Climate Change Implications for Flexible Pavement Design and Performance in Southern Canada

Brian N. Mills[1]; Susan L. Tighe, Ph.D., P.E.[2]; Jean Andrey, Ph.D.[3]; James T. Smith[4]; and Ken Huen[5]

Abstract: Two types of analysis were conducted to examine the impacts of midcentury scenarios of anthropogenic climate change on flexible pavement infrastructure in southern Canada. An analysis of deterioration-relevant climate indicators at 17 southern Canadian sites revealed that over the next 50 years low temperature cracking will become less problematic, structures will freeze later and thaw earlier with correspondingly shorter freeze season lengths, and higher extreme in-service pavement temperatures will raise the potential for rutting. Pavement performance simulations conducted using the mechanistic-empirical pavement design guide and data from the Canadian long term pavement performance program for six of these sites also suggest that rutting issues will be exacerbated by climate change and that maintenance, rehabilitation, or reconstruction will be required earlier in the design life. While the simulated effect of climate change was found to be modest, both in absolute terms and relative to variability in pavement structure and baseline traffic loads, pavement engineers would benefit by incorporating longer time series of weather and climate in their designs. Although the analysis was conducted for southern Canada, many of the findings and impacts may be similar for the northern United States.

DOI: 10.1061/(ASCE)0733-947X(2009)135:10(773)

CE Database subject headings: Canada; Climatic changes; Pavement design; Asphalt pavements; Pavement management; Flexible pavements.

Introduction

The Canadian road system is a valuable resource, both in absolute terms and relative to other transportation modes. Richardson (1996) estimated that the asset value of the system was about $100 billion while more recent figures indicate a replacement value of $46 billion for road infrastructure in Ontario alone (Ontario Ministry of Transportation 2007). Canadian economic and social activities are highly dependent on this infrastructure. In 2002, trucks carried 63% of the $531 billion worth of goods traded with the United States while automobiles accounted for almost 92% of the 188 million domestic trips taken in Canada (Transport Canada 2003). The mobility and economic prosperity enabled through the road system is underwritten by the direct capital and maintenance expenditures alluded to previously, but also substantive externalized costs such as one-sixth of Canadian greenhouse gas emissions that contribute to global anthropogenic climate change (Environment Canada 2007a)—the issue of concern in this paper.

While much effort has been devoted to understanding the contribution of road transportation to emissions of greenhouse gases, relatively little research has been completed to understand the implications of a changing climate for the design, management, and operation of road infrastructure (Andrey et al. 2004). The Intergovernmental Panel on Climate Change (IPCC), the international authority regarding the science of climate change, recently strengthened its contention that humans have had, and will continue to have, an increasing influence on the global climate system as measured by changes in temperature, precipitation, and other elements (Intergovernmental Panel on Climate Change 2007). Best estimates of global average annual temperature increase over the next century range from 1.8–4.0°C (Intergovernmental Panel on Climate Change 2007). These values correspond to a warming of 2.0–5.0°C in the annual temperature and a 5–30% increase in annual precipitation in southern Canada (Christensen et al. 2007). Even with drastic immediate reductions in greenhouse gas emissions (i.e., sufficient to stabilize atmospheric concentration levels observed in the year 2000), the Intergovernmental Panel on Climate Change (2007) expects global temperatures to warm by 0.6°C over the next century. The world is already very likely committed to a significant amount of warming, and there is a pressing need to understand what the implications of such changes are for roads and other aspects of transportation.

In response to this need the authors developed a project to examine the impacts of climate change on flexible pavement infrastructure in southern Canada (Mills et al. 2007). This paper presents a synthesis of the work that was completed. A review of pavement design and management practices and engineering

---

[1] Researcher, Adaptation and Impacts Research Div., Atmospheric Science and Technology Directorate, Environment Canada c/o Faculty of Environment, Univ. of Waterloo, Waterloo, ON N2L 3G1, Canada (corresponding author). E-mail: brian.mills@ec.gc.ca

[2] Canada Research Chair, Pavement and Infrastructure Management, Dept. of Civil and Environmental Engineering, Univ. of Waterloo, Waterloo, ON N2L 3G1, Canada. E-mail: sltighe@uwaterloo.ca

[3] Professor, Dept. of Geography and Environmental Management, Univ. of Waterloo, Waterloo, ON N2L 3G1, Canada. E-mail: jandrey@envmail.uwaterloo.ca

[4] Research Project Assistant and Ph.D. Candidate, Dept. of Civil and Environmental Engineering, Univ. of Waterloo, Waterloo, ON N2L 3G1, Canada.

[5] Former Research Engineer, Dept. of Civil and Environmental Engineering, Univ. of Waterloo, Waterloo, ON N2L 3G1, Canada.

Note. This manuscript was submitted on December 7, 2007; approved on May 27, 2009; published online on September 15, 2009. Discussion period open until March 1, 2010; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Transportation Engineering***, Vol. 135, No. 10, October 1, 2009. ©ASCE, ISSN 0733-947X/2009/10-773–782/$25.00.

models and approaches used to monitor, assess, and predict flexible pavement performance revealed that climate—and thus potentially climate change—is an important consideration in at least three deterioration processes: thermal cracking, frost heave and thaw weakening, and rutting (Mills et al. 2007). The objective of the study was to understand how scenarios of climate change affect the frequency, severity and duration of these conditions, and concomitant impacts on pavement performance. Two scenario-driven analyses were developed to investigate these generalized impacts in greater detail. The first involved examining a sample of deterioration-relevant climate indicators that are routinely applied or referenced in the management of pavement infrastructure. The second analysis employed the Mechanistic Empirical Pavement Design Guide (MEPDG) to simulate pavement deterioration and performance over time for a selection of sites. Results for baseline and anticipated future climate conditions were compared in both applications. The methods, data, and results from each analysis are discussed in turn following a general discussion of climate change scenarios.

Climate Change Scenarios

Climate change scenarios were derived from experiments using coupled atmosphere-ocean general circulation models (AOGCMs). AOGCMs and regional dynamic climate models nested within AOGCMs are the most advanced tools presently available to quantitatively estimate the transient global climate response to scenarios of future greenhouse gases, sulfate aerosols, and other elements that affect climate forcing (Carter et al. 1999, Barrow et al. 2004). Results from over 20 models and several experiments (i.e., emission and forcing assumptions) were considered by the IPCC in their most recent analysis (Intergovernmental Panel on Climate Change 2007). After considering available resources, required levels of effort, and choices made in recent comparable climate impact assessments, two climate change scenarios were adopted: the A2x emission experiment from the Canadian Centre for Climate Modeling and Analysis Coupled Global Climate Model 2 (CGCM2A2x) and the B21 experiment run through the Hadley Climate Model 3 (HadCM3B21). The technical specifications and performance of the CGCM2 and HadCM3 climate models in comparison to other leading AOGCMs are well-documented (Flato et al. 2000; Flato and Boer 2001; Gordon et al. 2000; Program for Climate Model Diagnosis and Intercomparison 2007). Emission assumptions for the A2x and B21 experiments, constructed from a range of future population growth and economic development patterns, are detailed in a special IPCC report on emission scenarios (Intergovernmental Panel on Climate Change 2000).

