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The impact of projected Canadian regional climate model data on flexible pavement performance

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Abstract

This paper explores the impact of projected climatic loading parameters, utilizing Environment and Climate Change Canada data, on flexible pavement performance and design. Despite the expectation that flexible roads should endure various structural and environmental conditions throughout their design life, premature damage often occurs within the initial 3–5 years of service. Therefore, understanding the impact of climate change on flexible pavements in the historical, short, intermediate, and long terms becomes crucial.

The pavement mechanistic empirical design (PMED) was employed to assess climatic loading effects on pavement design and performance. PMED-predicted rutting performance showed sensitivity when comparing historical and projected climatic loading parameters up to 2093. Preliminary results based on a 25-year design life for City of Windsor revealed a 72% higher rutting impact compared to historical data, shortening the pavement's design life by 28%, 56%, and 68% for short, intermediate, and long terms, respectively.

Key words: climate change impact, temperature effect, flexible pavement, stiffness of asphalt concrete, structural behaviour

Introduction

Canada's climate is changing and, according to the latest climate models, is projected to continue changing at increasingly rapid pace over the coming decades (Government of Canada 2022). Projected climate changes will have important implications for the long-term safety and functionality of flexible roads. In many ways, climate change presents a fundamental challenge to engineering and planning practice, given that transportation infrastructure has traditionally been planned and designed based upon historical climate data under the implicit assumption that the climate is static and the future climate conditions will mirror past ones. Li et al. (2011) concluded that future environmental factors pose an underlying challenge to the existing engineering practices since pavements have been designed according to historical climate data under a false assumption that climate will not change. This assumption increases the likelihood of shortening the design life of roads.

Climate change challenges traditional assumptions in pavement design and transportation system operations, urging practitioners to consider new risks. Navigating this task proves challenging due to inherent uncertainties in climate projections. Nevertheless, adapting to these changes is imperative for transportation professionals to deliver cost-effective and climate-resilient transportation infrastructure.

The Synthesis Report of the Intergovernmental Panel on Climate Change (IPCC 2023) indicated that without a strengthening of policies, a rise of projected emissions will result in a median global warming of 2.2–3.5 °C (very likely range) by 2100 (medium confidence). Prolonged heatwaves and extremely high temperatures will result in the early deterioration of infrastructure, shortening the design life of flexible pavements through asphalt binder softening and traffic-related rutting as reported by Parry et al. (2007). Applied Research Associates (2015) concluded that climate change and extreme weather events in the cities of Quebec and Montreal can impact pavement performance. These events must be considered when selecting climate resilient bound and unbound materials.

El-Basyouny et al. (2005) defined that the permanent deformation is the irreversible plastic movement characterized by surface change levels that cannot return to their original shape. Permanent deformation (rutting) is caused by the magnitude and number of applied traffic loads to the bound (asphalt matt) and unbound materials (sub-grade, base, and subbase) underneath the hot mix asphalt (HMA) top layer.

Permanent deformation or rutting is an inside distortion of the asphalt layers. It is considered one of the most common flexible pavement distresses at high temperature of asphalt matt caused by climate change concerning asphalt practitioners and designers. Hajj et al. (2007) noted that HMA mixtures not having sufficient shear resistance to withstand repetitive traffic loading over a lengthy period at a high temperature of asphalt concrete will be very prone to rutting. Although

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stiffer HMA materials will, in part, decrease this sort of rutting, it is typically considered more of a structural sub-grade rutting issue instead of a surface rutting problem. Therefore, HMA must be resilient enough to diminish the connected stresses and strains caused by traffic impact to an acceptable level.

Tighe et al. (2008) studied the sensitivity analysis of climate change impact on Southern Canadian roads using the earlier version of Mechanistic–Empirical Pavement Design Guide (M-EPDG) and M-EPDG historical climatic loading parameters of Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2). They found that rutting varied from one city to another, with a general trend of increased rutting in all Canadian cities. The study disadvantages are: (1) it was done on old version of M-EPDG; (2) it used MERRA-2 climate data, which is based on global and historical climate data.

Qiao (2015) assessed the impact of climate change on the degradation of flexible pavements in Southern Virginia, employing Version 1.1 of the M-EPDG. Through a sensitivity analysis involving a 5% increment in climatic loading parameters, namely, temperature, precipitation, wind speed, solar radiation, and groundwater level, it was determined that temperature significantly influences various pavement distress types. By extrapolating the temperature projections for the year 2050, the study concluded that a nationwide temperature increase could result in substantial deteriorations, manifesting as asphalt rutting, longitudinal cracking, and alligator cracking. To mitigate these potential deteriorations induced by climate change, upgrading the asphalt binder grade was recommended.

Maadani and Abd EL Halim (2016) concluded that the impact of the saturated side of the optimum moisture on resilient modulus (M_R) is more significant than the dry side. As the moisture content decreases (dry side of optimum) and increases (wet side of optimum), the M_R increases and decreases, respectively. Additionally, as the placement density increases, so does the resilient modulus. To overcome the long-term effects of climate change on pavement material characteristics, the pavement mechanistic empirical design (PMED) (NCHRP 2004b) was developed. The Enhanced Integrated Climatic Model (EICM) integrated into the PMED to stimulate the long-term performance of pavements according to the change of climatic conditions over the design period. However, it is noted that the PMED has superior capability over ASSHTO design guide (AASHTO guide for design pavement structures 1993) method, as the PMED method can incorporate different levels of analysis to capture the impact of the unbound materials state conditions (dry, optimum, and wet), mechanistic properties such as resilient modulus, density of unbound materials, complex modulus, creep compliance, and tensile strength of HMA. Maadani and Abd EL Halim (2016) reported that in seasonal and perennial frozen areas, pavements are affected by the freeze–thaw cycles. In most of the northern states of the USA and most of Canada, roads are affected by frost, and their strength and load-bearing capacity change with the seasons. Road construction in cold regions differs from warm regions in that it is constrained by daylight, weather, short construction season, and long distances in remote areas. Maadani and Abd EL Halim (2016) found that, in general, the pavements in frost-affected regions also require more maintenance. Asphalt and concrete surfaces undergo various environmental temperatures, loading and weather, which impact their structure, lifespan, and rigidity in distinct ways. Therefore, it is essential to analyze locations where new roads are being constructed for these conditions and design roads suited to these environments.

Dore (2002) noted that cold region pavements are subjected to harsh climatic and environmental factors in the presence of moisture and cold temperature. As water freezes, its volume expands, resulting in heave. Three factors cause pavement deterioration in the cold regions, and they are thermal contraction and fracture in the bound layer, volume changes caused by frost heave, and unbound material strength loss due to thaw during spring.

In a PMED structure design tool, air temperature, wind speed, precipitation, percent sunshine, and relative humidity on an hourly basis over the entire design life of the road are the climatic loading parameters-driven variables that can significantly affect the pavement layer and sub-grade properties and, hence, its load-carrying capacity. It is necessary to understand the impact of variations in climatic loading parameters across a broad spectrum, considering both daily and seasonal fluctuations. The transition from one season to another can exert a notable influence on pavement life and performance, emphasizing the importance of assessing these changes comprehensively. The variations of moisture and temperature envelopes of different structural layers of the road necessitate that many municipalities of North America enforce weight restriction in the spring of each year during the thawing seasons. The determination to enforce load restrictions is not solely based on the heightened stresses exerted on the unbound layers of the road; rather, it signifies a broader lack of comprehension regarding the evolving environmental conditions affecting the road layers. Fundamental pieces of information for modeling pavement performance and design include load limits during the spring season and the thickness of the frost-free base.

