenced by percent sunshine in comparison to faulting and cracking. Durham et al. (11) have also reported that percent sunshine has a significant impact on pavement performance as predicted by Pavement ME Design.

Wind speed is a crucial factor in calculation of convection heat transfer coefficient at the pavement surface. Figure 3 (j), (k) and (l) indicate the sensitivity of predicted performance to wind speed. Results showed that the pavement distresses generally decreased at higher wind speeds. Predictions were more scattered and the impact was found to be moderate considering the resultant percent change particularly with respect to IRI and faulting.

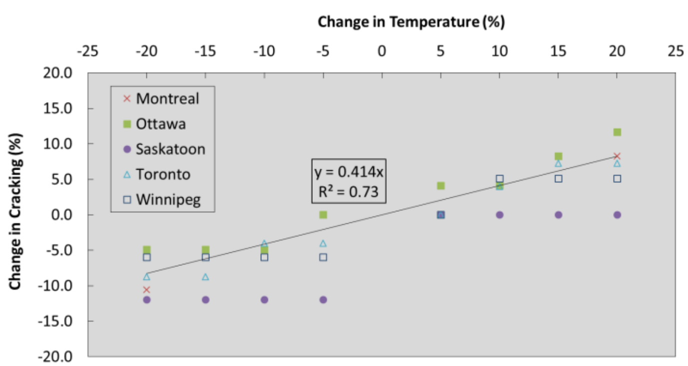
Figure 3 (m), (n) and (o) shows the sensitivity of predicted performance against precipitation. As anticipated, the analysis exhibited very small change in JPCP performance under different precipitation scenarios. This is due to the fact that infiltration modeling is not enabled in the current version of the software. Also, for simplicity, MEPDG does not consider the heat fluxes caused by precipitation. Overall, IRI and faulting slightly decreased in case of higher precipitation.


Change in Temperature (%)
Change in IRI (%)
Montreal
Ottawa
Saskatoon
Toronto
Winnipeg
y = 0.035x
R² = 0.87

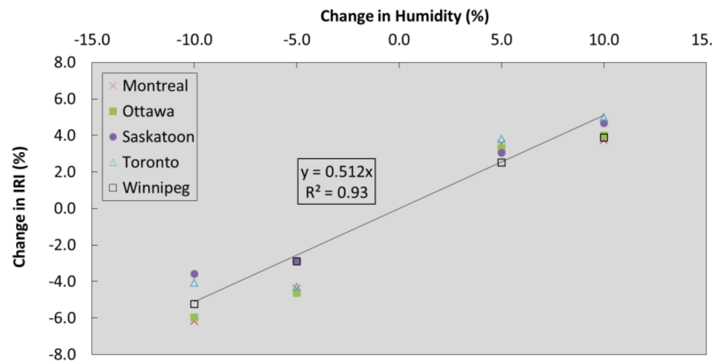
(a)


Change in Temperature (%)
Change in Faulting (%)
Montreal
Ottawa
Saskatoon
Toronto
Winnipeg
y = 0.088x
R² = 0.83

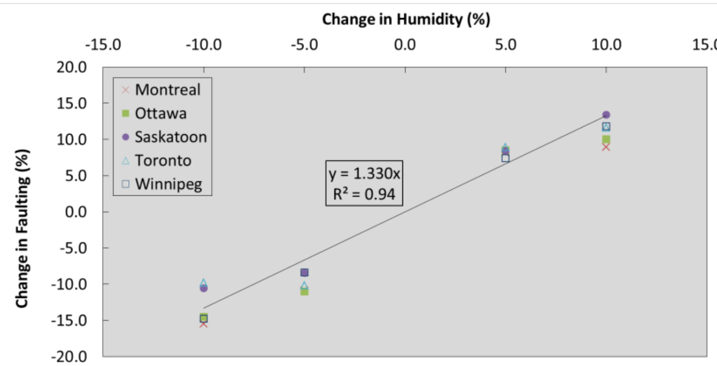
(b)