Surface temperature (minimum, maximum, and mean) and precipitation (total) data for each model and experiment were obtained through the Canadian Climate Scenarios Network (Environment Canada 2007b). Monthly data were available for baseline (1961–1990) and three future 30-year temporal windows centered on the 2020s, 2050s, and 2080s. Given that the average design life of pavement infrastructure is about 20–30 years, only the 2050s scenarios were examined in the current study. The scenario data consisted of output for climate model grid cells, each of which spans 2.5 (HadCM3) to 3.75 (CGCM2) degrees latitude and 3.75 (both models) degrees longitude (i.e., over 100,000 km^2). Scatterplots of potential changes in annual and seasonal mean surface temperature and precipitation were prepared to evaluate the magnitude of the CGCM2A2x and HadCM3B21 experiment results relative to other AOGCM scenarios for the study sites. A sample scatterplot for the Winnipeg, Manitoba site is presented in Fig. 1. In general, the CGCM2A2x and HadCM3B21 temperature and precipitation scenarios are average and conservative, respectively, when compared to other AOGCMs and experiments for southern Canada.

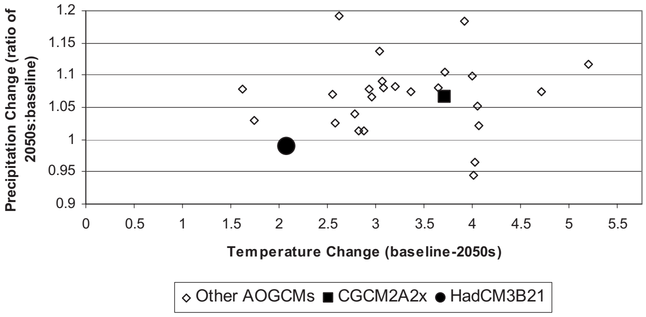

Fig. 1. Scatterplot of potential changes in mean annual temperature and precipitation from multiple AOGCM experiments for the Winnipeg, Manitoba analysis site

Analysis of Deterioration-Relevant Climate Indicators

Two sets of deterioration-relevant climate indicators or measures were identified for analysis based on the literature review (Mills et al. 2007): (1) performance grade asphalt cement (PGAC) high and low temperature threshold criteria and (2) freezing indices (FI) and thawing indices (TI). A suitable PGAC is intended to minimize thermal cracking at cold temperatures while simultaneously limiting traffic-induced rutting at hot temperatures. A reliability factor, most often 98% over the design life of the pavement structure, is associated with each PGAC and is determined as part of the calculations for each design. Grades are assigned in 6°C increments for both minimum and maximum pavement temperatures. For example, a PG 52-22 asphalt cement meets a minimum daily surface pavement temperature requirement of −22°C, and an average 7-day maximum temperature of 52°C, with 98% reliability over its design life. The minimum PG threshold refers to surface pavement temperatures while the maximum PG threshold refers to a temperature within the pavement, normally about 20 mm from the surface of the hot mix asphalt paving lift (Ontario Hot Mix Producers Association 1999). Empirical formulas developed through the Superpave and long term pavement performance (LTPP) programs were used to estimate pavement temperatures from air temperature data and determine appropriate PGAC ratings (Federal Highway Administration 2002) (see notaion at end of paper for variable definitions).

For maximum pavement temperature,

$$T_{p\,\max} = 54.325432 + 0.78T_{\text{air}\,\max} - 0.0025\text{Lat}^2 - 15.14\log_{10}(H+25) + z(9 + 0.61\sigma^2_{T\text{air}\,\max})^{0.5} \quad (1)$$

For minimum pavement temperature,

$$T_{p\,\min} = -1.56 + 0.72T_{\text{air}\,\min} - 0.004\text{Lat}^2 + 6.26\log_{10}(H+25) - z(4.4 + 0.52\sigma^2_{T\text{air}\,\min})^{0.5} \quad (2)$$

FI and TI are used in practice to establish winter weight premiums (WWPs) and spring load restrictions (SLRs) and to empirically model the depth of frost within the pavement structure, a

Table 1. Characteristics of Study Site Locations and PG Analysis Results

City[a]	Latitude/longitude	Mean annual temperature (°C)	Mean total precipitation (mm)	Superpave-based performance grade (PG) estimates[c]		
				Baseline	CGCM2A2x	HadCM3B21
Vancouver (1108447)[b]	49.2/123.1	10.1	1199.0	52-16	52-16	52-16
Kelowna (1123970)	49.9/119.4	7.7	380.5	58-28	58-28	64-28
Calgary (3031093)	51.0/114.0	4.1	412.6	52-40	58-34	58-40
Edmonton (3012205)[b]	53.5/113.5	2.4	482.7	52-46	58-40	58-46
Regina (4016560)	50.5/104.6	2.8	388.1	58-40	58-40	58-40
Winnipeg (5023222)[b]	50.0/97.2	2.6	513.7	58-40	58-40	58-40
Thunder Bay (6048261)	48.4/89.3	2.5	711.6	58-40	58-34	58-40
North Bay (6085700)	46.4/78.4	3.8	1007.7	52-34	58-34	58-34
Muskoka (6115525)	44.9/79.3	4.9	1098.6	58-34	58-34	58-34
Windsor (6139525)	42.3/82.9	9.4	918.3	58-22	58-22	64-22
Toronto (6158733)[b]	43.7/79.6	7.5	792.7	58-28	58-22	58-28
Ottawa (6106000)	45.3/75.7	6.0	943.5	58-34	58-28	58-34
Montreal (7025250)	45.5/73.6	6.2	978.9	58-34	58-28	58-34
Quebec (7016294)[b]	46.8/71.2	4.0	1207.7	58-34	58-34	58-34
Fredericton (8101500)	46.0/66.7	5.3	1143.3	58-34	58-28	58-34
Halifax (8202250)	44.6/63.6	6.3	1452.2	52-28	58-22	58-28
St. John's (8403506)[b]	47.6/52.7	4.7	1513.7	52-22	52-22	52-22

[a] Environment Canada Observing Station reference in parentheses.

[b] Site also used in MEPDG analysis.

[c] Numbers (e.g., 52, −16) refer to maximum and minimum pavement temperature thresholds (°C).

key determinant of its strength or structural adequacy. An FI threshold of 156 degree-days for WWPs was assumed in the study based on research performed by Minnesota DOT (2004). FI calculations commence each season (October 1–May 31) following the first day that mean daily temperature falls below 0°C. Degrees below (above) zero are added (subtracted) each day (for example, if the day 1 and day 2 temperatures are −8°C and +4°C, the cumulative $FI=8-4=4$ degree days) and accumulated until the threshold is reached and sustained for seven days, a surrogate for frost penetration to a sufficient depth (~40 cm) to increase pavement strength and justify extra loads on roads subject to SLRs. TI calculations were based on a modified Minnesota DOT approach as applied in recent work by Leong et al. (2005) and adjusted slightly by the authors. Once a site reached the critical FI, a daily TI (degree day count) was calculated for those days when the mean daily air temperature exceeded a reference value (−2°C). This value approximately corresponds to a temperature of 0°C at the base of the asphalt layer (i.e., to account for pavement response to radiation even though air temperatures are below 0°C). SLRs are assumed to be required in order to mitigate pavement damage when the cumulative daily TI reaches and sustains a critical value (13 degree days). To ensure that the thaw is prolonged sufficiently to affect the structure, additional criteria—attainment of at least 30 degree-days within seven days and an average TI of 21.5 degree-days—were applied to establish the recommended SLR date. For each year, the number of days between the achievement of a critical FI and realization of critical TI is calculated to determine a freeze season length.