The essence of constructing climate-resilient roads lies in acknowledging that the climate can no longer be considered a stationary process. Roads should be designed to endure the conditions anticipated to occur throughout their design life, recognizing the dynamic and evolving nature of the climate. Since the road performance prediction periods for the road design life are longer than the weather time series length, the deficiency is accommodated by recycling the same period weather history for the length of road design life. Long-term pavement performance (LTPP) collected hourly weather data from weather stations across the United States and Canada. Most weather stations have hourly weather series longer than 10 years. Significant quality checks are required for weather data before they are uploaded into the LTPP database. However, data gaps and errors are not rare. These issues can create problems when trying to use collected data as weather inputs to the M-EPDG.

Truax et al. (2011) noted a substantial disparity among climate models when generating projected climatic loading files. Despite advancements, challenges persist in determining the optimal utilization of existing weather station data. The M-EPDG demands climatic projections with hourly time resolution, a detail not readily furnished by global or regional climatic models. A subsequent study by Meagher et al. (2012) adopted an average 3 h interval for climatic data. This approach demonstrated that averaging mitigates the impact of extreme temperatures, particularly crucial in predicting phenomena like rutting and thermal cracking.

Scope and objective

The scope of this study is to analyze flexible pavement performance over different historical, short-, intermediate, and long-term 25-year cycles for each projected climate region. The objective is to conduct a sensitivity analysis of flexible road performances using PMED as impacted by seasonal climatic changes. The performance indicators that will be considered include: total permanent deformation, asphalt permanent deformation, asphalt bottom-up fatigue cracking, and International Roughness Index (IRI) accumulated throughout the design life. Top-down cracking and thermal cracking are not considered because of their low impact on the sensitivity analysis.

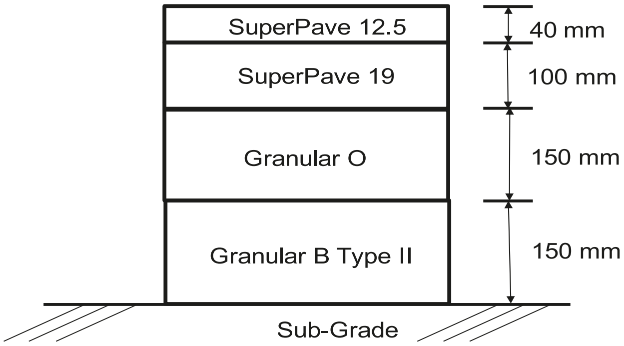
Methodology

PMED analytical modelling was used in this study to provide service life prediction to cover the design life span of the flexible roads on a specific site for four projected climatic loading terms using Environment and Climate Change Canada (ECCC) data. An analytical investigation, using generic data, was conducted to evaluate the sensitivity of climate change impact encountered in flexible pavement roads. Permanent deformation (asphalt and total), bottom-up cracking, and IRI accumulated throughout the 25-year design life were used to measure changes in the behaviour and characteristics of the pavement and the unbound materials that occur with two different site-specific climate conditions over the four terms design periods.

Analytical modelling

All analysis in this study was performed using PMED version 3.0 (NCHRP 2004b). Two cities were selected to evaluate the PMED sensitivity using both historical and projected ECCC climatic loading parameters to the variety of materials and loading conditions used and encountered in flexible pavement roads. The PMED integrates the EICM to replicate alterations in the behaviour and attributes of pavement and sub-grade materials in alignment with the prevailing climatic conditions throughout the design period. The climatic file considers a 25-year design cycle of climatic loading parameters such as ambient temperature, precipitation, wind speed, percent sunshine, and humidity. The PMED uses the hourly climate data to calculate pavement temperature with depth throughout the pavement structure. The air temperature input is only one of the factors that influence pavement temperatures. The other contributing factors include wind speed and percent sunshine. In general, higher wind speeds reduce pavement temperatures due to more turbulent air flow at the pavement surface. The percent sunshine value is used to calculate both shortwave and longwave radiation. The shortwave radiation controls the pavement temperature during the daytime, while the longwave radiation controls it at night.

Fig. 1. Site structural layers.



Site and traffic data

The site road is a four-lane street (two lanes in each traffic direction) and provides the opportunity to study the behaviour of road structures in relatively different climate regions. The traffic survey data obtained from the Ministry of Transportation of Ontario was utilized to predict the fleet composition, which remained consistent for all cities with two-way Annual Average Daily Truck Traffic of 6940, 3.9% of growth and speed of traffic of 70 km/h. The existing road structure located at Kinburn Side Road Hwy 417 rests on a native rock sub-grade. The pavement structure is composed of (1) an asphalt concrete surface of superpave 12.5 and 19 with a thickness of 40 and 100 mm, respectively, (2) a 150 mm thick dense granular aggregate base-coarse (Type O), and (3) a 150 mm thick granular B type II material sub-base (See Fig. 1).

Materials input files

Hot mix asphalt mixture

The HMA mix design process was used in the production of HMA that satisfies the requirements of the Ontario Provincial Standard Specification (OPSS 1003 2013) for material specification for HMA aggregate. Samples of the Superpave, SPs 12.5 and 19 mixes, using performance grade PG 58-28 were produced. These mixes were prepared following the requirements of the PMED AASHTO design guide.

Dynamic modulus

The dynamic modulus, a crucial stiffness element within the complex modulus, has been incorporated into the PMED. The AASHTO test standard, AASHTO T342 (2022), is a strain-controlled version of the complex modulus test, was used to capture the viscoelastic response of asphalt concrete (AC) materials. Tables 1 and 2 show the results of measured dynamic modulus for SPs 12.5 and 19 mm mixes. In this study, the

Table 1. Dynamic modulus results for SP 12.5.

	E* (MPa)					
Frequency (Hz)	0.1	0.3	1	5	10	20
−10	12 799	13 991	15 204	16 371	16 616	17 303
0	7118	8453	9849	11 822	12 569	13 316
20	919	1421	2181	3623	4500	5618
30	420	608	920	1646	2168	2858
40	180	240	356	653	885	1212

Table 2. Dynamic modulus results for SP 19.

	E* (MPa)					
Frequency (Hz)	0.1	0.3	1	5	10	20
−10	15 739	17 261	18 910	20 433	20 695	21 209
0	9068	11 243	13 238	15 507	16 243	17 378
20	1826	2603	3645	5455	6485	7613
30	431	619	966	1776	2358	3137
40	176	236	360	674	930	1299

Table 3. Shear modulus and phase angle.

PG binder	SP 12.5		SP 19	
T (°C)	G* (MPa)	δ (Degree)	G* (MPa)	δ (Degree)
−12	3676	76	8054	77
5	2090	75	5220	76
20	505	73	2213	76
38	110	71	370	73
54	50	69	126	71

complex modulus and phase angle of the asphalt binders PG 58-28 were calculated using the measured dynamic modulus for the SP 12.5 and 19 mm mixes as shown in Table 3.

