The Impact of Heat Waves on Predicted Ontario Pavement Performance Using Pavement Mechanistic Empirical Design Software

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Abstract

The consequences of climate change have begun to manifest globally, with noticeable impacts in Canada. An increase in frequency and severity of extreme weather events, such as floods, wildfires, and heat waves, has been prominent in the recent Canadian landscape. Canadian infrastructure may be compromised under these extreme weather events, if not properly designed and constructed. Flexible pavements may be particularly sensitive to extreme heat waves due to the viscoelastic properties of the asphalt binder. Previous work has examined the impact of heat waves on pavements in Southern and Southeastern Ontario to identify the critical conditions predicted to cause the greatest increase in rutting. Pavement performance under various heat wave scenarios has been predicted using Pavement Mechanistic Empirical Design (PMED) software for a typical Ontario highway cross-section. This study seeks to expand on the previous work by also considering Northern Ontario conditions, thus better representing all of Ontario's binder grade zones. Furthermore, the analysis has been repeated with an increased asphalt binder grade to assess the potential for better rutting resilience. The study identified that heat wave return-period was of greater risk to pavement performance than heat wave intensity. Furthermore, it was identified that increasing the asphalt binder grade and increasing the asphalt binder lift thickness were potential methods for increasing rutting resiliency.

Introduction

Extreme weather events have become more prevalent in recent years, with accounts frequently emerging detailing the destruction caused by extreme temperatures, precipitation, hurricanes, and windstorms. Infrastructure is particularly vulnerable to these extreme weather events, as traditional design practices often do not account for the increased severity and frequency that have been experienced in recent years. It is becoming increasingly clear that all industries must adapt to both the gradual progression of climate change and the escalating occurrence of extreme weather events. Pavement is likely to be among the various infrastructure impacted by climate change, with many studies reporting poor pavement performance following floods, hurricanes, and heat waves. It is important that agencies are aware of the potential risks to their pavements and find tools to better identify and model risk mitigation and adaptation strategies.

Canadian Heat Waves

Several unprecedented heat waves have been experienced throughout Canada over recent years. In Western Canada, the 2021 heat wave reached temperatures between 16 and 20 degrees Celsius above the seasonal average[1]. Historically, Toronto, Ontario has been the city with the highest number of extreme heat events throughout Canada, averaging four per year between 1937 and 1998[2]. A recent climate change projection completed by Li et al. suggests that in Ontario, the Toronto-Windsor corridor will continue to see the most extreme temperatures while Northern Ontario will likely experience more long-lasting periods of high temperatures[3]. The results of these studies suggest that the nature of future heat waves will vary from region to region, and that adaptation strategies will need to be tailored to the region.

Predicted Pavement Performance under Canadian Climate Change

Several recent studies have examined the predicted impact of climate change on pavement performance worldwide and in Canada. Specifically, in Ontario, the impacts of climate change have been investigated using two climate models (CGCM2A2x and HadCM3B21), revealing that changes in temperature, precipitation, and future traffic growth may negatively affect pavement performance[4]. Similarly, Swarna et al. reported a predicted increase in rutting and bottom-up fatigue cracking, with an overall decrease in predicted International Roughness Index (IRI) under climate scenarios generated with Global Climate Models (GCMs).

A few Canadian studies have begun to examine the impact of specific climate change induced extreme weather events on pavement performance. Notably, Lu et al. investigated the impact of 36 flooding events in Ontario at varying return periods and severities using Pavement Mechanistic Empirical Design (PMED) software[5]. The study found that short-duration exposure to extreme precipitation did not result in significant damages, however, increased frequency in extreme events resulted in changes to IRI. Matini et al. investigated the impact of both heat waves and floods of varying return periods and severity in the United States, also using PMED software[6]. The study found an increase in heat wave induced rutting of up to 2.9 percent, but the case studies were limited to geographic areas with sandy subgrades. Both studies have used PMED to model predicted pavement performance following extreme weather events, Lu et al. using a GCM and Matini et al. using empirically manipulated temperature data. To date, no Canadian studies have explored the impact of extreme heat events on pavement performance.