Low and high PGAC thresholds and the timing of recommended WWP and SLR assignments were calculated using daily temperature and climate change scenario data for 17 sites across Canada (Table 1). The primary criteria for selection were location (i.e., to capture a range of climatic regions in southern Canada), availability of complete daily records of temperature and precipitation, and proximity to test sections in the LTPP program (relevant for the MEPDG analysis).

The spatial resolution of AOGCM output is very coarse such that daily or monthly time series of variables are generally not suitable for direct input into climate impact analyses. Instead, the output is normally downscaled to match the scale at which the impact exposure unit is modeled (e.g., a point on a road network, hydrologic basin, city, etc.). Barrow et al. (2004) described several downscaling techniques ranging in sophistication from simply adjusting historic time series by an average change factor derived from output for a particular AOGCM cell (e.g., increase mean January temperature by 4°C or precipitation by 15%) to developing a high resolution dynamic regional climate model nested within a coarser AOGCM (e.g., Goyette et al. 2000). Statistical weather generators (e.g., Semenov et al. 1998; Wilks and Wilby 1999; Wilby et al. 2002) fall between these extremes, both in terms of sophistication and ease-of-use, and were used in the analysis of deterioration-relevant climate indicators. LARS-WG, a stochastic weather generator developed and described in detail by Semenov et al. (1998), was used to produce three random, synthetic, 50-year daily time series for the baseline and each climate change scenario. LARS-WG was first parameterized for each site using 1951–2000 daily temperature and precipitation data obtained from Environment Canada. LARS-WG preserves the basic statistics of the original data in simulating a synthetic series; thus it allows the user to examine a degree of random variability in the baseline. LARS-WG allows the user to insert monthly factors (i.e., changes in mean and standard deviations of temperature, mean precipitation) that are applied to the baseline parameters of a particular site and thus incorporated into the simulation of future daily time series. As with the baseline, three separate 50-year simulations of future daily data were completed for each site and scenario (CGCM2A2x, HadCM3B21). These data were then used to generate time series and calculate basic summary statistics for each of the deterioration-relevant climate indicators permitting comparison between baseline and changed climate states.

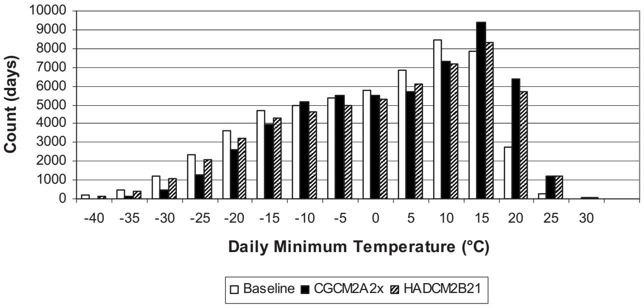

Fig. 2. Daily minimum air temperature statistics for Winnipeg site under baseline and future scenarios. (x-axis label refers to upper range limit, i.e., 0 range includes values >-5 and $\leqslant 0$)

PG Analysis Results

Daily minimum and 7-day mean maximum temperatures are expected to increase with climate change at all of the sites examined. In general, the CGCM2A2x scenarios yield the greater changes in both minimum and 7-day mean maximum temperature variables. For example, Fig. 2 shows the distribution of all daily minimum temperatures for the Winnipeg site under simulated baseline and future climate conditions. From this daily data, time series of the minimum temperature and the highest 7-day mean maximum temperature observed in each year were extracted and applied to the Superpave pavement temperature formulas to determine PG ratings. Results are summarized in Table 1. Baseline low temperature thresholds determined using the Superpave algorithm ranged from −16°C (Vancouver) to −46°C (Edmonton). Relative to the baseline, no change in PG rating occurred at any of the sites under the HadCM3B21 scenario while seven of 17 sites warmed up by one category under the CGCM2A2x scenario.

Baseline high temperature thresholds determined using the Superpave algorithm were either 52°C (Vancouver, Calgary, Edmonton, North Bay, Halifax, St. John's) or 58°C (Kelowna, Regina, Winnipeg, Thunder Bay, Windsor, Muskoka, Toronto, Ottawa, Montreal, Fredericton) for surface mixes. The upper limit of this range expanded to 64°C (Kelowna, Windsor) after results from the climate change scenarios were considered. PG ratings for six of 17 sites increased by one grade under the HadCM3B21 scenario relative to the baseline; ratings for four of these sites also increased by one grade under the CGCM2A2x scenario.

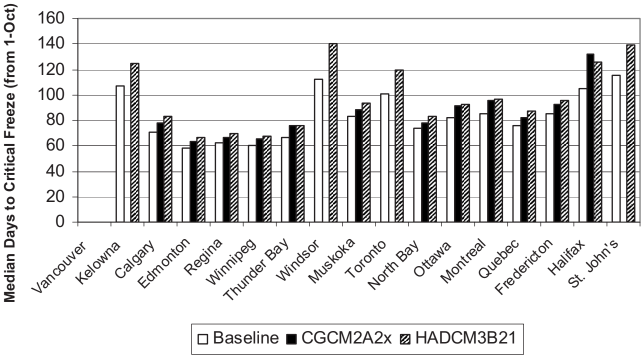

Fig. 3. Median number of days required to reach the critical freeze index for all sites under baseline and future climate scenarios

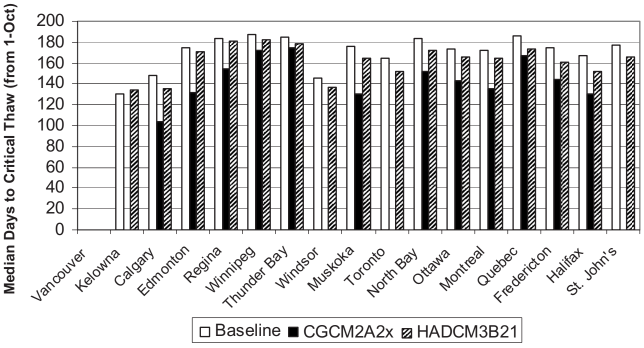

Fig. 4. Median number of days required to reach the critical thaw index for all sites under baseline and future climate scenarios

Freeze and Thaw Analysis Results

The median number of days to reach critical FI and TI thresholds, counted from October 1, are plotted for all sites in Figs. 3 and 4. With exception of Vancouver, where freeze thresholds were never satisfied in any of the baseline or future scenarios, the baseline median duration until freeze ranged from 58 days (Edmonton) to 116 days (St. John's). The corresponding baseline median number of days until thaw ranged from 131 (Kelowna) to 187 (Winnipeg).