Creep compliance and tensile strength

The determination of creep compliance and tensile strength adhered to the specifications outlined in AASHTO T322 (2020). This involved applying a static compressive load of a fixed magnitude along the diametric axis of a specimen for a duration of 100 s. The measured horizontal and vertical deformations from each side and axial load were used to calculate the creep compliance. Tables 4 and 5 show the measured results of creep compliance of the SPs 12.5 and 19 mm mixes. The indirect tensile strength was measured by applying load on the HMA specimen along its diametric axis at a constant rate of 12.5 mm/min until failure. The test was performed at a temperature of −10 °C. The determined tensile strength values were 3.59 and 3.73 MPa for SP 12.5 and 19 mixes, respectively.

Unbound and sub-grade materials

The National Cooperative Research Program (NCHRP 2004a) has embraced the resilient modulus as a parameter to characterize the mechanistic response of both unbound and sub-grade materials. The advanced design level recommends using actual laboratory test data for the resilient modulus, determined using measured environmental parameters and simulated traffic loading conditions. The resilient modulus, moisture content, soil density, Atterberg parameters, and sieve analysis are the primary parameters needed for level 1 of the analysis. The liquid and plastic limits of these materials were determined using ASTM standard test D4318 (2018) and the values are shown in Table 6.

AASHTO T99 (2022) standards were employed to establish the correlation between the moisture content and density of solid compacted within a mold of either 101.6 or 152.4 mm diameter, utilizing a 2.5 kg rammer dropped from a height of 305 mm. The resilient modulus was determined using the AASHTO T307 (2021) procedure for representative material samples. Optimum moisture content, resilient modulus (M_R), and density are given in Table 7.

Climatic files

The PMED (NCHRP 2004b) requires climatic loading parameters. Under the changing climate, as the environmental data will change over time, the historical data cannot represent future climatic conditions. Therefore, to take the impact of climate change into account, it is essential to provide PMED with projected climatic data over the course of the road design life.

The projected climatic loading parameters such as air temperature, precipitation, wind speed, humidity, and cloud cover were generated by ECCC using Canadian Regional Climate Model, version 4 for Canadian cities from 1950 to 2100 at high resolution (50 km) and used in PMED runs. There are four different emissions scenarios or shared socio-economic pathways (SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5), from lowest to highest (in terms of carbon dioxide concentration in the atmosphere). In this study, we have selected the highest emission scenario (SSP5-8.5) because it is the one represent-

Table 4. Creep compliance results for SP 12.5 mm mix.

Loading time (s)	Creep compliance (1/MPa) Low at −20 °C	Mid at −10 °C	High at 0 °C
1	226	387	727
2	234	421	884
5	253	467	1070
10	267	517	1279
20	281	573	1528
50	303	667	1980
100	323	773	2424

Table 5. Creep compliance results for SP 19 mm mix.

Loading time (s)	Creep compliance (1/MPa) Low at −20 °C	Mid at −10 °C	High at 0 °C
1	114	125	158
2	120	137	177
5	125	147	220
10	129	158	259
20	133	166	303
50	142	176	386
100	149	190	474

Table 6. Plasticity properties for all materials.

Soil type	Liquid limit (LL)	Plasticity index (PI)
Granular material (Type O)	28.7	8.4
Granular base (Type II)	0.0	0.0

Table 7. Unbound material physical properties.

Material	Soil condition	Moisture content (%)	M_R (MPa)	Density (kN/m^3)
Granular material (Type O)	Dry	3.4	169	21
	Optimum	5.2	148	22
	Wet	5.9	131	21
Granular base (Type II)	Dry	4.5	126	20
	Optimum	6.1	120	22
	Wet	6.6	116	21

Table 8. Historical and projected climatic data for road design life.

Term number	Term	Road design life, 25 years
1	Historical	1993–2017
2	Short	2018–2042
3	Intermediate	2043–2067
4	Long	2068–2092

ing current conditions and is likely to continue with a similar trend.

In this study, it was assumed that the road section was built in 1993 for the design life of 25 years. More details of term number, terms, and projected design period are shown in Table 8.

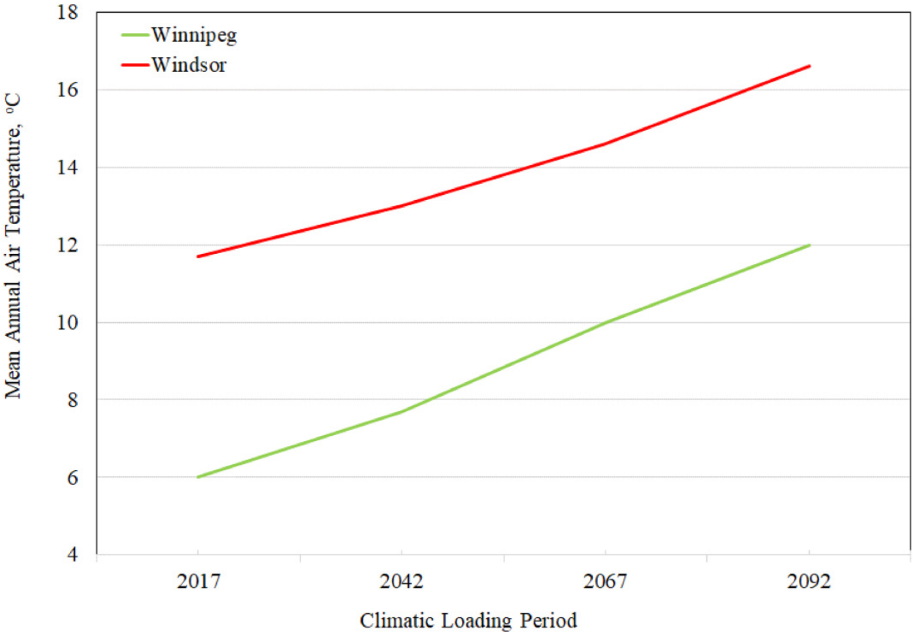
The near-surface air temperature, wind speed, and precipitation are directly available from climatic models. As for the percent sunshine, it could be indirectly estimated through the total cloud fraction parameter as one of the climate models output.

The relative humidity is available as a direct output from some climate models; however, there are some other models that provide other forms of humidity (e.g., specific humidity) that can be converted to the relative humidity.

Analysis and discussion

Analytical study was performed to examine the PMED ability to capture the impact of seasonal variations and the changes from season-to-season. The study considered climatic loading parameters such as ambient temperature, pre-

Fig. 2. Calculated mean annual air temperature (MAAT).



cipitation, wind speed, percent sunshine, and humidity in predicting the performance of flexible roads.

Runs were performed to examine the ability of the PMED software to capture the impact of different climatic loading parameters and to predict performance distresses of the asphalt, such as total permanent deformation (rutting), asphalt permanent deformation (rutting), bottom-up cracking, and IRI accumulated throughout historical (1993–2017), short (2018–2042), medium (2042–2067), and long terms (2068–2092). The design life (25 years) for each climate data term was used to measure changes in the behaviour and characteristics of the asphalt and the unbound materials. To cover two different distinct climate regions in Canada, two cites were selected. Central Canada: Windsor, ON, and the Prairies: Winnipeg, MB.

ECCC climatic loading parameters

As mentioned previously, for this study encompassing two distinct climate regions in Canada, two cities were selected: Windsor representing Central Canada, and Winnipeg representing the Prairies. Projected climatic data prepared by ECCC for road design terms for Windsor, ON, and Winnipeg, MB are shown in Table 8. The calculated environmental loading parameters for ECCC specific city files are shown next.

