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Examining the effects of climatic factors on flexible pavement performance and service life

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ABSTRACT

The potential risk of climate change increases interest in how it may affect the deterioration rates of flexible pavements and how pavement service lives would be altered as a consequence. Previous studies demonstrated that temperature is the most influential environmental factor for the Mechanistic-Empirical Pavement Design Guide (MEPDG: version 1.1). In this paper, temperature factors, both the increase in average annual temperature and seasonal variation in temperature are examined through a sensitivity analysis. The sensitivity of the pavement performance to temperature, as well as other environmental factors such as precipitation, wind speed, percent sunshine and groundwater level are also included as a reference. This study concluded that temperature factors, both the increase in average annual temperate and seasonal variation, are the most influential in the pavement performance. Moreover, pavement service life may experience considerable reduction due to climate change in some regions.

INTRODUCTION & AIM

Climatic factors affect the performance of flexible pavements, especially temperature and moisture. These factors have long been a consideration in pavement design or practice because they may alter the deterioration of pavement materials and stiffness, thus impacting pavement performance. For instance, the choice of asphalt binder is closely related to the local temperature conditions to satisfy structural and functional requirements. Although proper design of a pavement includes consideration of climatic factors, distresses caused by environment are inevitable and sometimes crucial.

Researchers have studied the impact of climate on pavement performance. Tighe et al. (*1*) performed an analysis on flexible pavements in Canada and suggested that deterioration in rutting, longitudinal cracking and fatigue (alligator) cracking will be accelerated by climate change. Kim et al. found that climatic factors impact transverse cracking on flexible pavements (*2*). Moreover, the results for the International Roughness Index (IRI) are inconclusive; while some researchers have found it to be sensitive to climate change (*3*); others suggested that IRI is not sensitive to climate change (*2*). In most studies, however, climate was only represented by an overall climate (e.g., combination of temperature, precipitation, and other climate factors), thus it is unknown which climatic inputs caused the greatest differences and which were negligible in the result. A recent study conducted by Byram et al. discovered that temperature is the most influential factor for flexible pavements (*4*). The study, examined the sensitivity of climatic inputs of an American pavement analysis tool, the Mechanistic-Empirical Pavement Design Guide (*6*), on several pavements throughout the U.S..

As temperature is found to be the climatic factor that most influences the performance of flexible pavements, it is of importance to determine how a seasonal variation in temperature will impact flexible pavements. If this impact is of concern, how does its severity compare to other factors? Therefore the aim of this study is to investigate the sensitivity of climatic factors including temperature (average annual temperature and seasonal variation), precipitation, wind speed, percent sunshine, and groundwater level for typical pavement structures in selected locations and to calculate and compare the pavement service lives experienced before and after changes in climate.

PAVEMENT SURFACE ENERGY BALANCE

The pavement surface temperature is affected by environmental factors, such as air temperature, solar radiation, radiation of the asphalt surface and wind speed. The short-wave radiation from sunlight is the main input energy for pavements and the percentage of sunshine is one factor used to determine the net short wave radiation (*5*). Air temperature is sometimes related to the long wave radiation emitted from the atmosphere, which is another heating source (*6*). Parts of the input energy are lost through pavement surface radiation and convection. Air temperature and wind speed are associated with the process of heat transfer by convection. The remaining energy is absorbed by the pavement and transfers downwards to sub layers. Asphalt material properties (e.g., surface short wave absorption, heat capacity, and thermal conductivity) are found to influence the pavement temperature profile (*7*, *8*). In addition, effects from other processes such as transpiration, condensation, evaporation, and sublimation, are sometimes negligible as the effects are rather small or their effects may cancel each other (*6*).

Pavement temperature is believed to have an impact on asphalt rutting, age hardening and thermal cracking (*9*). Due to the visco-elastic nature of bituminous binders, temperature plays an important role in the stiffness and rutting performance of asphalt pavement. Increased asphalt rutting is expected under greater asphalt temperatures, especially when the traffic volume is large and the traffic speed is slow. Nevertheless, the effect of temperature is smaller on rutting in granular materials and subgrade soil. Flexible pavements are more prone to age hardening under increased pavement temperature (*10*). Age hardening is undesirable on the road surface, because it can reduce the ability of pavement to flex under traffic (*10*). As a result of age hardening, the asphalt surface becomes brittle and vulnerable to cracking. When pavements cool, cracking begins to propagate due to thermal tensile stress. In general, there are two different types of thermal cracking: 1) low-temperature transverse cracking and 2) thermal fatigue cracking. The former is caused by the shrinkage of asphalt due to cold extremes, while the latter results from asphalt aging and residual stress due to a large number of loading cycles.