Under the climate change scenarios studied, the number of days required to achieve critical FI and TI substantially increased and decreased, respectively. Assuming that CGCM2A2x conditions prevail, Kelowna, Windsor, Toronto, and St. John's join Vancouver in the subset of sites where over 50% of all seasons fail to reach critical FI (and therefore TI); elsewhere the median duration before reaching critical FI increases from 4 days (North Bay) to 27 days (Halifax) while critical TI is achieved 10 days (Thunder Bay) to 31 days (Muskoka) earlier. Critical FI is reached under the HadCM3B21 scenario in at least 50% of seasons at all sites (except Vancouver). Under this scenario, median values for most sites increase by about one to two weeks relative to the baseline, except for Kelowna, Toronto, Windsor, Halifax, and St. John's, where the median increased by up to 28 days. Critical TI is reached earlier in the season under the HadCM3B21 scenario at all sites except Kelowna, with median values ranging from 2 (Regina) to 14.5 (Halifax) days less than the baseline. Median values increased at Kelowna by 3 days.

Combining the FI and TI results allows examination of changes in the duration of the freeze season. Mean freeze season lengths for all of the study sites are presented in Fig. 5. Baseline

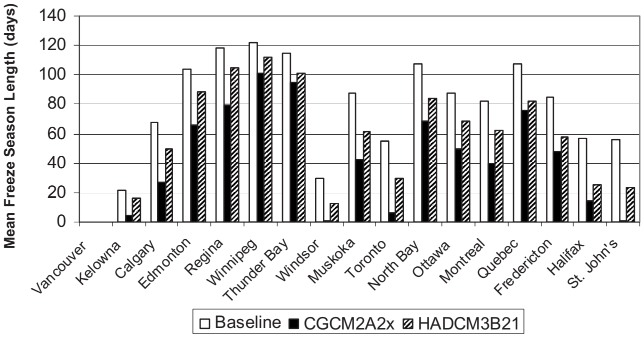

Fig. 5. Mean freeze season length for all sites under baseline and future climate scenarios

Table 2. MEPDG Analysis Site Characteristics

Province	British Columbia	Alberta	Manitoba	Ontario	Quebec	Newfoundland
LTPP Site Identification	82-1005	81-1804	83-6450	87-1806	89-1021	85-1808
Latitude/longitude (degree)	49.2/−123.1	53.5/−113.5	50.0/−97.2	43.7/−79.6	45.5/−73.6	47.6/−52.7
Elevation (m)	4.3	723.3	238.7	173.4	35.7	140.5
Climate station reference[a]	Vancouver	Edmonton	Winnipeg	Toronto	Quebec City	St. John's
Traffic						
Two-way AADTT[b]	1240	1420	498	2744	1912	256
Truck traffic in design lane (%)	100	100	100	100	100	100
Pavement Structure						
Layer 1: asphalt[c]	9.7	8.4	5.1	4.1	5.3	8.1
Layer 2: asphalt[c]	—	—	5.6	10.2	—	—
Layer 3: base[c]	23.9	32.8	11.4	18.0	7.9	11.4
Layer 4: subbase[c]	31.0	24.6	10.7	79.2	38.1	43.2
Pavement material						
Base[d]	CG	CG	CG	CG	CG	CG
Subbase[d]	RRG	RRG	RRG	A-4	CG	CG
Subgrade[d]	SM	SM	SM	ML	SP	GW

[a] See Table 1.

[b] Average annual daily truck traffic.

[c] Units in cm.

[d] CG-crushed gravel; RRG-river-run gravel; GW-gravel or sandy gravel, well-graded; ML-silts, sandy silts, or diatomaceous soils; SM-silty sand or silty gravelly sand; SP-sand or gravelly sand, poorly graded; additional material property information is provided in Mills et al. (2007, Appendix C).

mean values ranged from zero days in Vancouver to 122 days in Winnipeg. Vancouver, Kelowna, and Windsor were the only sites that experienced "freeze-free" seasons under baseline conditions. Baseline standard deviations were similar for most sites (generally 15–20 days) except for Vancouver (no freeze seasons therefore no variability) and Calgary and Edmonton where the influence of periodic winter chinook conditions likely introduces greater variability.

The mean duration of the freeze season dropped substantially under the climate change scenarios examined, from roughly 8% at Winnipeg (HadCM3B21) to 98% at the St. John's and Windsor sites (CGCM2A2x). The CGCM2A2x scenario consistently produced greater reductions in season length than the HadCM3B21 scenario. At least one in three seasons might not experience a freeze under the CGCM2A2x at the Vancouver, Kelowna, Toronto, Halifax and St. John's sites while rare (~1 in 100) occurrences might also happen in Calgary, Muskoka, and Ottawa. As expected, where the mean season length remained relatively long under the climate change scenarios (i.e., >50 days), the standard deviation increased relative to the baseline. At sites where the mean season length was less than 50 days, the standard deviation under climate change was reduced relative to the baseline.

MEPDG Pavement Performance Simulation

The MEPDG is a new tool developed by the U.S. National Cooperative Highway Research Program (NCHRP) and AASHTO to assist engineers in making decisions about asphalt and concrete pavement design and rehabilitations based on the application of state-of-practice mechanistic-empirical principles (National Cooperative Highway Research Program 2004). A significant improvement in MEPDG from past design guides is the development of the Enhanced Integrated Climate Model (EICM). The EICM is a one-dimensional coupled heat and moisture flow program that simulates changes in the behavior and characteristics of pavement and subgrade material in response to climatic conditions (Applied Research Associates, Inc. 2004, National Cooperative Highway Research Program 2004). This feature permits the calculation of transient distresses throughout the life of the pavement that are not tied to one particular test site or location. It must be noted that MEPDG is still being refined and improved and, although useful for exploratory studies such as the current investigation, it is not yet suitable as the primary decision input for pavement construction and rehabilitation (National Cooperative Highway Research Program 2006a,b). The main inputs required to run MEPDG include: general site and project information, analysis parameters, traffic assumptions, pavement structure, material properties, and climate.

A 20-year-design life, commencing during the month of August, was chosen for the analysis of pavement performance for all MEPDG applications. The key analysis parameters and associated design thresholds—international roughness index (IRI) (2.7 m/km), longitudinal cracking (378.8 m/km), transverse cracking (189.4 m/km), alligator cracking (25% surface coverage), AC rutting (6.4 mm), and total rutting (19.1 mm)—were assumed to be triggers for pavement repair, rehabilitation, and reconstruction decisions. A reliability factor was also assigned to each parameter to account for uncertainties in predicting future pavement deterioration. Results for the standard MEPDG output at 50% (typical for local or collector road design) and 90% (principal arterial or freeway design) reliability levels were simulated for this study.

Six test sites representing a range of pavement structures and materials that are found in Canada were selected from the LTPP program (LTPP 2007) for analysis. Baseline traffic, pavement structure, and pavement material characteristics, summarized in Table 2, were extracted from the LTPP database (LTPP 2007) while climate data for the nearest suitable observing station (see Table 1) were obtained from Environment Canada.