Change in Temperature (%)
Change in Cracking (%)
Montreal
Ottawa
Saskatoon
Toronto
Winnipeg
y = 0.414x
R² = 0.73

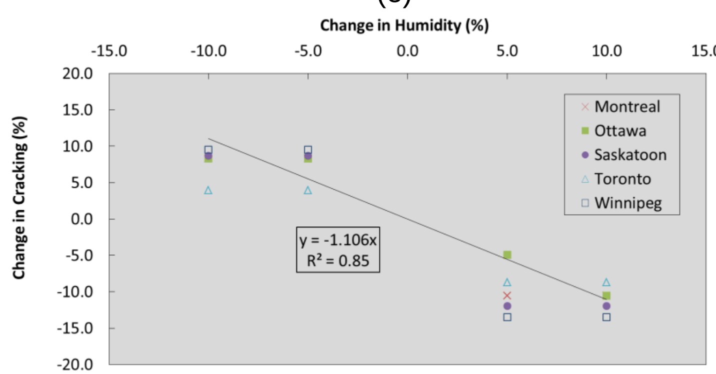
(c)


Change in Humidity (%)
Change in IRI (%)
Montreal
Ottawa
Saskatoon
Toronto
Winnipeg
y = 0.512x
R² = 0.93

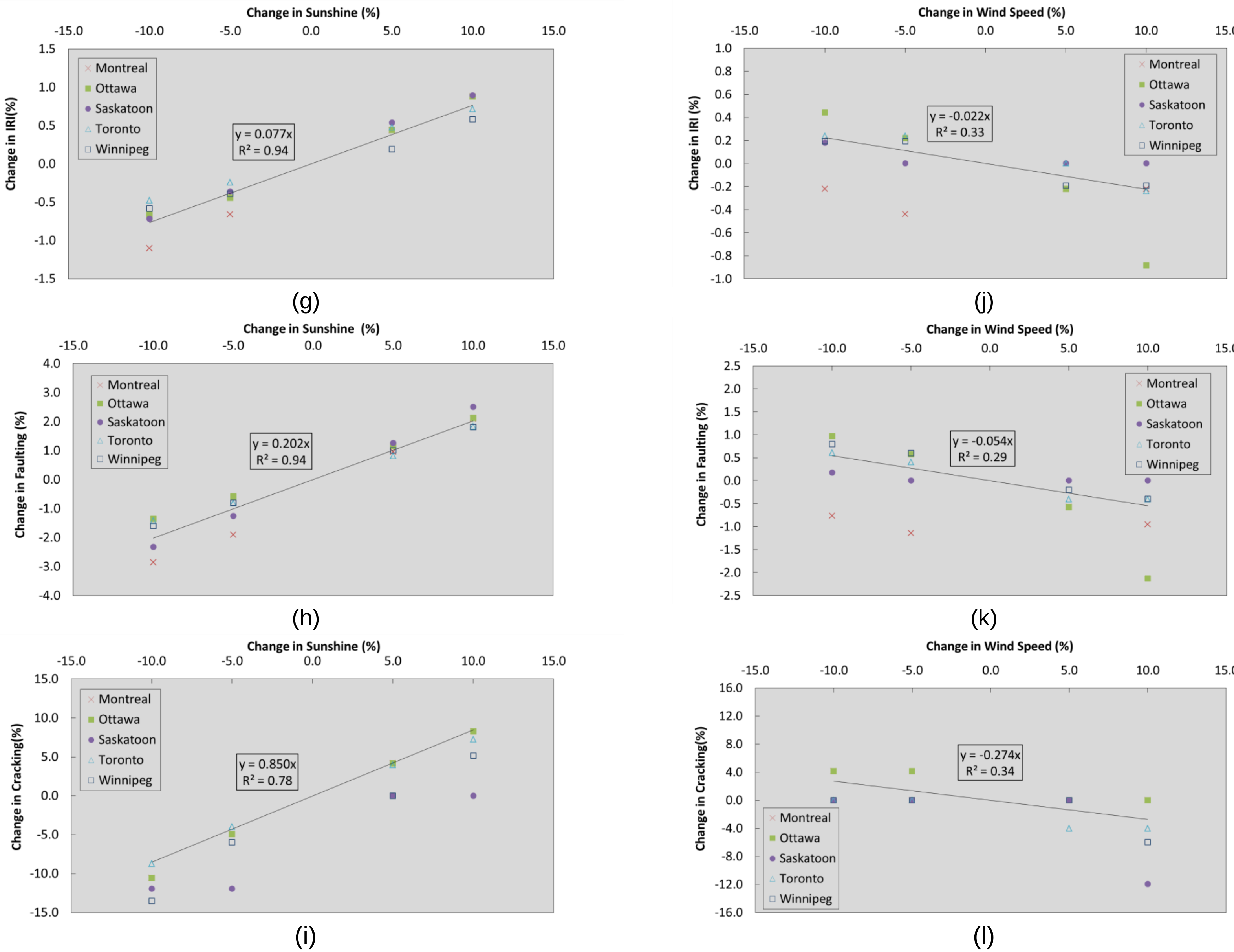
(d)