WATER BALANCE

The moisture content of soil is affected by many factors, including climate, soil type, and the water table level. The climate condition, especially rainfall, is important since precipitation is a main source of soil moisture. Soil moisture can also be related to runoff, evapotranspiration and water transfer between soil layers (*11*). In the MEPDG (*6*), subgrade moisture is considered by Soil Water Characteristic Curves (SWCC). SWCC is used to describe the variations of water storage capacity within the macro- and micro-pores of soil, taking suction into consideration (*12*).

Excessive moisture content may result in a reduction in resilient modulus and stiffness in unbound materials and subgrade soil, especially when fine materials exist. Therefore the road is prone to greater permanent deformation (*13*). A decrease of effective stress due to excessive pore pressure may be another reason for the reduction in permanent deformation resistance (*14*). Meanwhile, the tensile strain related to fatigue can be increased, resulting in more fatigue cracking. Furthermore, water infiltration into asphalt mixture can aggravate distresses such as ravelling and stripping. However, due to the lack of a modeling method, these distresses are excluded from this study. In addition, the moisture condition in a pavement depends on the quality and condition of the drainage of the pavement.

FROST HEAVE AND THAW

Frost heave and thaw can be an important climate-associated consideration for pavements located in colder areas. When frost heaving occurs, pavements gain strength due to the frozen subgrade However, the strength can be dramatically reduced during the spring period when the ground thaws and ice melts. The excessive water may cause great moisture related problems for the subgrade (*15*). It is believed that spring thaw is the most influential seasonal phenomenon for road deterioration (*16*). Frost damage results in an uneven pavement surface, longitudinal and transverse cracking and an increased percentage of rutting were observed to occur during a spring thaw (*17*).

ENHANCED INTEGRATED CLIMATE MODEL (EICM)

In the MEPDG, a climatic model called the Enhanced Integrated Climate Model (EICM) is incorporated to correlate climate records to pavement temperature and moisture conditions (*6*). This aids in the prediction of pavement performance. With EICM, the MEPDG can show a change in pavement performance due to climatic variations. This is primarily why the MEPDG is adopted for pavement modeling in this study.

The detailed inputs for EICM are hourly climatic measurements, including temperature, precipitation, wind speed, percent sunshine, ground water table, and daily records of sunrise/sunset times. EICM is capable of modeling temperature and moisture profiles in pavements and subgrade with three sub models including (*6*):

- The climatic-material-structural model,
- The CRREL (United States Army Cold Regions Research and Engineering Laboratory) Frost Heave and Thaw Settlement Model, and
- The Infiltration and Drainage Model.

CLIMATE CHANGE AND LOCATION SELECTION

An increasing body of evidence shows that climate is unlikely to remain unchanged in the future. Observations indicate that the annual average global surface temperature has increased by 0.75 °C between 1850 to present. This upward trend has occurred more quickly during the past 50 years. In some areas (e.g., the eastern part of North America) precipitation has significantly increased during the last century. Moreover, the sea level has increased 150 mm since 1900. Hot/cold extremes, storm and flooding are observed to be more frequent in some areas (*18*).

According to the Inter-governmental Panel on Climate Change (*18*), the emission of greenhouse gases (GHG) is believed to be the reason for climate change. Corresponding GHG emission levels to variations of societal development, IPCC defined different emission scenarios as described in the IPCC Special Report on Emissions Scenarios (*19*). Based on those scenarios, software called MAGICC/SCENGEN was used for the projection of future changes in temperature, precipitation on a local scale and the sea level on a global scale. Using the IPCC's (*18*) emission scenario A1B, which is characterized by a society comprising a prosperous economy, a peaking population in the mid-century, and balanced energy sources of fossil and non-fossil energies, projections for the future climate for any given location may be made by the study approach adopted here.

A recent National Cooperative Highway Research Program (NCHRP) project reviewed the potential impact of regional climate change on highway system and recommended three regions for analysis (*20*):

1. Northwest: A combination of increases in annual temperature, a change in precipitation and a change in the sea-level is expected to occur in this area, which makes it a typical area to study. Historical climatic data gathered during a period of 113 months as measured at the Seattle-Tacoma International Airport (Seattle, WA) were used to represent this area.
2. Midwest: The greatest temperature increase is expected in this area, thus making it representative of the impact of dramatic escalations in temperature. Climatic data gathered during a 116 months period as measured at the St Paul International Airport (Minneapolis, MN) were used to represent this area.
3. Southeast: Extreme climatic events are expected in this area. Furthermore, as a middle range of changes is expected in this area, it may represent the average case nationally. Climatic data from a period of 116 months as measured at Richmond (VA) International Airport were used to represent this area.

Worth mentioning, the airports where the temperature measurements were made mostly locate in the suburban of the city, which may result in underestimations of the temperatures in urban areas due to the heat-island effect.