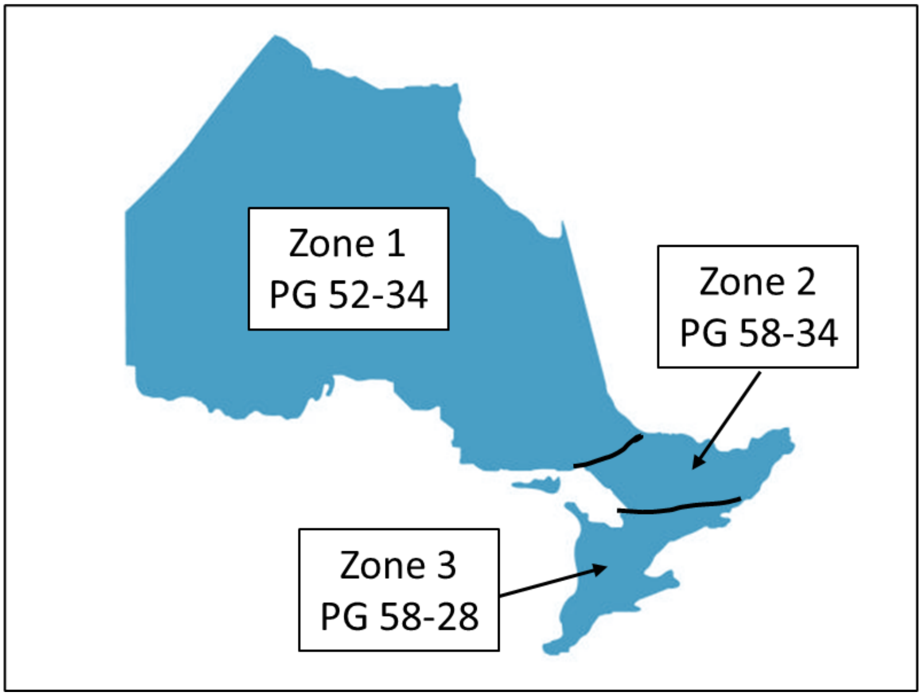
Pavement Mechanistic Empirical Design Software

A widely available tool to model pavement performance is AASHTOWare, a PMED software leveraging transfer functions to convert predicted stresses and strains to performance indicators. The software is closely linked with the United States Federal Highway Administration (FHWA) to support their national design standards and pull from federal databases of design inputs. The software converts hourly ambient temperatures into hourly pavement temperatures using the Enhanced Integrated Climate Model (EICM), which are then used as a factor in predicting pavement performance. Although there is discussion surrounding the accuracy of EICM in Northern Climates, some studies suggest that it is appropriate for use in Canada[7]. Other barriers to using AASHTOWare in Canada include availability of calibration factors, availability of local Level 3 data, and software input limitations. The Province of Ontario has addressed most barriers through documentation detailing calibration and standard values for input parameters. It should be noted that the most recent update to the validation report was in 2019 for previous versions of the software, which may be the source of some inaccuracy and inefficiencies. Completing studies in provinces outside of Ontario presents some challenges and raises questions as to the accuracy of the results.

Ontario Asphalt Binder Grade Zones

The Ministry of Transportation Ontario (MTO) implements a zoning system to identify the base asphalt binder grade across the province. As one of the largest provinces in Canada, Ontario spans two identifiable climatic regions[8] and three respective asphalt binder grade Zones. Presently, MTO Zone 1 is located within the Northeast Forest climatic region and represents the majority of Northern Ontario. MTO Zone 3 is located in the Great Lake climatic region and represents Southwestern Ontario, including the Greater Toronto Area (GTA) and extending as far east as Kingston. MTO Zone 2 spans both climatic regions and is considered a transition zone, although it predominantly lies in the Great Lake climatic region. The base asphalt binder grades for Zones 1, 2, and 3, are PG 52-34, PG 58-34, and PG 58-28, respectively. The approximate locations of the Zone delineations is represented in Figure 1.