Mean annual air temperature

Projected climatic data for road design terms shown in Table 8 were used to summarize and describe the average climatic conditions of a particular city in terms of Mean annual air temperature (MAAT). Figure 2 shows a general trend of temperature increase in both Windsor and Winnipeg. The highest MAAT is about 17 and 12 °C with an increase in projected term 4 design life of about 42% and 56% compared to historical trends in the cities of Windsor and Winnipeg, respectively.

Changes in the projected range of temperatures, including seasonal changes in MAAT, can also impact highway systems. The increase in MAAT ranges will likely benefit highways in some ways, while increasing risks in others.

Mean annual degree days

The newest change in LTPPBind was on September 2018, including switching to Degree Days above 10 °C instead of high 7 days consecutive air temperature. In Climate Adaptation and Asphalt Selection Tool—CAAST (Maadani et al. 2023), the calculation is not limited to the range between April and September as it is in LTPPBind but instead includes the whole year. In Fig. 3, the general trend shows that the mean annual degree days (MADD) increases gradually over the projected years, reaching the highest values of 4805 and 3977 °C for the cities of Windsor and Winnipeg, respectively, by year 2092. Analysis of Fig. 3 indicated that both cities show an increase in MADD of 10%, 25%, and 39% in projected terms 2, 3, and 4, respectively.

Mean annual precipitation

The PMED was used to calculate the mean annual precipitation (MAP) for both cities. The highest MAP is about 1100 and 686 mm in Windsor and Winnipeg, respectively, with an increase of 8% and 0%, respectively, compared to historical data, as shown in Fig. 4.

Fig. 3. Calculated mean annual degree days (MADD).

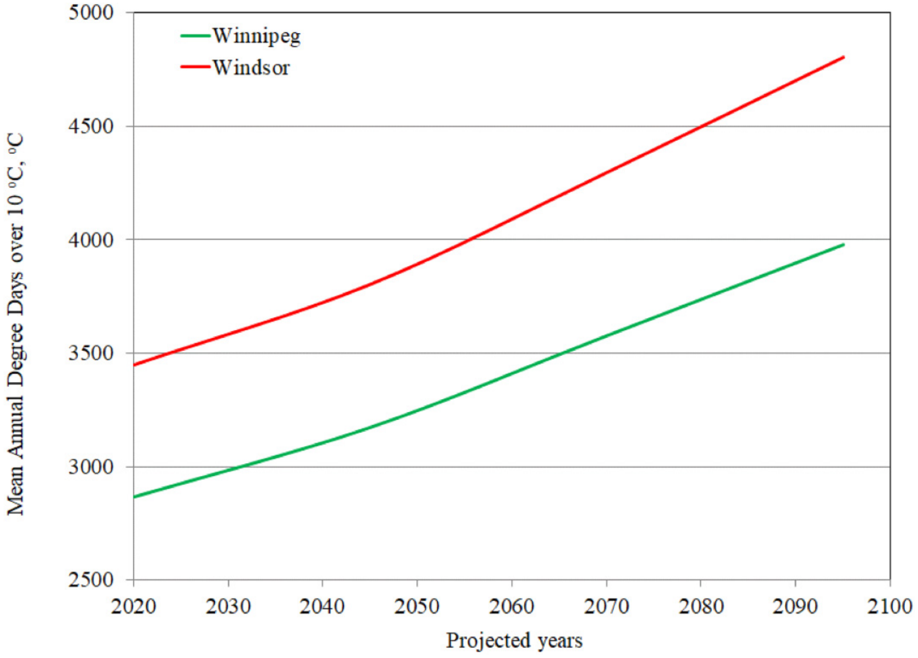
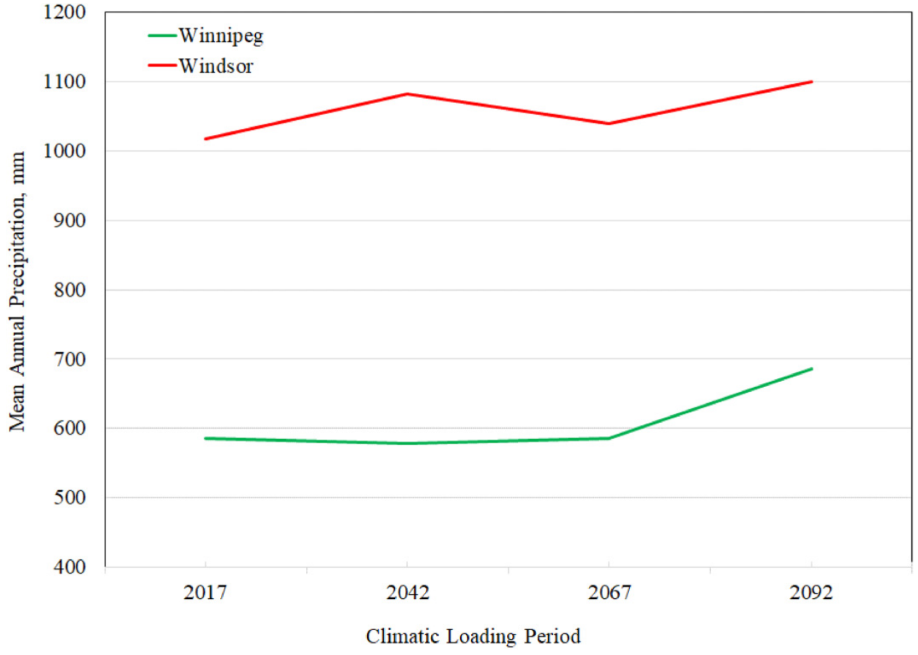


Fig. 4. Mean annual precipitation (MAP) analysis using pavement mechanistic empirical design (PMED).



Freezing index and freeze and thaw cycles

Using PMED to analyze the projected climate data, it was found that increased temperature resulted in less frost. This finding is important in terms of flexible road performance. Figure 5 indicated that climate warming is causing a general decrease in the freezing index. Figure 5 shows a reduction of 21%, 49%, and 66% for the city of Windsor in the short, intermediate, and long terms of climate change, respectively. Following a similar pattern, the city of Winnipeg showed a reduction of 38%, 74%, and 89% for the short, intermediate, and long terms of climate change, respectively.

Soil in cold regions may undergo several freeze and thaw cycles each year, as shown in Fig. 6. The resilient modulus as a measure of unbound material stiffness increases tremendously when frozen during winter, then drops below normal stiffness right after thawing season and slowly recovers to normal values during the late spring and summer. These variations in unbound material stiffness are captured in the new

Fig. 5. Freezing Index (FI) analysis using pavement mechanistic empirical design (PMED).