The climate data consisted of hourly records of air temperature, relative humidity, cloud amount, and wind speed, and 6-hourly or daily records of precipitation for the period 1990–2005. Since MEPDG requires hourly data, the 6-hourly and daily precipitation amounts were distributed evenly across respective

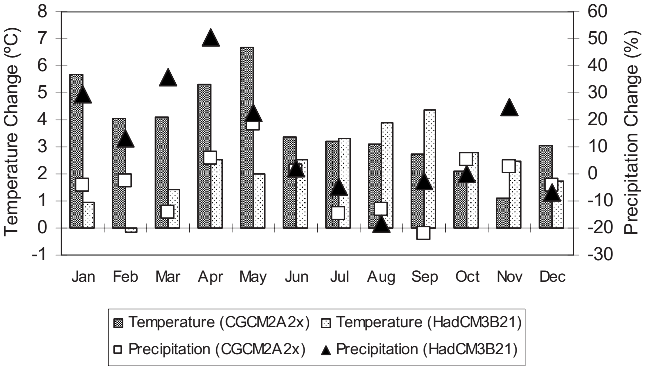

Fig. 6. CGCM2A2x and HadCM3B21 temperature and precipitation change scenarios (2050s relative to baseline) for the Manitoba site (Winnipeg)

periods. The percent sunshine variable required by MEPDG was derived from hourly cloud amount information. Potential midcentury (2040–2069) average changes in precipitation and temperature relative to the climate model baseline (1961–1990) were extracted for each site and used to adjust hourly values in the baseline time series. For illustration, the scenarios applied to the Manitoba (Winnipeg) site are graphed in Fig. 6. Significant variation is observed between months and between the CGCM2A2x and HadCM3B21 scenarios for both mean temperature (–0.2 °C to +6.7 °C) and precipitation (−18.2% to +50.1%) variables.

A series of simulations were then conducted to understand the separate and combined influence of climate and climate change, pavement structure, and traffic growth:

- Influence of climate and climate change alone. Monthly scenarios for the CGCM2A2x and HadCM3B21 climate modeling experiments that were used in the freeze-thaw and PG analyses discussed previously were applied to the MEPDG control data at six sites assuming no change in baseline traffic volume.
- Influence of structure type and baseline traffic volume. The various structural types and baseline traffic volumes represented in the 6 sites were evaluated using baseline and CGCM2A2x climate change scenarios for one location (Winnipeg, Man.).
- Combined influence of traffic growth and climate change. The first set of experiments were rerun for 6 sites assuming a 4% increase in annual average daily truck traffic (AADTT) and compared.

In total, 48 runs of MEPDG were completed in this analysis. Results are presented herein.

Results and Discussion

Influence of Climate and Climate Change Alone

Baseline and climate change scenario results for all performance parameters and all sites are summarized in Table 3. Baseline values (reported in either m/km or mm) and relative percent changes for each climate scenario represent conditions at the completion of the 20-year-design life (i.e., terminal results). Performance parameter values under baseline conditions varied considerably among the sites. For example, IRI values ranged from 1.55 m/km at the British Columbia (Vancouver) site to 2.54 m/km at the Man. site, reflecting differences in structure, traffic loads, and climate. The only distress variable that remained relatively constant across most sites was transverse cracking. Initiated by extreme cold temperatures, transverse cracking lengths quickly reached maximum values of about 400 m/km at all sites except the B.C. location which experiences the mildest climate among the sites analyzed. This result likely indicates an overprediction of this particular form of cracking and underlying issues with the distress algorithms and assumptions within the MEPDG. In prac-

Table 3. MEPDG Pavement Performance Results for All Sites (Climate Change Alone)

		Cracking (% change)			Deformation (% change)	
Analysis site	IRI (% change)	Longitudinal	Alligator	Transverse	AC	Total[a]
British Columbia (baseline)	1.55 m/km	6.8 m/km	0.7%	19.1 m/km	2.1 mm	10.7 mm
CGCMA2x	−0.7	−1.9	7.5	−96.9	16.9	3.8
HadCM3B21	1.9	0.0	10.5	87.1	19.3	4.8
Alberta (baseline)	2.34 m/km	551.1 m/km	28.9%	399.6 m/km	5.5 mm	19.0 mm
CGCMA2x	1.3	9.3	11.4	0.0	22.7	−0.5
HadCM3B21	1.7	5.8	7.3	0.0	31.8	4.7
Manitoba (baseline)	2.54 m/km	450.8 m/km	48.2%	399.6 m/km	2.9 mm	14.5 mm
CGCMA2x	2.0	2.9	6.0	0.0	35.9	−0.9
HadCM3B21	2.4	2.9	5.8	0.0	34.1	2.3
Ontario (baseline)	1.92 m/km	33.3 m/km	4.6%	399.6 m/km	4.2 mm	12.1 mm
CGCMA2x	1.0	1.7	10.5	0.0	27.0	9.0
HadCM3B21	1.6	5.7	13.1	0.0	28.9	10.3
Quebec (baseline)	2.12 m/km	1647.7 m/km	0.5%	399.6 m/km	5.3 mm	21.8 mm
CGCMA2x	−0.9	0.0	4.4	0.0	13.9	−3.2
HadCM3B21	−0.5	−0.7	2.2	0.0	16.8	−0.8
Newfoundland (baseline)	1.79 m/km	5.3 m/km	0.1%	399.6 m/km	1.2 mm	9.1 mm
CGCMA2x	−1.1	5.4	14.3	0.0	21.9	−1.1
HadCM3B21	−0.6	4.3	14.3	0.0	21.9	0.6

[a] Includes all layers (asphalt, base, subbase, and subgrade).

tice, it is believed that by adopting the PGAC, a significant portion of the transverse thermal cracking can be addressed.

As noted, the primary objective of the MEPDG analysis was to evaluate relative, not absolute, changes in pavement performance between baseline and future climate change scenarios. The most significant differences between baseline and future climate scenarios were observed for the asphalt concrete (AC) rutting parameter. AC rutting increased at all sites, from a minimum of 14% at the Quebec site (CGCM2A2x scenario) to a maximum of 36% at the Man. location (CGCM2A2x scenario). Increases relative to the baseline were similar (within in a few percent) for both climate change scenarios except for the Alberta site where the HadCM3B21 scenario produced about 9% more AC rutting than the CGCM2A2x scenario. Much less change was observed for the total rutting parameter which suggests that deformation was reduced in the lower layers thus compensating for AC rutting. Changes in total rutting ranged from a reduction of 3% at the Que. site (CGCM2A2x scenario) to an increase of about 10% at the Ontario site (HadCM3B21 scenario). As with rutting in the AC layer, the changes relative to the baseline for both climate scenarios were consistently within a few percentage points of each other. However, the direction of the changes differed for the Alta., Man., and Newfoundland sites with slight reductions under the CGCM2A2x climate and small increases in total rutting under HadCM3B21 conditions.