Figure 1. Ontario asphalt binder grade zones



Objectives

The primary objectives of this study are as follows:

a) Predict the impact of heat waves of increasing severity on typical Ontario pavements in the three binder grade zones.
b) Compare the predicted pavement performance under heat wave conditions across Ontario to better understand future needs for adaptation strategies.
c) Examine the efficacy of PMED software to simulate extreme weather conditions in Ontario.

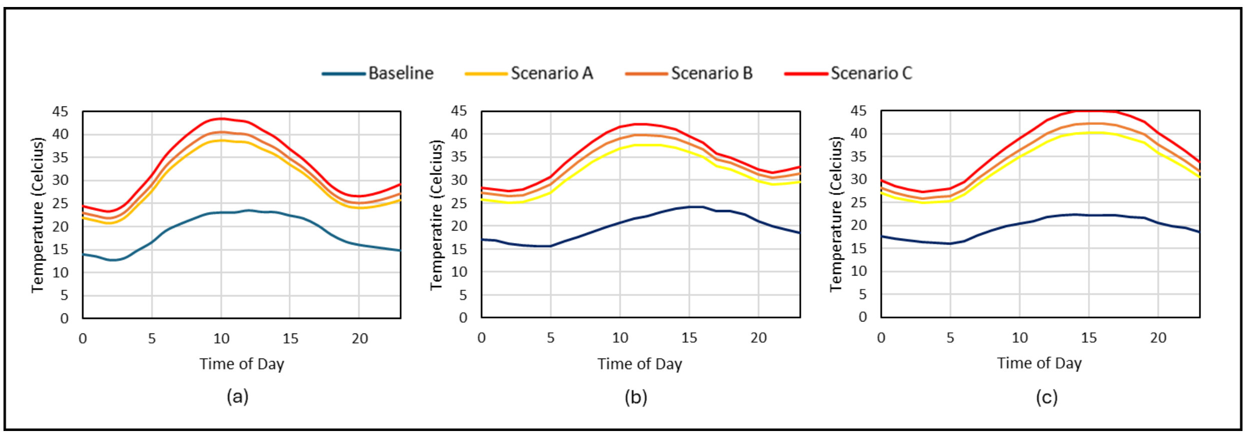
Methodology

The methodology for the work was completed in 4 primary phases, as described in the following sections.

Phase 1: Creating Heat Wave Scenarios

Heat wave scenarios were created for Thunder Bay, Toronto, and Ottawa based on historical heat events having occurred in each City in 2024, 2011, and 2018, respectively. The heat waves and years were selected based on the most severe heat event in recent recorded history, independently for each City, noting that typical climate and weather patterns for each City widely varies. In each case, the hottest day of the historical heat event was compared to seasonal averages. The increase above average was used to fit an hourly model representing the temperature trends over the hottest day during each heat event. The models were then scaled to increase the maximum temperature by 5, 7, and 10 degrees Celsius, temperatures that were noted of importance in the previous study by Matini et al[6]. Scaling was done according to the actual degree increase above average, i.e. only the maximum daily temperature saw the total increase of 5, 7, or 10, meanwhile evening temperatures increased according to the trend line for that particular hour. The heat wave scenarios used in this study are provided for reference in Figure 2.

Figure 2. Heat Wave Scenarios for (a) Thunder Bay, (b) Ottawa and (c) Toronto



As previously discussed, studies have shown that climate change will likely cause an increase in daily temperatures in Ottawa and Toronto and an increase in heatwave duration in Thunder Bay. As such, this study seeks to simulate these patterns and understand their potential impact on pavement performance.

Phase 2: Building PMED Climate Inputs

Standard climate files were obtained from the Long-Term Pavement Performance database directly through the AASHTOWare interface. The climate files were directly manipulated to reflect the above indicated heat wave scenarios. The theoretical heat wave scenarios were placed starting on July 1st in each respective year, as historical heat waves typically occur around this time. Furthermore, previous studies have placed their simulated extreme weather events around the same time.

According to the Climate Atlas, presently, the duration of a typical heat wave is between three to four days in Southern Ontario and two to three days in Northern Ontario. However, as previously discussed, it is anticipated that heat waves in Northern Ontario are expected to increase in duration. The first heat wave in each scenario was placed 3 years after pavement construction, which was considered to mitigate some effects of early service life rutting (i.e. when the asphalt binder is at its lowest stiffness and more vulnerable).