Change in Humidity (%)
Change in Faulting (%)
Montreal
Ottawa
Saskatoon
Toronto
Winnipeg
y = 1.330x
R² = 0.94

(e)


Change in Humidity (%)
Change in Cracking (%)
Montreal
Ottawa
Saskatoon
Toronto
Winnipeg
y = -1.106x
R² = 0.85

(f)



Change in Sunshine (%)
Change in IRI(%)
Montreal
Ottawa
Saskatoon
Toronto
Winnipeg
y = 0.077x
R² = 0.94
(g)
Change in Wind Speed (%)
Change in IRI (%)
Montreal
Ottawa
Saskatoon
Toronto
Winnipeg
y = -0.022x
R² = 0.33
(j)
Change in Sunshine (%)
Change in Faulting (%)
Montreal
Ottawa
Saskatoon
Toronto
Winnipeg
y = 0.202x
R² = 0.94
(h)
Change in Wind Speed (%)
Change in Faulting (%)
Montreal
Ottawa
Saskatoon
Toronto
Winnipeg
y = -0.054x
R² = 0.29
(k)
Change in Sunshine (%)
Change in Cracking(%)
Montreal
Ottawa
Saskatoon
Toronto
Winnipeg
y = 0.850x
R² = 0.78
(i)
Change in Wind Speed (%)
Change in Cracking(%)
Montreal
Ottawa
Saskatoon
Toronto
Winnipeg
y = -0.274x
R² = 0.34
(l)