In general, modest increases under climate change conditions were observed for the various cracking parameters relative to the baseline. A slight rise in longitudinal cracking was reported for most sites except for B.C. and Que., where no change or small decreases were recorded. Somewhat larger increases, from 2% (Que. site, HadCM3B21 scenario) to 14% (Nfld. site, CGCM2A2x scenario), were observed for alligator cracking. The high relative changes at the Nfld. site are associated with very small absolute changes in baseline cracking. In terms of transverse cracking, deterioration reached maximum values of approximately 400 m/km under each of the climate change scenarios tests as it did for the baseline run at 5 of the 6 sites, resulting in a zero net change. At the warmer B.C. site, transverse cracking was virtually eliminated under the CGCM2A2x scenario (97% reduction) but almost doubled (87% increase) under HadCM3B21 conditions. Despite issues with this form of cracking in the MEPDG, the B.C. results for the CGCM2A2x scenario are intuitively consistent with our understanding of cracking processes and may be more representative of future patterns in much of southern Canada than results from the other sites. The increase in cracking stemming from the HadCM3B21 scenario coincides with a regional area of relative cooling during the early winter period that is somewhat anomalous when compared to most areas in Canada.

The least amount of change between baseline and future climate scenarios was observed for the IRI performance parameter. Very small changes (i.e., less than 3%) in terminal IRI were observed under the CGCM2A2x and HadCM3B21 climate scenarios examined. Slight decreases in roughness were apparent at the two eastern (both scenarios) and B.C. (CGCM2A2x scenario) sites while slight increases were apparent at the remaining locations.

Terminal values of performance indicate the state of a pavement at the end of its service life. Just as important is the time-dependent evolution of deterioration relative to maintenance, rehabilitation, and reconstruction thresholds. Parameter limits associated with a 20-year-design life as defined earlier were used to explore changes in the timing of maintenance requirements. At the 50% reliability level, 11 out of 36 possible parameter limits (6 sites × 6 parameters) were exceeded at some point during the 20-year-design life under baseline climate conditions. Thresholds were not achieved for any parameter at the B.C. site or for the IRI and AC rutting parameters at any of the sites. Total rutting (all layers), longitudinal cracking, and alligator cracking criteria were met at 1 (Que., 10.9 years), 3 (Alta., 14.8 years; Man., 17.1 years; Que., 2.8 years), and 2 (Alta., 17 years; Man., 8.1 years) sites, respectively. With the exception of B.C., all sites reached transverse cracking thresholds early during the first winter season. As noted previously, transverse cracking would be negligible based on a proper PG selection.

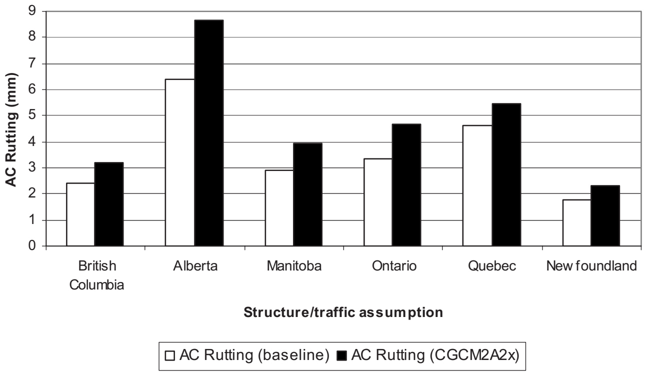

Fig. 7. Changes in AC rutting resulting from application of different structure/traffic characteristics to baseline and CGCM2A2x climate scenarios for Winnipeg, Manitoba

After analyzing the climate change scenarios, two parameter limits (13 of 36) were added to those exceeded under baseline conditions. As with the baseline, no parameter limits were reached for the B.C. site and IRI criteria were not met at any site under the CGCM2A2x or HadCM3B21 climate scenarios. For most other parameters and sites, the general influence of climate change was to reduce the amount of time until maintenance, rehabilitation, or reconstruction thresholds were met. The reductions ranged from less than 1 year (Man., alligator cracking, CGCM2A2x, and HadCM3B21 scenarios) to over 5 years (Alta., AC rutting, and HadCM3B21 scenario). Results for the Que. site (total rutting, longitudinal cracking) and for the transverse cracking parameter were just the opposite, with climate change inducing a slight delay in the timing when limits were reached.

Influence of Pavement Structure and Baseline Traffic

In addition to showing the relative impact of the climate change scenarios, the results from Table 3 suggest that other variables, especially pavement structure and baseline traffic, are significant factors shaping pavement deterioration. To better understand the role of structural and baseline traffic assumptions, all of the structures represented in this phase of the study were run through MEPDG under the same baseline climate and CGCM2A2x climate change scenario (Winnipeg, Man.). Terminal deterioration results for IRI, longitudinal cracking, alligator cracking, AC rutting, and total rutting indicators were analyzed. Results for AC rutting are displayed in Fig. 7. The most striking observation is that relative differences between various structure and traffic situations, as represented among the set of sites in the study, are much greater than those associated with changes in climate at the Winnipeg site. In particular, longitudinal and alligator cracking seem insensitive to changes in climate relative to variations in structure and traffic levels while AC rutting appears to be the most sensitive to shifts in climate among the indicators studied.

Both the magnitude and direction of change are influenced by structural and traffic assumptions. For example, while the CGCM2A2x results for AC rutting were consistently higher than the baseline climate for all structures, relative rutting increased more for the Alta. structure (36%) than for the Nfld. structure (18%). Changes in IRI, total rutting, and longitudinal cracking between the baseline climate and CGCM2A2x scenario were inconsistent across the structure types, increasing in some instances (e.g., IRI for Alta., Man. and Ont. structures) and decreasing in others (e.g., IRI for B.C., Que. and Nfld. structures).

Combined Influence of Climatic Change and Traffic Growth

While many structural factors or assumptions remain constant throughout the pavement design life, the amount of traffic does not. Loads in most regions of southern Canada are likely to increase through time in conjunction with trends in population and economic growth. In order to understand the effect of increasing traffic, the MEPDG control and climate change scenario data sets for each site were run again assuming a 4% per annum compound growth in AADTT. 4% is a best practice value and is suitable for estimating AADTT growth over a 20-year-design life.

Results for IRI for both the static and annual 4% growth scenarios, under baseline climate and climate change conditions, are presented in Table 4. The complete series of results is available in Mills et al. (2007). Terminal deterioration is expressed in absolute terms and as a relative percent of the control (no traffic growth, baseline climate) for each scenario combination. The timing of reaching critical thresholds is specified for both 50 and 90% reliability levels as determined by MEPDG, representing high and low volume road facilities.

As expected, larger loads induced greater terminal deterioration and earlier achievement of maintenance-related thresholds for all pavement distress indicators except for transverse cracking, which is influenced primarily by climatic and material factors. Relative increases in AC and total rutting were consistent across all sites although somewhat less than the relative increase in terminal truck growth (49%). Increases in IRI and especially longitudinal and alligator cracking exhibited more variability across the sites. This observation is likely due to variability in pavement structures and baseline traffic volumes that were previously discussed.

The impacts of the CGCM2A2x and HadCM3B21 climate change scenarios relative to the no growth baseline that were described in detail for the first set of MEPDG analysis were generally unaffected by the application of a 4% per annum growth in traffic. While higher traffic loads increased the absolute deterioration and resulted in earlier achievement of maintenance-related thresholds, the relative changes from the CGCM2A2x or HadCM3B21 scenario to respective no growth and 4% growth traffic baseline climate scenarios did not deviate by more than 3%. We thus did not observe a synergistic effect between climate and traffic growth, as simulated through MEPDG. Further analysis, including possible refinement of the model, is necessary to fully explore this important issue.