The above information was used to inform the alternatives used in this study, which are summarized in Table 1. It should be noted that the study in Toronto and Ottawa focused on heat wave return period, while the study in Thunder Bay focused on heat wave duration.

Table 1. Climate alternatives with varying return periods, heat wave scenario, and heat wave duration

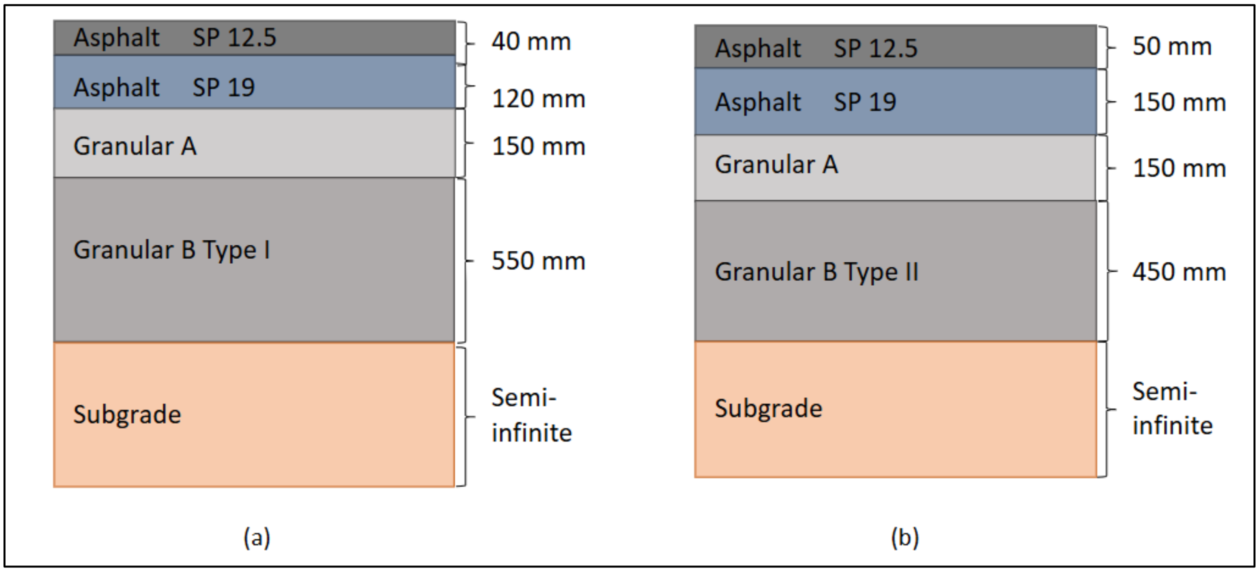
Alternative	Heat wave return period	Heat wave scenario	Heat wave duration (consecutive)	Location	Notes
1	NA	NA	5 days	TO, OT, TB	Baseline
2	7 years	A (5 degrees)	5 days	TO, OT	
3	7 years	B (7 degrees)	5 days	TO, OT	
4	7 years	C (10 degrees)	5 days	TO, OT	
5	5 years	A (5 degrees)	5 days	TO, OT	
6	5 years	B (7 degrees)	5 days	TO, OT	
7	5 years	C (10 degrees)	5 days	TO, OT	
8	3 years	A (5 degrees)	5 days	TO, OT	
9	3 years	B (7 degrees)	5 days	TO, OT	
10	3 years	C (10 degrees)	5 days	TO, OT	Worst case
11	5 years	A (5 degrees)	5 days	TB	
12	5 years	B (7 degrees)	5 days	TB	
13	5 years	C (10 degrees)	5 days	TB	
14	5 years	A (5 degrees)	10 days	TB	
15	5 years	B (7 degrees)	10 days	TB	
16	5 years	C (10 degrees)	10 days	TB	Worst case

Note: TO = Toronto, OT = Ottawa, TB = Thunder Bay.