In this study, climatic inputs were increased by 5 % to estimate the sensitivity of pavement performance. This percentage was selected for the analysis for two reasons:

- An increase of 5% is a close overall estimation of the projection made under the IPCC A1B scenario, as determined by increases in temperature, precipitation, and the sea level (Table 1).
- Climatic projections for wind speed and percent sunshine are not yet available using MAGICC/SCENGEN. However, an increase of 5 % was added to those parameters to provide the standard baseline for sensitivity analysis.

TABLE 1 Climatic Projection for Three Locations.

	Virginia (VA)		Minnesota (MN)		Washington (WA)		Sea level (in)
	Temp (°F)	Preci (%)	Temp (°F)	Preci (%)	Temp (°F)	Preci (%)	
Climatic projection 2050 A1B	3.1	4.5	4.6	5.3	3.2	-1.2	5.9
Increase by 5%	2.9	5.0	2.4	5.0	2.6	5.0	3.0

(Temp = temperature, and Preci = precipitation.)

In each location, a hypothetical pavement structure was created (Table 2) based on the information available in the Long-term Pavement Performance (LTPP) database for the three targeted states. Traffic for all three roads was assumed to be 3800 AADTT, which is typical for interstate highways in Virginia according to the LTPP database. The axle configuration was set as default values from MEPDG (*6*). The traffic volume was assumed to be constant during the design life of pavements.

TABLE 2 Pavement Structure for Seattle, WA, Minneapolis, MN and Richmond, VA.

Seattle, Washington					
Layer	Material	Thickness (in)	PG grade	Thermal conductivity (hr-ft-F)	Heat capacity (lb-F)
1	Asphalt concrete	4	52-10	0.67	0.23
2	Asphalt concrete	5	52-10	0.67	0.23
Layer	Material	Thickness	Input modulus (psi)		
3	Granular base (A-3)	8	24500		
4	Subgrade (A-7-6)		8000		
Minneapolis, Minnesota					
Layer	Material	Thickness (in)	PG grade	Thermal conductivity (hr-ft-F)	Heat capacity (lb-F)
1	Asphalt concrete	6	52-34	0.67	0.23
2	Asphalt concrete	6	52-34	0.67	0.23
Layer	Material	Thickness	Input modulus (psi)		
3	Granular base (A-1-a)	12	42000		
4	Subgrade (A-7-6)		11500		
Richmond, Virginia					
Layer	Material	Thickness (in)	PG grade	Thermal conductivity (hr-ft-F)	Heat capacity (lb-F)
1	Asphalt concrete	4.5	70-22	0.67	0.23
2	Asphalt concrete	3	70-22	0.67	0.23
Layer	Material	Thickness	Input modulus (psi)		
3	Granular base (A-1-a)	5	42000		
4	Subbase (A-7-6)	6	12000		
5	Subgrade (A-7-6)		8000		

TEMPERATURE MODIFICATION

The climatic data comprise records from a period of approximately 10 years (Figure 1). The climatic records include the hourly values of temperature, precipitation, wind speed, percent sunshine and groundwater level. To represent a future temperature profile, the temperature record is modified using two functions, calculated individually: 1) A linear function to represent the increase in average annual temperature (red line in Figure 1) and 2) A sine function representing the additional seasonal variation (green line in Figure 1).

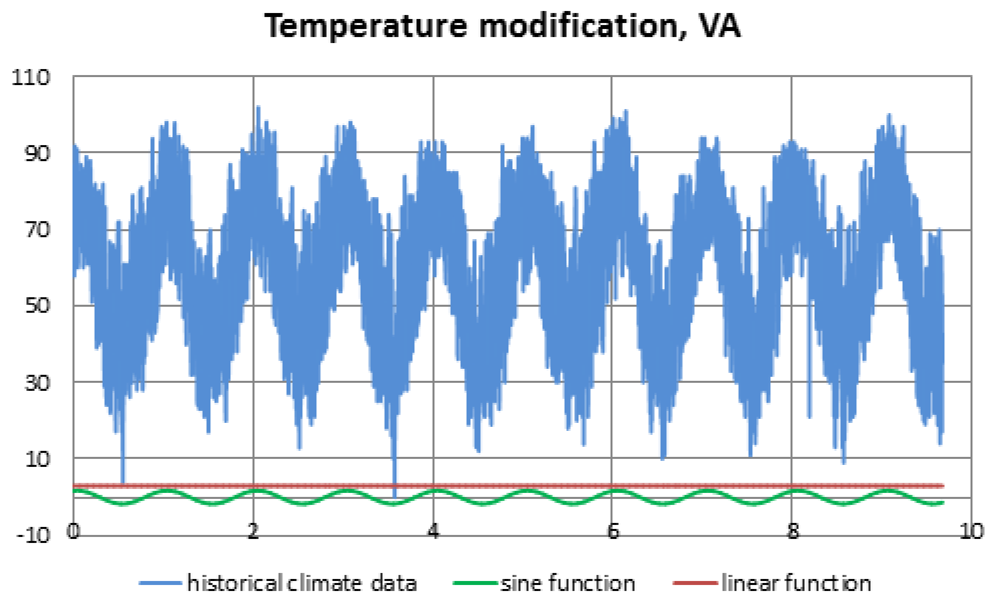

Figure 1 Temperature modification for Richmond, VA. (Vertical axial: temperature (°F), horizontal axial: year.)