Conclusions

Current and past designs generally assume a static climate whose variability can be adequately determined from records of weather conditions which normally span less than 30 years and often less than 10 years. The notion of anthropogenic climate change challenges this assumption and raises the possibility that the frequency, duration, or severity of thermal cracking, rutting, frost heave, and thaw weakening may be altered, leading to shifts in pavement deterioration rates if corrective actions are not taken. The analyses provided empirical evidence to support this contention for several sites in Canada. Similar results may be expected for locations in the northern United States. The analysis of deterioration-relevant climate indicators at 17 sites suggests that, over the next 50 years, low temperature cracking will become less problematic; structures will freeze later and thaw earlier with correspondingly shorter freeze season lengths; and higher extreme in-service pavement temperatures will raise the potential for rutting. Evidence from the 6 sites examined in the MEPDG analysis was not as universal but nonetheless suggests that rutting (AC and total) and cracking (longitudinal and alligator) issues will be exacerbated by climate change. In general, maintenance, rehabilitation, or reconstruction will be required earlier in the design life. The MEPDG analysis also revealed that the absolute impacts of climate change are closely associated with the underlying structural, material, and traffic characteristics of a particular site—generalizations from the results must therefore be considered with caution.

The results of this study are dependent on many assumptions, particularly those concerning representativeness of sites and treatment of climate scenarios. Site selection for both analyses was driven by data availability (e.g., LTPP, Environment Canada) and engineering expertise. While selected sections were representative of climates typically experienced in southern Canada, additional sites that capture an even broader range of climates and pavement structures found within Canada could have been analyzed and a greater number of climate change scenarios, and alternative or more sophisticated means of downscaling scenario data, could have been incorporated into the research. While such additions would no doubt contribute to greater confidence in the results, it is likely that the general findings would not change significantly.

None of the potential impacts suggested through this study fall beyond the range of conditions presently experienced in North America—analogous pavement structures and environmental and traffic situations are represented in the LTPP database. PG ratings and other material properties can be altered and structural designs can be improved for new asphalt pavements. Maintenance schedules can be advanced (or deferred) and systems can be put in place to monitor and predict freezing and thawing effects on pavement strength and restrict traffic accordingly.

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

Table 4. IRI Performance Results for All Sites and Scenarios

	International roughness index (IRI)		
Site and scenario	m/km	Change relative to control (%)	Years to 2.7 m/km maintenance threshold (50/90% reliability)[a]
British Columbia			
Control: Baseline climate+no traffic growth	1.55	—	NR/NR
CGCM2A2x+no traffic growth	1.54	−0.7	NR/NR
HadCM3B21+no traffic growth	1.58	1.9	NR/NR
Baseline climate+4% AADTT growth	1.58	1.9	NR/NR
CGCM2A2x+4% AADTT growth	1.57	1.3	NR/NR
HadCM3B21+4% AADTT growth	1.57	3.9	NR/NR
Alberta			
Control: Baseline climate+no traffic growth	2.34	—	NR/14.3
CGCM2A2x+no traffic growth	2.37	1.3	NR/13.9
HadCM3B21+no traffic growth	2.38	1.7	NR/13.8
Baseline climate+4% AADTT growth	2.53	8.1	NR/12.9
CGCM2A2x+4% AADTT growth	2.59	10.7	NR/12.3
HadCM3B21+4% AADTT growth	2.60	11.1	NR/12.1
Manitoba			
Control: Baseline climate+4% traffic growth	2.54	—	NR/12.4
CGCM2A2x+no traffic growth	2.59	2.0	NR/12.0
HadCM3B21+no traffic growth	2.60	2.4	NR/11.9
Baseline climate+4% AADTT growth	2.85	12.2	18.9/11.0
CGCM2A2x+4% AADTT growth	2.92	15.0	18.2/10.8
HadCM3B21+4% AADTT growth	2.95	16.1	18.1/10.8
Ontario			
Control: Baseline climate+4% traffic growth	1.92	—	NR/NR
CGCM2A2x+no traffic growth	1.94	1.0	NR/NR
HadCM3B21+no traffic growth	1.95	1.6	NR/NR
Baseline climate+4% AADTT growth	1.97	2.6	NR/NR
CGCM2A2x+4% AADTT growth	1.99	3.7	NR/NR
HadCM3B21+4% AADTT growth	2.01	4.7	NR/NR
Quebec			
Control: Baseline climate+4% traffic growth	2.12	—	NR/17.8
CGCM2A2x+no traffic growth	2.10	−0.9	NR/18.3
HadCM3B21+no traffic growth	2.11	−0.5	NR/17.9
Baseline climate+4% AADTT growth	2.19	3.3	NR/16.8
CGCM2A2x+4% AADTT growth	2.16	1.9	NR/17.1
HadCM3B21+4% AADTT growth	2.18	2.8	NR/16.8
Newfoundland			
Control: Baseline climate+4% traffic growth	1.79	—	NR/NR
CGCM2A2x+no traffic growth	1.77	−1.1	NR/NR
HadCM3B21+no traffic growth	1.78	−0.6	NR/NR
Baseline climate+4% AADTT growth	1.81	1.1	NR/NR
CGCM2A2x+4% AADTT growth	1.79	0.0	NR/NR
HadCM3B21+4% AADTT growth	1.80	0.6	NR/NR

[a] NR (not reached during 20-year design life).

Recommendations for Future Research and Application

Future MEPDG simulations should be run using the most current version together with climate scenarios developed using more sophisticated downscaling techniques than was possible in this study. Incorporating other climate-related road infrastructure issues, for instance those associated with concrete pavements, surface-treated roads, airfields, bridges, and culverts, would also be beneficial. At a minimum, long time series of historic climatic and road weather observations—ideally greater than 30 years in the case of climate—should be incorporated into analysis of pavement deterioration and applied to update SLRs and WWPs or assign performance graded materials.

Acknowledgments

The authors acknowledge the funding and in-kind contributions provided by Environment Canada and the federal Climate Change

Impacts and Adaptation Program managed by Natural Resources Canada (Project No. A812). Special thanks are extended to Winnie Li, a co-op student, for assistance with running the MEPDG scenarios and to Suzanne Parm, a graduate student who assisted with the freeze-thaw analysis. Constructive comments and editing suggestions from three anonymous reviewers are also appreciated.

Notation

The following symbols are used in this paper:

H = depth from surface, mm;
Lat = latitude of location, decimal degrees;
$T_{\text{air min}}$ = average annual extreme minimum daily air temperature, °C;
$T_{p \text{ min}}$ = minimum pavement temperature at depth, °C;
z = z-score for appropriate level of reliability assuming standard normal distribution ($z = 2.055$, 98% reliability); and
$\sigma_{T\text{air min}}$ = standard deviation of annual extreme minimum daily air temperature, °C.