Phase 3: Selecting a Pavement Structure

As previously discussed, Ontario is pre-divided into three asphalt binder grade zones. In addition to climatic variation between the zones, typical traffic experienced across the province varies heavily. One standard pavement structure was selected for use in Toronto and Ottawa, based on industry experience, and to provide easy comparisons between performance. As the Northern Ontario location was used to investigate the impact of heat wave duration, separate from the Toronto and Ottawa investigation, a different pavement structure was selected that was considered more appropriate for the region. A schematic of the pavement structures used in this study is provided in Figure 3.

Figure 3. Pavement Structures for (a) Thunder Bay, and (b) Ottawa and Toronto



Furthermore, it should be noted that the asphalt binder grades in this study were based on the respective MTO zoned and bumped according to traffic (Toronto = PG 58-28, Ottawa = PG 58-34, Thunder Bay = PG 52-34) and typical traffic data was retrieved from MTO iCorridor, as would be done in a typical design.

Phase 4: Pavement Mechanistic Empirical Design Analysis

AASHTOWare Pavement Mechanistic Empirical Design was the software used to complete this study. The province of Ontario provides guidelines for the use and calibration of AASHTOWare in provincial design projects, and as such, is the most popular choice locally. Recommended Level 3 inputs were used for the analysis based on the MTO guidelines. A design life of 20 years was selected for use in all three locations, which is considered standard in Ontario. Parameters predicted by AASHTOWare that were monitored through the study include rutting, International Roughness Index (IRI), and pavement surface temperatures.

Results and Discussion

A distinction has been made in the reporting and discussion of the results herein between the Toronto and Ottawa study, and the Thunder Bay study. The results of the heat wave return period study in Ottawa and Toronto are reported first, followed by the heat wave duration study in Thunder Bay.

<u>Toronto and Ottawa: Heat Wave Return Period</u>

Climate alternatives 1 through 10, as described in Table 1, were used in the analysis of heat wave return periods on predicted pavement performance in Ottawa and Toronto. Climate change modelling has predicted that heat wave intensity and frequency is likely to increase in Southern Ontario, as depicted in the hypothetical climate alternatives generated in this study. Using AASHTOWare, the predicted increase in rutting under the various climate alternatives is summarized in Table 2.

Table 2. Predicted rutting under varying heat wave intensities and return periods

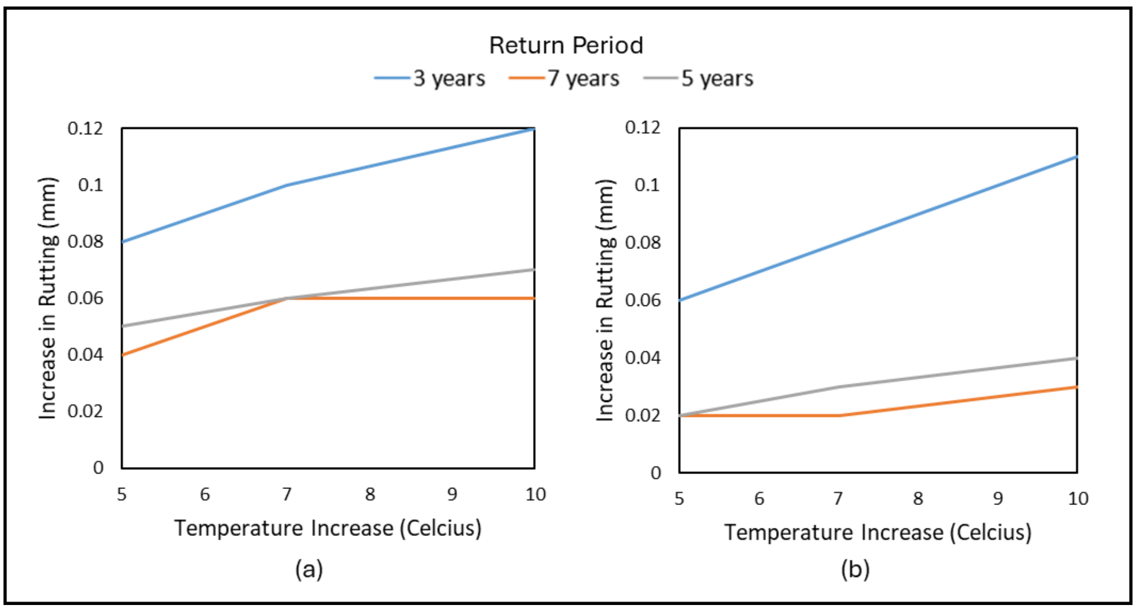
Alternative	TORONTO		OTTAWA	
	AC Rutting (mm)	% Change Over Baseline	AC Rutting (mm)	% Change Over Baseline
1	0.85	-	2.92	-
2	0.87	2.35	2.96	1.37
3	0.87	2.35	2.98	2.05
4	0.88	3.53	2.98	2.05
5	0.87	2.35	2.97	1.71
6	0.88	3.53	2.98	2.05
7	0.89	4.71	2.99	2.40
8	0.91	7.06	3.00	2.74
9	0.93	9.41	3.02	3.42
10	0.96	12.94	3.04	4.11