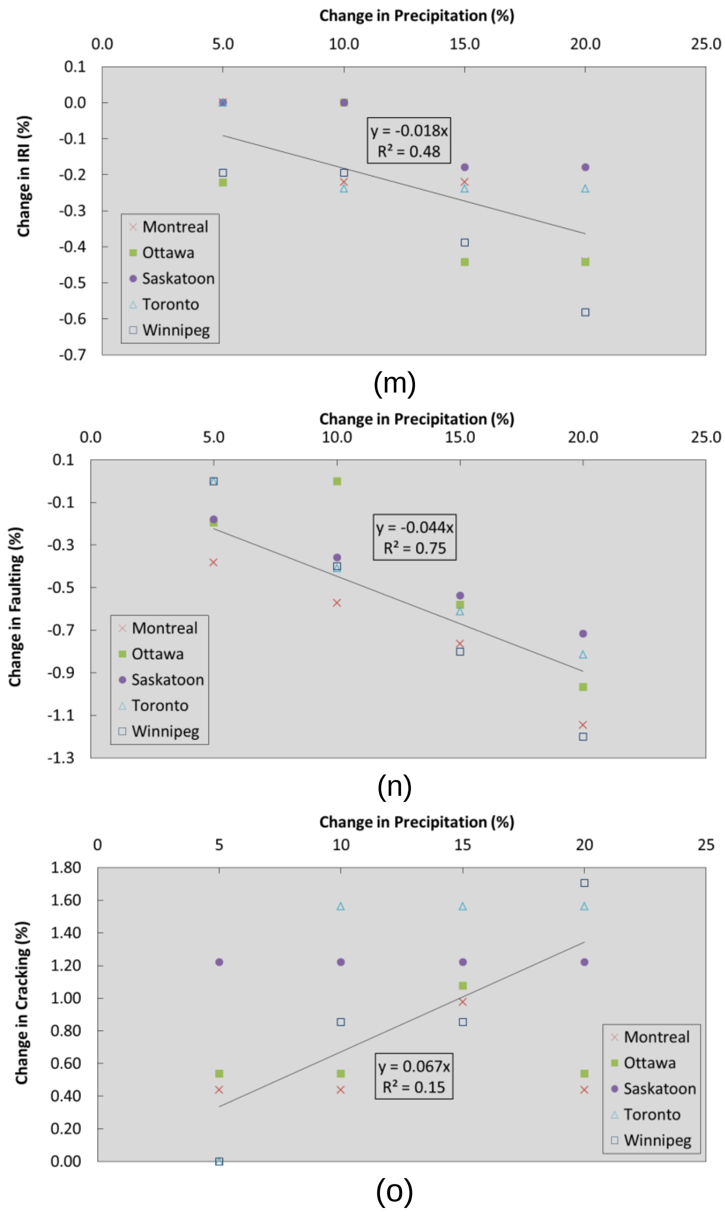


Figure 3- Sensitivity of predicted performance to different climatic factors

Effect of Climate Change

In order to evaluate the impact of climate change scenarios on the JPCP performance over time, comparisons and analyses were performed by considering two analysis periods. The baseline scenario (historical period) was defined as the 25-year period from 1976 until 2000 and the medium-term future scenario was assumed as the 25-year period from 2026 until 2050. The assessment was aimed at determining the extent to which MEPDG-predicted performances are going to be influenced by projected climate change. Table shows the comparison between climate statistics associated with two considered scenarios. Climate change projections revealed that the future pavements in the selected cities are expected to experience higher average temperature, fewer freeze/thaw cycles and more precipitation. Figure 4 shows the potential impact of climate change on the JPCP distresses for five cities in this study.

Based on the observed deterioration trends, faulting generally increased under 2050-climate scenario in comparison to the base line scenario. It must be pointed out that temperature is a fundamental factor in predicted joint faulting particularly due to its effect on joint LTE. While during colder temperatures the LTE by PCC aggregates interlock will be lower due to wider joint openings, the LTE by the supporting base layer will be higher and thereby the combined LTE across the joint may be higher during particularly freezing temperatures. Increase in joint faulting can be also attributed to the increased number of wet days as a result of more precipitation.

With respect to change in ride quality as represented by IRI, it was noticed that IRI slightly decreased with increasing years under 2050-climate scenario. While joint faulting, cracking and spalling are recognized as the most critical factors in JPCP smoothness (2), other factors such as freezing index and number of freeze/thaw cycles are also contributing to MEPDG's IRI prediction model. Therefore, it is highly likely that warmer weathers and consequently less risk of frost-related damage to structure may lead to lower predicted IRI.

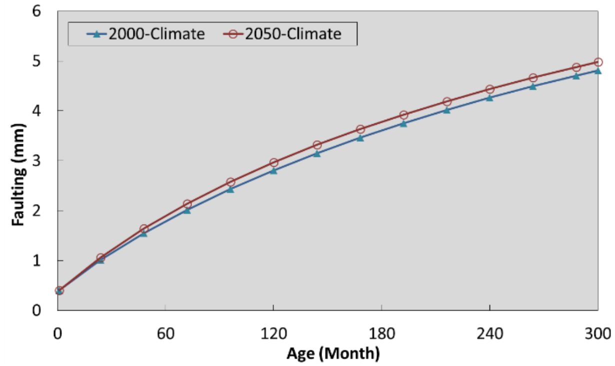
In this trial, the predicted value of the slab cracking was negligible under two different scenarios in most cases. Nonetheless, it is well-understood that both built in and transient temperature and moisture gradient control the crack propagation in PCC slab through curling and warping phenomenon. Thus, hot weather problems such as high ambient temperature and solar radiation if combined with high wind speed and low relative humidity tend to create large built-in temperature gradient and consequently reduce the strength and durability of JPCP.