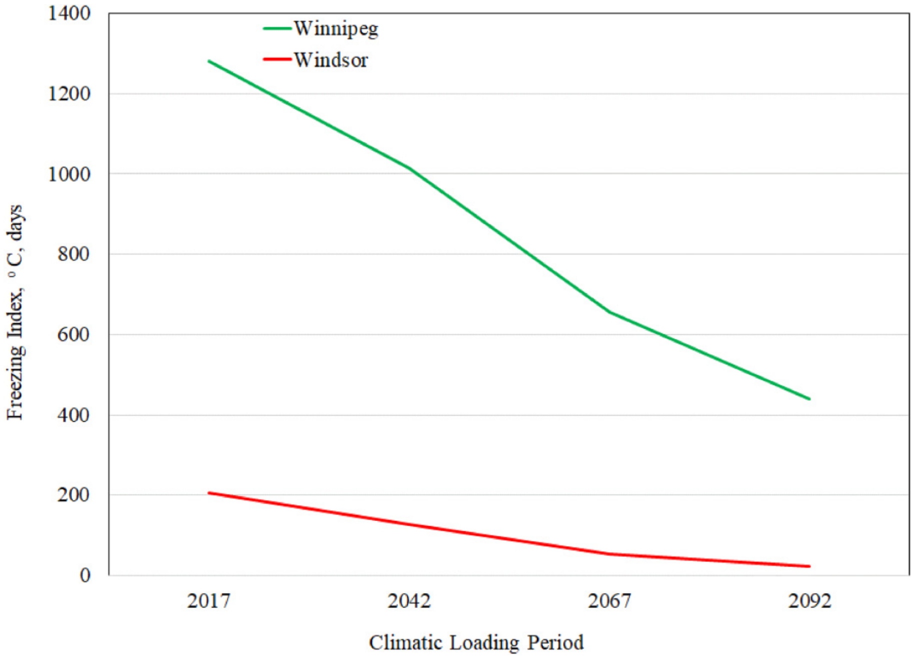
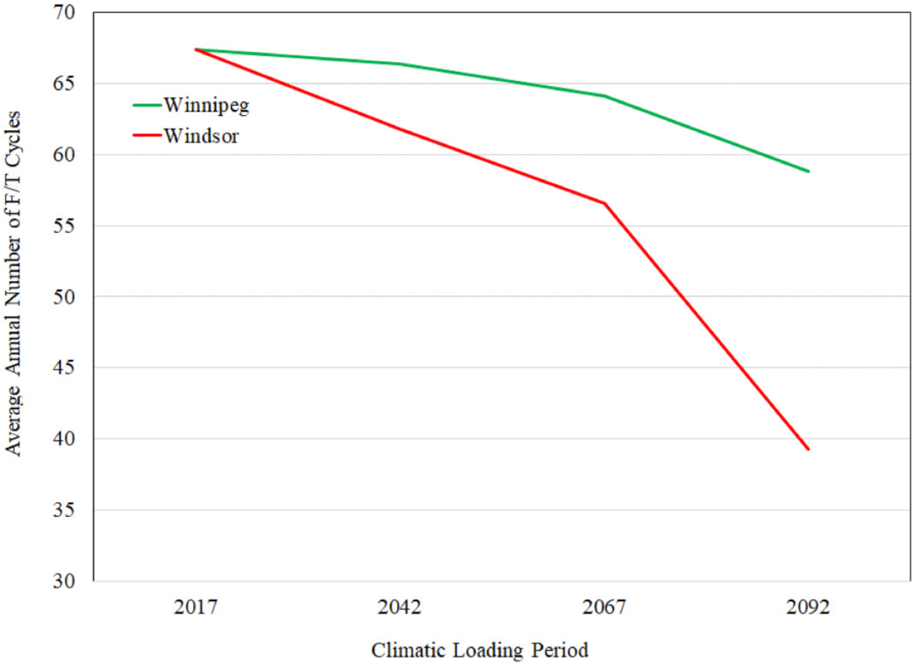


Fig. 6. Annual number of freeze and thaw cycles.

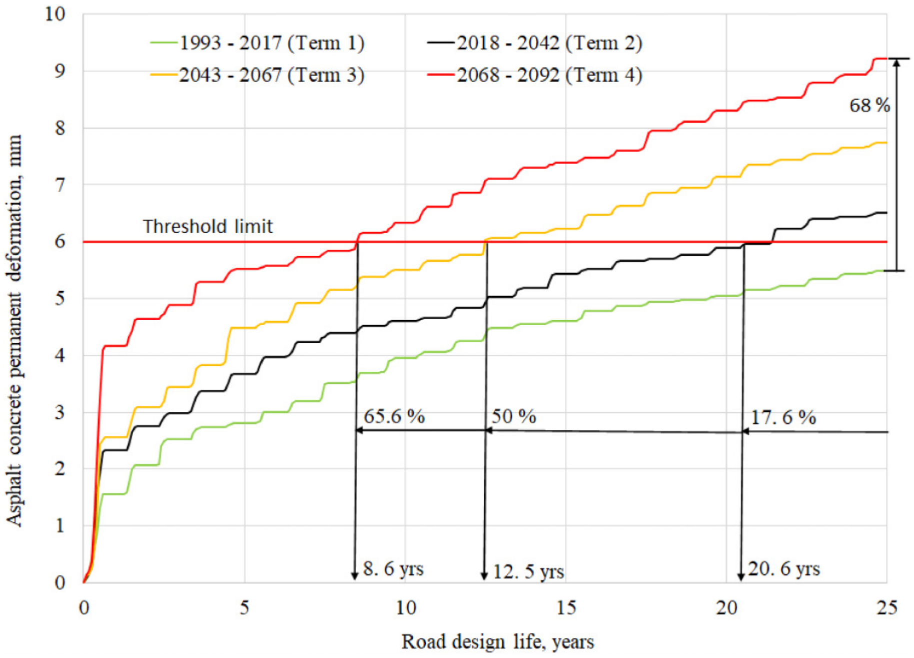


PMED using EICM using empirical model for freeze–thaw adjustment factors using site-specific climate input files for the cities of Windsor and Winnipeg. The general trend is that the number of freeze and thaw (F/T) cycles decrease with time. Further analysis of Fig. 6 showed a reduction of 8%, 16%, and 42% in the city of Windsor for short, intermediate-, and long-term impacts of climate change. The city of Winnipeg showed a reduction of 1%, 5%, and 13% for short-, intermediate-, and long-term impacts of climate change. The variability among cities was determined by the climatic region of each respective city.

Projected seasonal impact on flexible roads

Analysis to examine the effects of historical, short, intermediate, and long terms climate change impacts as shown in Table 8 on flexible road structural layers was carried out using PMED. Distress performances accumulated throughout the 25 years design life for each term were evaluated using

Fig. 7. Temperature impact on asphalt permanent deformation—Windsor.



the optimum conditions for the unbound materials, PG 58-28 binder properties from Tables 1–5.

Temperature impact

The following are the results of key performance distresses such as predicted asphalt permanent deformation, asphalt bottom-up cracking and IRI, respectively.

Asphalt permanent deformation

The results of permanent deformation accumulated throughout the 25 years design life was evaluated using climatic loading parameters as shown in Fig. 7. It can be noticed that the asphalt permanent deformation predictions for the projected Term 4 for warm regions with MAAT of 17 °C were about 68% higher than the relatively cold historical term (1993–2017—Term 1) of MAAT about 12 °C. The PMED model exhibited good sensitivity to different climatic cycles.

Furthermore, Fig. 7 shows the city of Windsor's typical results of the impact of different projected climate change terms on the asphalt permanent deformation.

The general trend is that asphalt permanent deformation increases with time. Further analysis showed that the design life of pavement shortened by 18%, 50%, and 66% based on the short term (2018–2042—Term 2), intermediate term (2043–2067—Term 3), and long term (2068–2092—Term 4), respectively.