It was observed that predicted absolute rutting was greater in Ottawa, however the percent increase in rutting over the baseline was greater in Toronto. Although relatively close geographically, Toronto and Ottawa are subject to vastly different climate trends. Natural terrain features including the Great Lakes and the Ottawa Valley heavily influence the local climate, which may be responsible for higher average temperatures in Ottawa and the more severe heat waves in Toronto. In both locations, the climate alternatives with the most frequently reoccurring heat waves caused the greatest increase in predicted rutting, as expected. However, it should be noted that the actual measurable increases in rutting are relatively small. This may be a result of the AASHTOWare pavement temperature models reducing the acute heat wave events to overall seasonal averages, which studies have shown are of a smaller concern to overall pavement performance.

Although heat waves are expected to predominantly impact the predicted rutting, the predicted IRI was also monitored throughout the climate alternatives. As rutting is generally not considered to affect the IRI (despite being slightly factored into the AASHTOWare IRI models), any significant changes would be related to an increase in temperature cracking or distortions. However, the IRI was noted to vary less than 0.5% throughout all climate alternatives in Ottawa and Toronto, suggesting that IRI will not be impacted by an increase in heat wave severity or frequency under the onset of climate change. Similarly, it can be inferred that an increase in temperature cracking is not a likely result of heat waves.

For further examination on the relationship between the heat wave return period and the predicted impact of the heat wave on pavement performance, predicted increase in rutting has been plotted against the temperature increase as illustrated in Figure 4.

Figure 4. Increase in Predicted Rutting by Return Period for (a) Toronto and (b) Ottawa



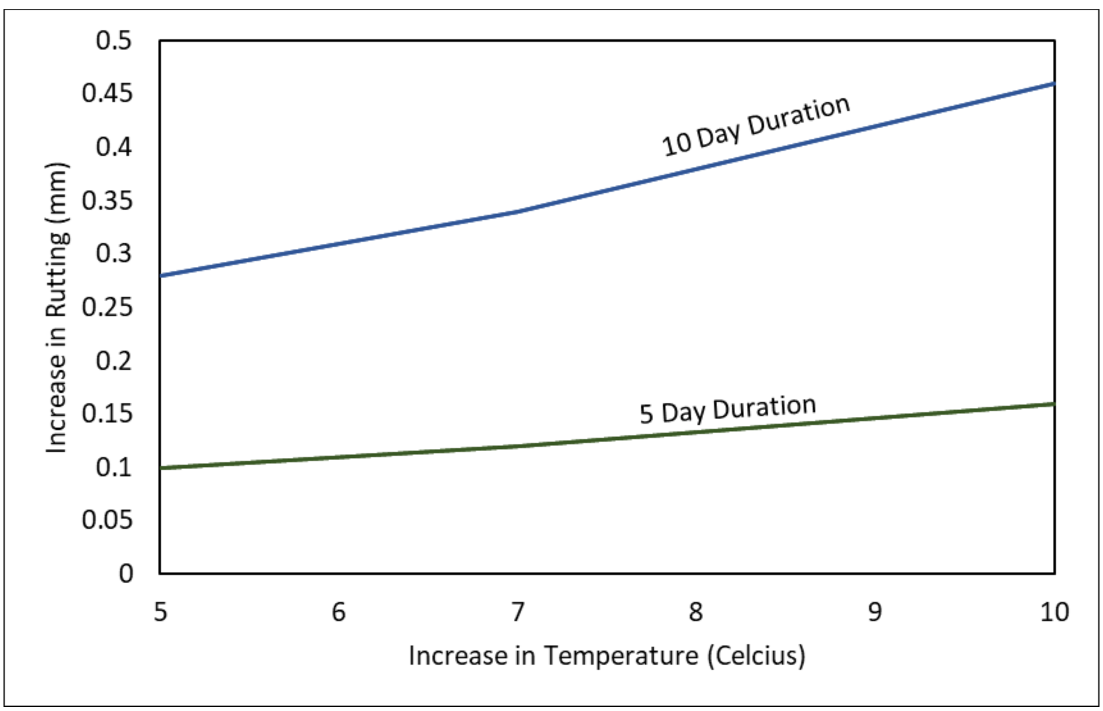
The relationship between rutting and temperature increase is strongly evident when separating the alternatives by heat wave return period. Overall, the increase in rutting is relatively linear, with stronger trends observed in the alternatives with the shortest return period. Further to note is that a one degree increase in maximum heat wave temperature has a more pronounced effect on rutting when the heat wave event reoccurs every three years. Contrastingly, a heat wave occurring at a seven year return period results in only marginal increases in rutting under the same temperature rise.