Table 3- Annual climate statistics under baseline and projected climate

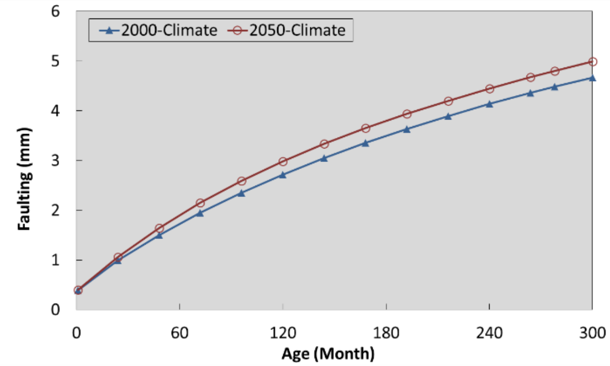
City	Mean Annual Air Temperature (°C)		Mean Annual Precipitation (mm)		Freezing Index (°C-days)		Number of. Freeze/Thaw Cycles	
	2000 Climate	2050 Climate	2000 Climate	2050 Climate	2000 Climate	2050 Climate	2000 Climate	2050 Climate
Montreal	7.83	10.88	975.61	1130.05	663.35	315.81	70.91	59.91
Ottawa	7.53	10.56	950.72	1049.27	684.06	335.62	65.11	55.72
Saskatoon	3.93	6.54	470.41	550.42	1371.47	940.41	75.10	66.93
Toronto	8.96	11.88	869.19	980.19	442.15	170.75	65.26	61.04
Winnipeg	5.27	8.31	562.86	621.28	1397.71	899.59	68.91	61.91

Conclusion

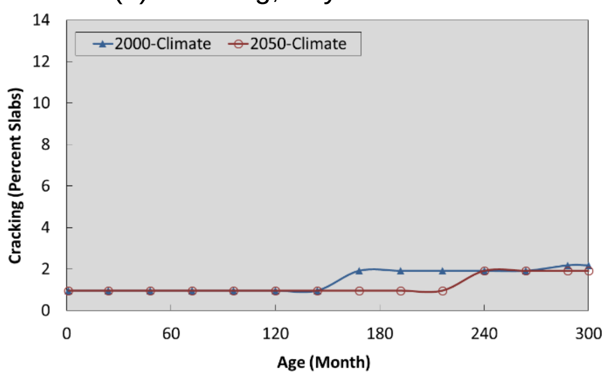
Changes in the climate system will influence JPCP pavement performance and therefore, it is crucial to adapt the pavement design practice to suit this new reality. Focusing on five major Canadian cities, variations in MEPDG-predicted performance due to environmental impacts was evaluated and quantified in this study. Comparison of rigid pavement distresses predicted by AASHTOWare Pavement ME Design using current NARR and MERRA databases indicated that MERRA- predicted distresses are often quite higher than the ones calculated using NARR. In addition, a sensitivity analysis was conducted to investigate the impact of temperature, precipitation, sunshine, wind speed and humidity on IRI, joint faulting and slab cracking. It was found that software outputs were less sensitive to precipitation in comparison to other climatic factors. Finally, the impact assessment of projected change in climate based on CanRCM4 model indicated that increase in predicted joint faulting became more noticeable under climate change scenario.