In the same fashion, Fig. 8 shows that the design life of pavement for the city of Winnipeg shortened by 18%, 38%, and 58% based on term 2, term 3, and term 4, respectively.

Asphalt bottom-up fatigue cracking

The bottom-up fatigue cracks consistently and significantly increase from the baseline run. As the dynamic modulus of the asphalt layer decreases at higher temperatures, more damage will occur, or higher amounts of fatigue cracking will be predicted. Increasing predicted amounts of fatigue cracking is almost expected in all mechanistic–empirical methods using repeated load beam fatigue tests. The number of the predicted cracks will not only be dependent on the increasing temperatures but also on the length of the spring thaw, where the resilient modulus of the supporting base layer might be lower for an extended length of time relative to the baseline climate period. The typical result shown in Fig. 9 is the impact of the projected climate of the city of Windsor on bottom-up fatigue cracking increases with time and shortens the road design life by about 58%, 64%, 66%, and 70% of the normal cycle of design life for terms 1, 2, 3, and 4, respectively.

Results illustrated in Fig. 10 shows the impact of the projected climate of the city of Winnipeg on bottom-up fatigue cracking. The city of Winnipeg's bottom-up fatigue cracking increases with time and shortens the road design life by about 54%, 58%, 61%, and 66% of the normal cycle of design life (25 years) for terms 1, 2, 3, and 4, respectively.

International Roughness Index

IRI is dependent on the site factors, predicted distresses of rut depth, fatigue cracking, and thermal cracking. Some of the site factors are climate-based (annual rainfall, freezing index, etc.). The impact of different projected climate loading cycles of the cities of Windsor and Winnipeg on the IRI

Fig. 8. Temperature impact on asphalt permanent deformation—Winnipeg.

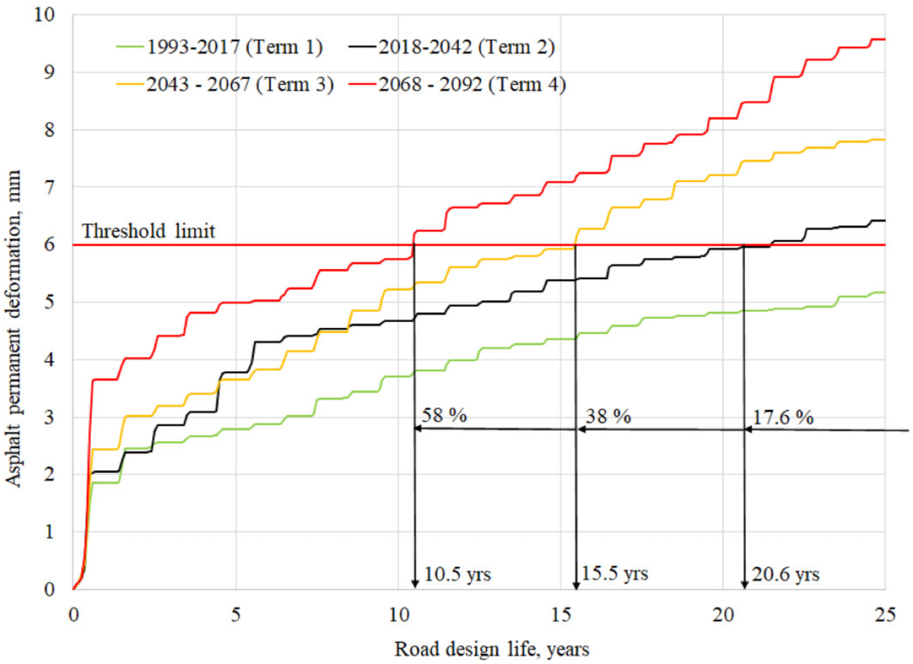
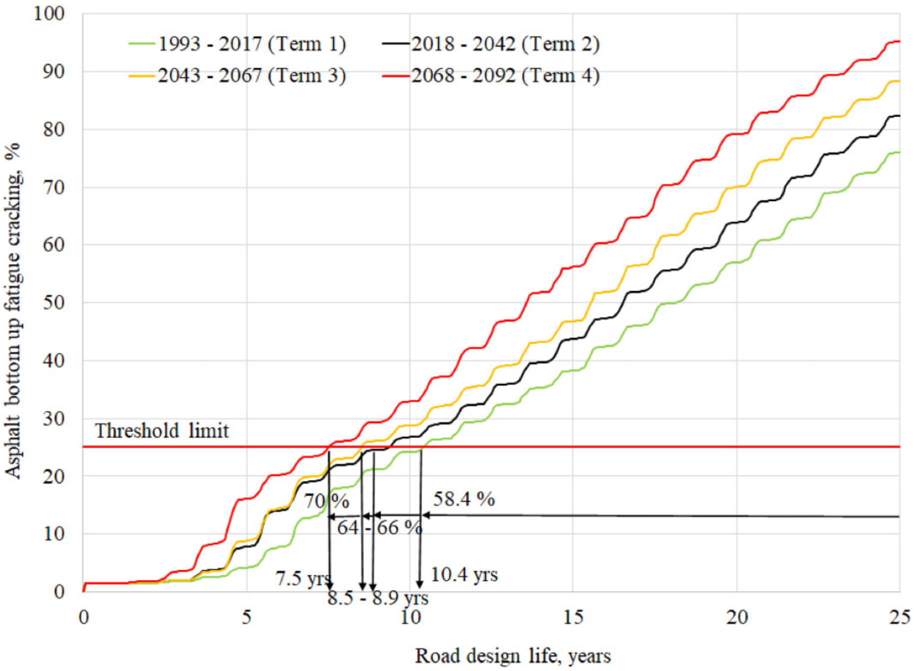


Fig. 9. Temperature impact on asphalt bottom-up fatigue cracking—Windsor.



are illustrated in Figs. 11 and 12, respectively. Predicted IRI increases with time, and it shortens the road design life (25 years) for the city of Windsor as shown in Fig. 11 by about 26%, 29%, 30%, and 36% of the normal cycle of design life for terms 1, 2, 3, and 4, respectively.

Further analysis of Fig. 12 indicated the impact of projected climate change on the IRI in the city of Winnipeg. It shows reduction of the road design life of 26%, 29%, 30%, and 34% of the normal cycle of design life for terms 1, 2, 3, and 4, respectively.

Precipitation impact

The following are the typical results of the impact of precipitation on total permanent deformation for the cities of Windsor and Winnipeg.

Fig. 10. Temperature impact on Asphalt bottom-up fatigue cracking—Winnipeg.