Based on the above, it can be gathered that rutting will continue to increase approximately linearly as heat wave temperatures increase. For example, in 2021 a British Columbia heat wave resulted in a 20-degree Celsius increase in temperatures above seasonal averages. In a situation where this type of heat event begins to reoccur routinely, there is the potential to increase rutting by up to 19% over the local baseline, if projecting the same temperature trends observed in Toronto and Ottawa to this level of increase.

Thunder Bay: Heat Wave Duration

Climate alternatives 11 through 16, with an additional baseline, have been used to assess the impact of heat wave duration on Northern Ontario pavements. The increase in rutting over the baseline scenario is plotted against the increase in heat wave temperatures in Figure 5.

Figure 5. Increase in Predicted Rutting by Heat Wave Duration in Thunder Bay



The results of the heat wave duration study immediately suggest that there is a much stronger correlation between these factors than the return periods. While increasing the maximum heat wave temperature did have a noticeable impact on the increase in rutting, doubling the heat wave duration nearly tripled the increase in rutting over the baseline. Implications of these results would suggest that Northern Ontario may be more vulnerable to climate change induced heat waves than Southern Ontario, given that the nature of their heat waves are to be longer in duration, and not necessarily in greater frequency or intensity. Furthermore, it was observed that the increase in rutting trended upwards more notably in the 10 day alternatives than the 5 day alternatives. Therefore, every degree increase above seasonal average will have a relatively greater impact on rutting during a longer heat wave than a shorter one. While the durations were fixed at 5 days and 10 days for the purposes of this study, it is not unreasonable to expect real heat waves to exceed these lengths based on heat waves experienced in the most recent years. Rutting may become a more predominant issue in Northern Ontario than it has previously been as the onset of climate change begins to become more prominent.

Similarly to the results of the heat wave return period study, it was found that IRI was minimally impacted by the heat wave duration, with a very slight increase observed only in the worst-case scenario. Regardless, the Terminal IRI predicted in all Thunder Bay alternatives was within the acceptable threshold prescribed by the MTO. Although several of the rutting thresholds were also within acceptable tolerances, the greater percent increase is considered to be of note and relevant to possible future trends.

Increase in PGAC Grade

Previous studies have echoed the need for increased asphalt binder grades across the country to better adapt pavements to the future onset of climate change. To understand the potential impact of an increased binder grade on pavements under severe heat wave events, the worst-case scenario from Thunder Bay has been repeated with an increased binder grade. The results are summarized in Table 3.