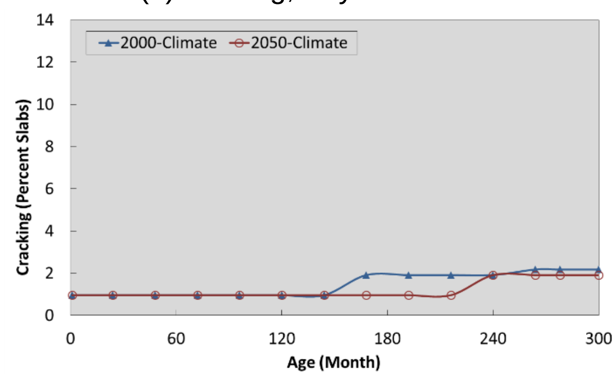
(a)- Faulting, City of Montreal



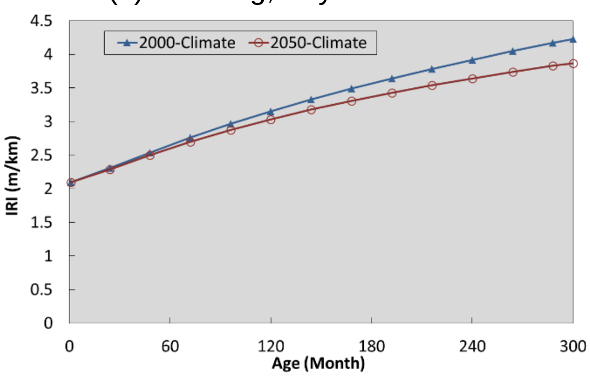
(d) Faulting, City of Ottawa



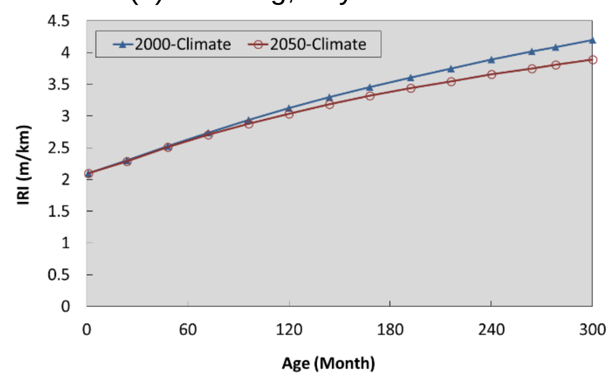
(b) Cracking, City of Montreal



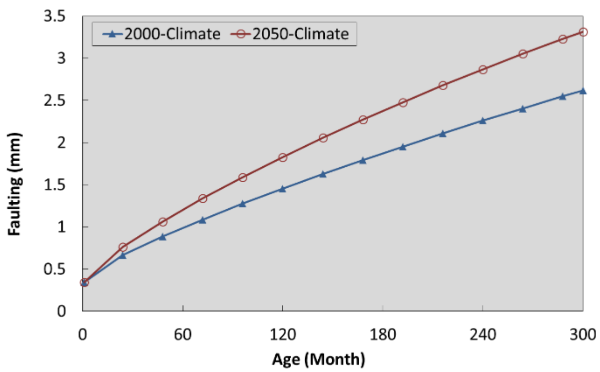
(e) Cracking, City of Ottawa



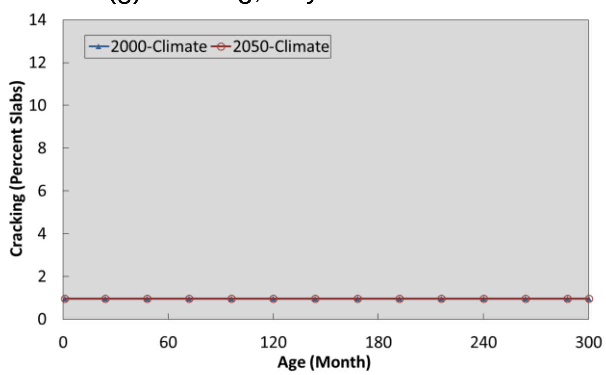
(c) IRI, City of Montreal



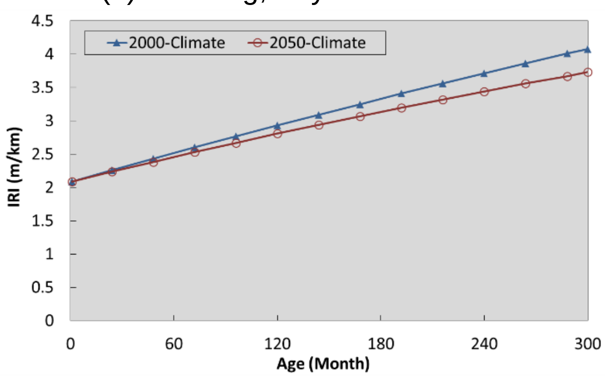
(f) IRI, City of Ottawa



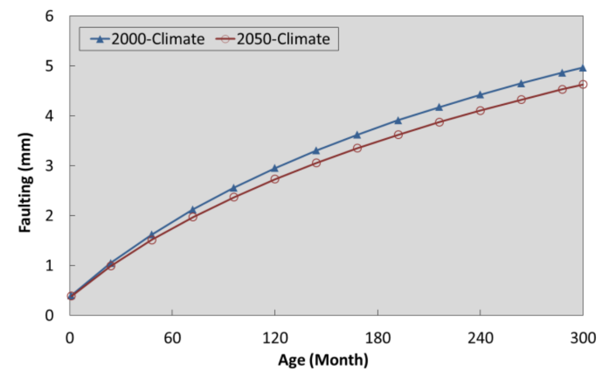
(g) Faulting, City of Saskatoon



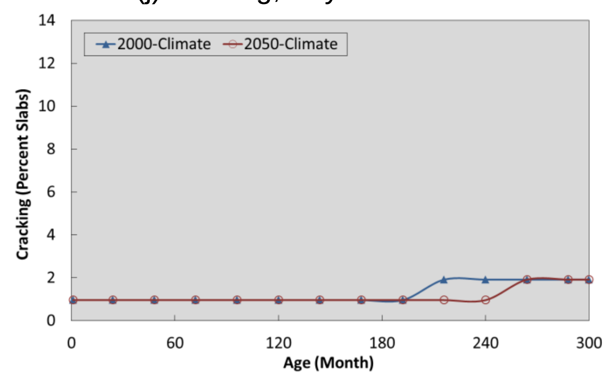
(h) Cracking, City of Saskatoon



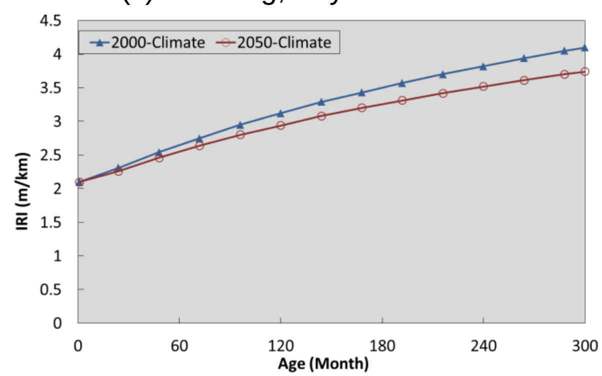
(i) IRI, City of Saskatoon



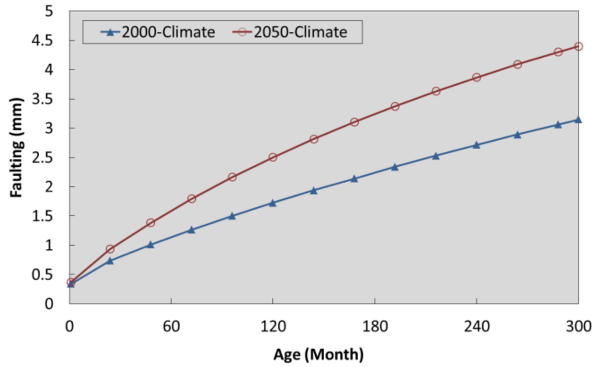
(j) Faulting, City of Toronto



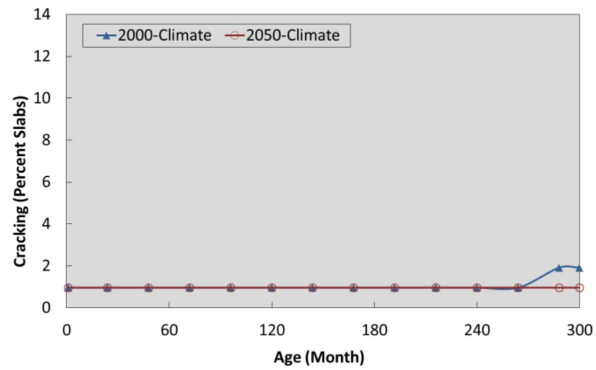
(k) Cracking, City of Toronto



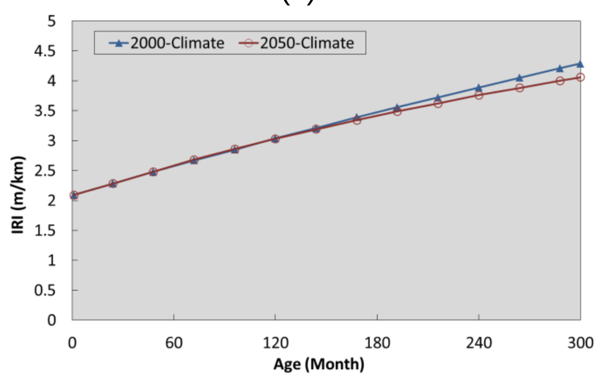
(l) IRI, City of Toronto



(m) Faulting, City of Winnipeg



(n)



(o)

Figure 4- Impact of climate change on predicted performance

Acknowledgments