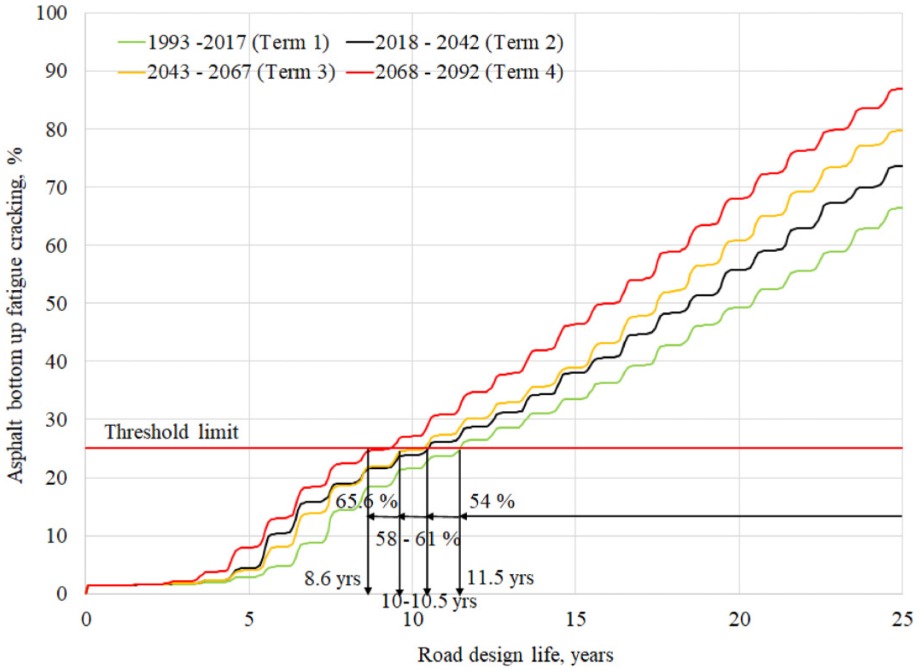
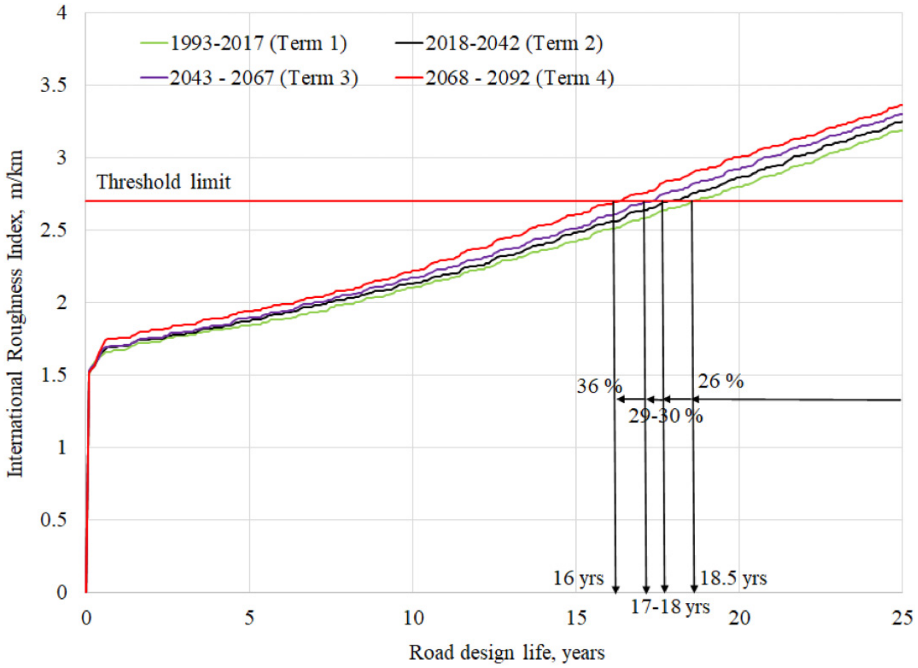


Fig. 11. Temperature impact on International Roughness Index (IRI)—Windsor.



Total permanent deformation

Runs were performed to investigate the sensitivity of the PMED on the impact of the total precipitation (rain and snow) on moisture state of the soil conditions (optimum) in terms of resilient modulus and density of unbound materials, The total permanent deformation of the asphalt concrete, base, sub-base, and sub-grade materials was determined, as shown in Fig. 13.

The total permanent deformation curves indicated a good road design life (25 years) in case of term 1, but showed a reduction in the road design life by 18%, 38%, and 57% for terms 2, 3, and 4, respectively. Predicted total rutting performance agreed with the asphalt concrete rutting, indicating the impact of climate change on shortening the road design life.

Figure 14 illustrates the effect of increased precipitation on the total permanent deformation for the city of Winnipeg's

Fig. 12. Temperature impact on International Roughness Index—Winnipeg.

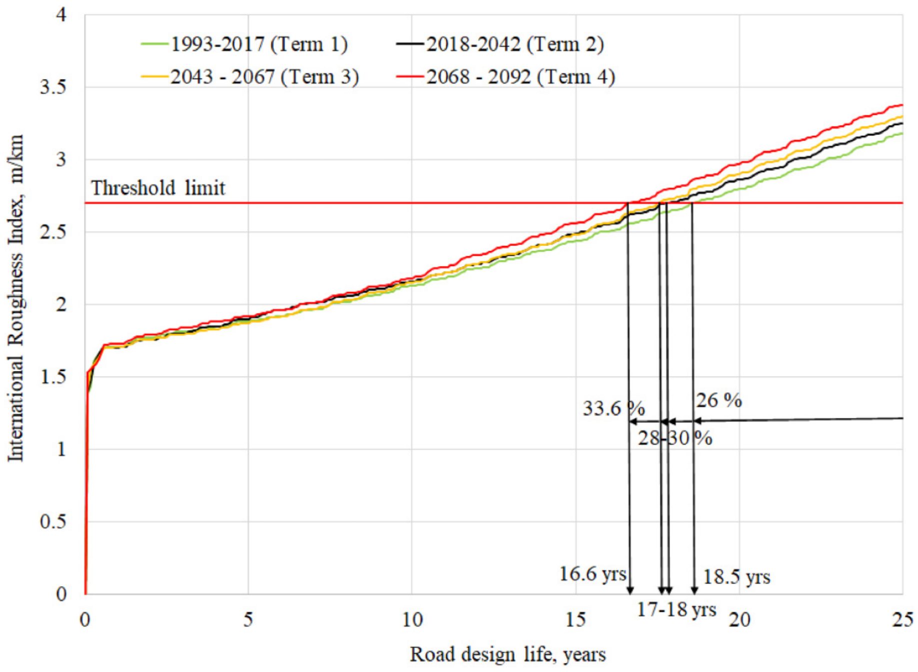
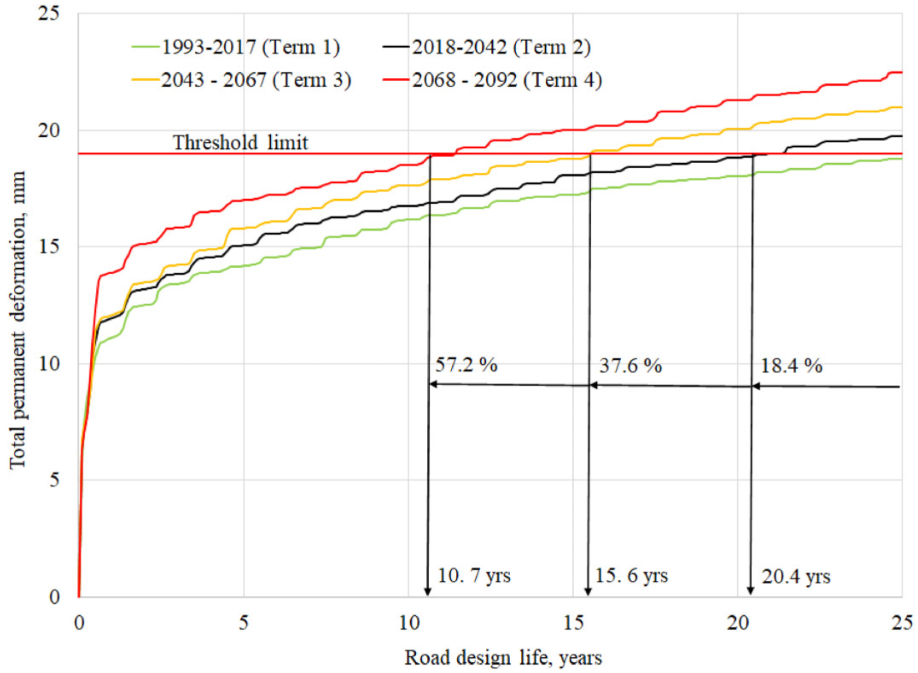


Fig. 13. Precipitation impact on total permanent deformation—Windsor.