Table 3. Effect of Increasing PG Grade on Predicted Rutting in Thunder Bay

Baseline Rutting (mm) PG 52-34	Alternative 16 Rutting (mm) PG 52-34	Alternative 16 with Increased PG Grade (mm) PG 58-34
4.86	5.32	4.20

Using the same asphalt binder grade, the heat wave scenarios included in Alternative 16 caused an approximately 10 percent increase in predicted rutting beyond the baseline scenario. However, when repeating the analysis with an increased binder grade, the rutting was reduced to below that predicted in the baseline scenario, even when including the most severe heat wave alternative. An increased asphalt binder grade may not only contribute to mitigating against extreme heat wave events, but may also be better suited to our current climate conditions, which have greatly changed since the original creation of the PG grading system and the Ontario binder grade zones.

It should also be noted that since AC rutting is difficult to isolate and measure in the field, MTO does not consider it to be a rejectable parameter. Instead, they would observe total pavement deformation, which has not been reported in this study due to the number of contributing variables beyond pavement temperature including: precipitation, ground water levels, and subgrade quality, among other.

Discussion

In Ontario, rutting is generally not a pavement distress that is predominant or a frequently occurring problem in most regions. However, under climate change scenarios of reoccurring severe heat waves, it is not unlikely that rutting will become a more prevalent issue. Previous studies have suggested that increasing the local asphalt binder grade by one level has the potential to significantly reduce the amount of heat wave induced rutting, which was successfully replicated in this study. While rutting is not necessarily a direct contributor to IRI, if left untreated, an increase in cracking, pot holes and general distortion may occur, ultimately increasing the IRI. From a safety perspective, increased rutting may cause ponding resulting in hydroplaning and may present a significant concern to road operators. In some cases, implementing an increased asphalt binder grade presents the challenge of requiring polumer modification, which may be a barrier to adoption in small municipalities with limited operating budgets. Ultimately, climate change adaptation measures will be important in the future, although more research may be needed to justify the upfront increase in capital costs.

While the results of the study suggest that there is some merit to using AASHTOWare to predict future heat wave impacts, there are some significant impediments to overcome prior to widespread use. AASHTOWare has been developed primarily with data obtained from the United States. There are often barriers to effectively using AASHTOWare in Canada, including the maximum permissible pavement thickness that the software will acknowledge, which is frequently exceeded in Northern Ontario where frost heave protection is of upmost importance. However, AASHTOWare demonstrates the ability to reflect slight changes in rutting following slight changes to the climate data. Developing additional calibration factors local to Canadian environments is paramount to effectively using the software and advancing future climate change adaptation initiatives.

Conclusions

Heat waves are an extreme weather event that have become more prevalent in recent years, greatly impacting the Canadian landscape. This study has identified that heat waves may influence the performance of Ontario pavements, causing an increase in rutting, a pavement distress unfrequently experienced in the province today outside of major urban areas. By examining three independent locations in each of Ontario's binder grade zones, the following has been concluded:

- All locations were predicted to have an increase in rutting following the simulated heat waves, including variations in intensity, return period, and duration.
- When comparing heat wave intensity and heat wave return period, heat wave return period was found to be a more important factor in pavement performance.
- Correlation was stronger between increased rutting and heat wave duration than the correlation between increased rutting and heat wave return period, suggesting that the long heat waves anticipated in Northern Ontario may be of particular concern.
- IRI was not found to be affected by any of the heat wave alternatives at any of the locations, apart for small increases of 0.5 percent or less in the worst case scenarios, exclusively.
- In Thunder Bay, the worst case heat wave was predicted to increase rutting by approximately 10 percent. When implementing an increase in binder grade at this location, the rutting under the same heat wave alternative was brought to below the baseline levels.

Study Limitations

Limitations:

- This study depended exclusively on the predictions made within AASHTOWare Pavement ME software and the accuracy is limited to the capabilities of the software.
- Heat wave scenarios used within this study were developed based on historical events and are not necessarily a prediction of future heat waves. The study should be repeated with heat waves generated using a global climate change model.
- The Ontario calibration factors for AASHTOWare may have varying accuracy geographically across the province which may result in results of varying reliability.
- AASHTOWare displayed low sensitivity to some of the parameters included in the simulation.

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