This project is being undertaken as part of NRC's Climate Resilient Buildings and Core Public Infrastructure initiative and was made possible through funding from Infrastructure Canada under the Pan Canadian Framework on Clean Growth and Climate Change.

References

1- Palko, K. and Lemmen, D.S. (Eds.). 2017. Climate risks and adaptation practices for the Canadian transportation sector 2016. Ottawa, ON: Government of Canada.

2- ARA Inc., 2004. Guide for mechanistic-empirical design of new and rehabilitated pavement structures, Champaign.

3- Li, Q., Mills, L. and McNeil, S., 2011. The implications of climate change on pavement performance and design, University of Delaware University. Transportation Center

4- Willway, T., Reeves, S. and Baldachin, L. 2008. Maintaining Pavements in a Changing Climate, Britain Department for Transport.

5- IPCC. 2018: Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. In Press.

6- USGCRP. 2017: Climate Science Special Report: Fourth National Climate Assessment, Volume I [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, 470 pp., doi: 10.7930/J0J964J6.

7- Bush, E. and Lemmen, D.S., editors. 2019. Canada's Changing Climate Report; Government of Canada, Ottawa, ON. 444 p.

8- Scinocca J.F., Kharin V.V., Jiao Y., Qian M.W., Lazare M., Solheim L., Flato G.M., Biner S., Desgagne M., Dugas B. 2016.Coordinated global and regional climate modeling, Journal of Climate, 29 (1), pp. 17-35, doi: 10.1175/JCLI-D-15-0161.1

9- MTO MERO. 2019. Ontario's Default Parameters for AASHTOWare Pavement ME Design Interim Report.

10- Brink, W., Von Quintus, H. and Osborne Jr, L.F., 2017. Updates to hourly climate data for use in AASHTOWare pavement mechanistic–empirical design. Transportation Research Record, 2640(1), pp.11-20.

11- Durham, S.A., Cetin, B., Schwartz, C.W., Forman, B. and Gopisetti, L.S.P., 2019. Improvement of Climate Data for Use in MEPDG Calibration and Other Pavement Analysis (No. FHWA-GA-19-1610). Georgia. Dept. of Transportation.