25-year road design life. It was found that rutting was reduced by 34% in case of historical term 1, and in the same manner as city of Windsor, the impact of precipitation on total permanent deformation shortened the road design life in the city of Winnipeg by 43%, 46%, and 55% for terms 2, 3, and 4, respectively.

Further analysis of the seasonal impact on road service life illustrated in Figs. 7–14 of different performance distresses in the cities of Windsor and Winnipeg are summarized in Tables 9–12. The maximum loss of road service life among the studied cities using total permanent deformation, asphalt permanent deformation, asphalt bottom-up fatigue cracking, and IRI is about 57%, 66%, 70%, and 36%, respectively, observed in the term 4 of the city of Windsor across various performance distresses.

Fig. 14. Precipitation impact on total permanent deformation—Winnipeg.

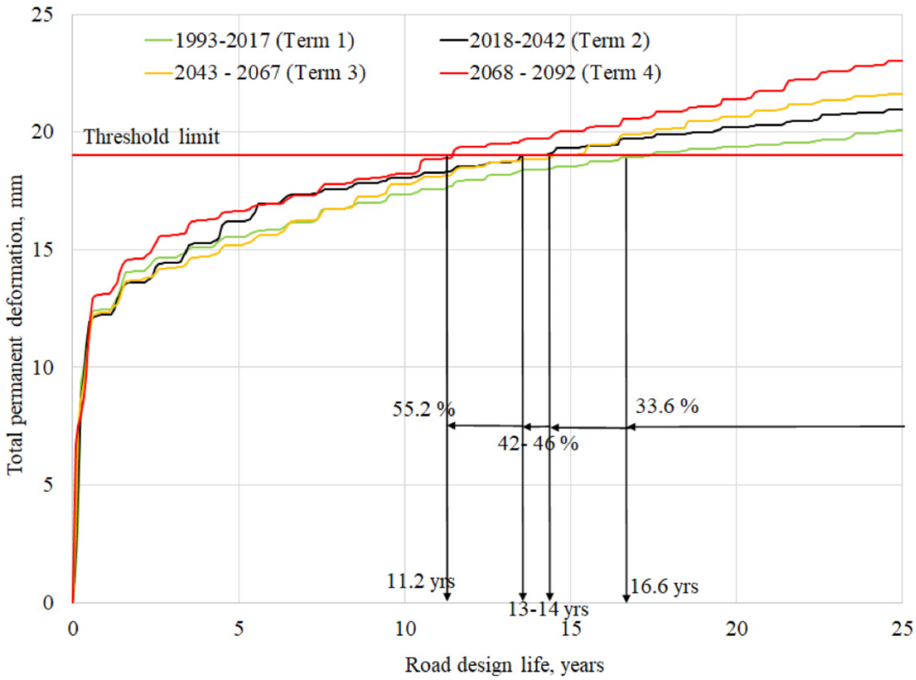


Table 9. Summary of precipitation impact on road service years and percentage of loss using total permanent deformation

Distress performance	Total permanent deformation				
City	Projected terms	1993–2017	2018–2042	2043–2067	2068–2092
Windsor	Service years	25	20.4	15.6	10.7
	Percentage of loss	0	18.4	37.6	57.2
Winnipeg	Service years	16.6	14.3	13.4	11.2
	Percentage of loss	33.6	42.8	46.4	55.2

Table 10. Summary of temperature impact on road service years and percentage of loss using asphalt permanent deformation.

Distress performance	Asphalt permanent deformation				
City	Projected terms	1993–2017	2018–2042	2043–2067	2068–2092
Windsor	Service years	25	20.6	12.5	8.6
	Percentage of loss	0	17.6	50	65.6
Winnipeg	Service years	25	20.6	15.5	10.5
	Percentage of loss	0	17.6	38	58

Table 11. Summary of temperature impact on road service years and percentage of loss using asphalt bottom-up cracking.

Distress performance	Asphalt bottom-up cracking				
City	Projected terms	1993–2017	2018–2042	2043–2067	2068–2092
Windsor	Service years	10.4	8.9	8.5	7.5
	Percentage of loss	58.4	64.4	66	70
Winnipeg	Service years	11.5	10.5	9.7	8.6
	Percentage of loss	54	58	61.2	65.6

Conclusions and recommendations

Conclusions

1. The accumulation of excessive deformation in the asphalt concrete layer during the low asphalt concrete stiffness state is associated with high temperature. Traffic-induced stresses transmitted to the backfill layers beneath the asphalt concrete are directly influenced by the state condition of asphalt concrete stiffness. High temperatures result in low asphalt concrete stiffness. Hence, unprece-

Table 12. Summary of seasonal impact on road service years and percentage of loss using International Roughness Index.

Distress performance	International Roughness Index				
City	Projected terms	1993–2017	2018–2042	2043–2067	2068–2092
Windsor	Service life	18.5	17.75	17	16
	Percentage of loss	26	29	32	36
Winnipeg	Service life	18.5	17.8	17.6	16.6
	Percentage of loss	26	28.8	29.6	33.6

dented higher stresses are transmitted through the asphalt concrete layer to unbound materials of the road structure combined with increased annual total precipitation.

2. The general trend of the seasonal impact showed that all performance distresses indicators increase with time. Asphalt permanent deformation and asphalt bottom-up fatigue cracking are the two key performance parameters that assist road engineers and practitioners in determining the end of service life and the need for rehabilitation or reconstruction. The asphalt permanent deformation and asphalt bottom-up fatigue cracking reduced the road design life by about 66% and 70% in term 4.
3. The total precipitation impact on total permanent deformation resulted in a shortened road design life by 18%, 38%, and 57% for short terms 1, 2, 3, and 4, respectively.
4. The PMED model is sensitive to different climatic loading parameters. Asphalt permanent deformation performance predictions for the projected warm (MAAT = 17) region are about 68% higher than the projected cold (MAAT = 12) of the same region. This resulted in shortening the span road design life to 66%.

Recommendation

This study recommends that global calibration of PMED is required but not sufficient to account for projected climatic loading files; instead, locally calibrated transfer function, using appropriate parameters, will enable the predicted distress to better match field observations.

Study limitations

The limitations of this study include that it is based on one generic section, which is assumed to be representative of field conditions, including material structural layers (thickness and properties), the traffic conditions were assumed to be the same for all cases and the projected climate scenario was selected for SSP5-8.5.

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Data availability

Data generated or analyzed during this study are available from the corresponding author upon reasonable request.

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The authors declare there are no competing interests.

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