References

Andrey, J., Mills, B., and Warren, F. J. (2004). "Transportation." *Climate change impacts and adaptation: A Canadian perspective*, D. S. Lemmen and F. J. Warren, eds., Government of Canada, Ottawa, 131–149, ⟨http://adaptation.nrcan.gc.ca/perspective/index_e.php⟩ (Oct. 2007).

Applied Research Associates, Inc. (2004). *Guide for mechanistic-empirical design of new and rehabilitated pavement structures*, NCRHP Project 1-37A, National Cooperative Highway Research Program, Washington, D.C.

Barrow, E., Maxwell, B., and Gachon, P. (2004). *Climate variability and change in Canada: Past, present and future, ACSD Science Assessment Series No. 2*, Meteorological Service of Canada, Environment Canada, Toronto, Ontario.

Carter, T. R., Hulme, M., and Lal, M. (1999). *Guidelines on the use of scenario data for climate impact and adaptation assessment, version 1*, Task Group on Scenarios for Climate Impact Assessment, Intergovernmental Panel on Climate Change.

Christensen, J. H., et al. (2007). "Regional Climate Projections." *Climate change 2007: The physical science basis. Contribution of Working Group I to the fourth assessment report of the Intergovernmental Panel on Climate Change*, S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller, eds. Cambridge University Press, Cambridge, U.K.

Environment Canada. (2007a). *Canada's 2005 Greenhouse Gas Inventory: A Summary of Trends*, ⟨http://www.ec.gc.ca/pdb/ghg/inventory_report/2005/2005summary_e.cfm⟩.

Environment Canada. (2007b). *Canadian Climate Change Scenarios Network (CCCSN)*, ⟨http://www.cccsn.ca⟩ (Oct. 2007).

Federal Highway Administration. (2002). *Superpave asphalt mixture design, version 8.0*, U.S. Federal Highway Administration, ⟨http://www.tfhrc.gov/pavement/asphalt/prodrsrch/mixturedesign/mixdsgn.pdf⟩, (Nov. 2007).

Flato, G. M., and Boer, G. J. (2001). "Warming asymmetry in climate change simulations." *Geophys. Res. Lett.*, 28(1), 195–198.

Flato, G. M., Boer, G. J., Lee, W. G., McFarlane, N. A., Ramsden, D., Reader, M. C., and Weaver, A. J. (2000). "The Canadian Centre for Climate Modelling and Analysis Global Coupled Model and its climate." *Clim. Dyn.*, 16(6), 451–467.

Gordon, C., Cooper, C., Senior, C. A., Banks, H., Gregory, J. M., Johns, T. C., Mitchell, J. F. B., and Wood, R. A. (2000). "The simulation of SST, sea ice extents and ocean heat transports in a version of the Hadley Centre coupled model without flux adjustments." *Clim. Dyn.*, 16, 147–168.

Goyette, S., McFarlane, N. A., and Flato, G. M. (2000). "Application of the Canadian Regional Climate model to the Laurentian Great Lakes region: Implementation of a lake model." *Atmos.-Ocean.*, 38(3), 481–503.

Intergovernmental Panel on Climate Change. (2007). "Emission Scenarios: Summary for Policymakers." *Special Report of IPCC Working Group III*, Intergovernmental Panel on Climate Change, Geneva ⟨http://www.ipcc.ch/pdf/special-reports/spm/sres-en.pdf⟩ (Nov. 2007).

Intergovernmental Panel on Climate Change. (2007). "Summary for Policymakers." *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, S. Soloman et al., eds., Cambridge University Press, Cambridge, U.K., ⟨http://www.ipcc.ch⟩ (Nov. 2007).

Leong, P., Tighe, S., and Doré, G. (2005). "Using LTPP data to develop spring load restrictions: A pilot study." *Proc., 84th Annual Meeting* (CD-ROM), Transportation Research Board, Washington, D.C.

LTPP. (2007). "LTPP: Long term pavement performance program." *U.S. Federal Highway Administration*, ⟨http://www.fhwa.dot.gov/pavement/ltpp/⟩ (Nov. 2007).

Mills, B., Tighe, S. L., Andrey, J., Smith, J. T., Parm, S., and Huen, K. (2007). "The road well-traveled: Implications of climate change for pavement infrastructure in southern Canada." Adaptation and Impacts Research Division, Environment Canada, and University of Waterloo, Waterloo, Canada, ⟨http://adaptation.nrcan.gc.ca/projdb/pdf/134b_e.pdf⟩.

Ministry of Transportation of Ontario. (2007). *Quick facts: Provincial highway management*, Ministry of Transportation of Ontario, ⟨http://www.mto.gov.on.ca/english/about/quickfacts.htm⟩ (Sept. 2007).

Minnesota DOT. (2004). "Guidelines for seasonal load limit starting and ending dates." *Technical Memorandum No. 04–20-MAT-03*, Engineering Services Division, ⟨http://www.dot.state.mn.us/tecsup/tmemo/active/tm04/20mat03.pdf⟩ (Oct. 2007).

National Cooperative Highway Research Program. (2004). *Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures*. National Cooperative Highway Research Program, Transportation Research Board, National Research Council, Washington, D.C., ⟨http://www.trb.org/mepdg/software.htm⟩ (Nov. 2007).

National Cooperative Highway Research Program. (2006a). "Independent review of Mechanistic-Empirical Design guide and software." *Research Results Digest 307*, National Cooperative Highway Research Program, Transportation Research Board, Washington D.C., ⟨http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rrd_307.pdf⟩ (Nov. 2007).

National Cooperative Highway Research Program (2006b). "Changes to the Mechanistic-Empirical Design Guide software through version 9.000, July 2006." *Research Results Digest 308*, National Cooperative Highway Research Program, Transportation Research Board, Washington D.C., ⟨http://onlinepubs/trb.org/onlinepubs/nchrp/nchrp_rrd_308.pdf⟩ (Nov. 2007).

Ontario Hot Mix Producers Association. (1999). "The ABCs of PGAC." *Ontario Hot Mix Producers Association fact sheet*, ⟨http://www.ohmpa.org/lib/db2file.asp?fileid=189⟩ (Nov. 2007).

Program for Climate Model Diagnosis and Intercomparison. (2007). *Coupled Model Intercomparison Project (CMIP)* ⟨http://www-pcmdi.llnl.gov/projects/cmip/index.php⟩ (Oct. 2007).

Richardson, S. (1996). "Valuation of the Canadian road and highway system." *Rep. No. TP 1279E*, Transport Canada, Ottawa, Ontario.

Semenov, M., Brooks, R., Barrow, E., and Richardson, C. (1998). "Comparison of the WGEN and LARS-WG stochastic weather generators in diverse climates." *Clim. Res.*, 10, 95–107.

Transport Canada. (2003). "Transportation in Canada 2003 Annual Report." *Rep. No. TP13198E*, Transport Canada, Ottawa, Ontario.

Wilby, R. L., Dawson, C. W., and Barrow, E. M. (2002). "SDSM-a decision support tool for the assessment of regional climate change impacts." *Environ. Modell. Software*, 17(2), 145–157.

Wilks, D. S., and Wilby, R. L. (1999). "The weather generation game: a review of stochastic weather models." *Prog. Phys. Geogr.*, 23(3), 329–357.