Temperature modification can be expressed as follows (Equation 1):

$$T_{new} = T_{original} + T_f \quad (1)$$

Where,

T_{new} = modified temperature

$T_{original}$ = original temperature as determined in the temperature measurement; and

T_f = modification by either linear T_l or sine function T_s.

Linear function

In this study, it was assumed that the increase in temperature was constant (i.e., the linear function was horizontal). Arguably, the increase in temperature may not be constant in the future, even in a period of 10 years. However, the increase during a 10-year period should be rather small. Therefore, this is still a reasonable estimate unless more accurate temperature projection for each ten years is available. The linear function is formulated as follows (Equation 2):

$$T_l = 0.05 \times T_a \quad (2)$$

Where,

T_a = average annual temperature gathered from temperature measurements.

The factor 0.05 corresponds to 5% sensitivity, which is used in all climatic factors in this study.

Sine function

The sine function is designed to add seasonal variations in temperature records while maintaining the average annual temperature. Temperature modified with the sine function adds hot/cold extremes in summer/winter. It should be noted that this function does not reflect the variations in daily temperature, which may also change in the future. However, a single sine function cannot ideally describe variations of daily temperature because of its uncertainty and randomness. Therefore, more knowledge is needed to modify daily temperature variations. Temperature variation modification (the green line in Figure 1) by the sine function can be expressed by Equation 3:

$$T_s = a \times sin(b \times Y + c) \quad (3)$$

Where,

Y = year of temperature measurement; and

a, b, c = constant.

Constant a determines the maximum value of T_s. The gap between the maximum and minimum values of T_s is $2a$, which is calculated by multiplying the sensitivity (5%) by the gap between the maximum and minimum temperatures in the measurements. Due to the fact that some extreme measurements are not representative, some are filtered with approximately 95% confidence (± 2σ), considering temperature measurements to be normally distributed. Constant b is a factor that is determined by the period of the sine function, which is one year in this case (b = 2π/1= 6.28). Constant c is determined by the time when the first measurement began.

SENSITIVITY ANALYSIS

The sensitivity of temperature, both the average annual temperature and variation was increased by 5% in this study. Other climatic factors such as precipitation, wind speed, sunshine, and the ground water table are increased by 5% as a reference. The sensitivity was calculated as follows (Equation 4):

$$Sensitivity = \frac{\Delta F(t) / F(t)}{\Delta t / t} \quad (4)$$

Where,
$F(t)$ = function where t is involved;
ΔF = increment in the function;
t = parameter; and
Δt = increment in the parameter (5% × t).

Table 3 illustrates the climatic conditions of each location. The ground water table was assumed to be 5 ft below the pavement surface, and a negative was added. The increase in ground water level was assumed to be the same as the sea-level rise.

TABLE 3 Average Annual Values of Climatic Factors Based On Approximately 10 Years' of Climate Records (*6*).

	Temperature (°F)	Temperature Variation (°F)	Precipitation (in)	Wind Speed (mph)	Sunshine Percentage (%)	Ground water table (ft)
Seattle, WA	51.6	45	38.2	6.3	28.6	-5.0
Minneapolis, MN	47.1	90.6	30.2	8.1	38.8	-5.0
Richmond, VA	58.4	69	45.1	6.5	44.2	-5.0

It should be noted that in the event the hourly sunshine percentage results in unrealistic value after an increase of 5% (sunshine percentage should be less than 100%), the extra calculated sunshine percentage was equally distributed to the remaining hours, thus maintaining realistic values. This step was repeated until all extra sunshine percentages were finally distributed.

PAVEMENT SERVICE LIFE

Pavement service life is measured as the time from opening a road to traffic until the pavement provides substandard service quality. The service quality is commonly characterized by the distress conditions of the pavement. Index values are usually set with threshold values, indicating the minimum acceptable service quality, and the first index to be exceeded defines the service life. This approach can be expressed by Equation 5:

$$SL = min(SL_1, SL_2, SL_3 \ldots) \quad (5)$$

Where,
SL = service life; and
SL_1, SL_2, SL_3 ... = service life calculated with each distress.

The distresses selected in this study include longitudinal cracking, transverse cracking, fatigue cracking, roughness (IRI), asphalt rutting and total rutting, which are the direct outputs of the MEPDG.

Although roughness and fatigue cracking are believed to be less influenced by climate (*21*) they are also included for comparison. Other distresses such as block cracking, raveling, and potholes are not considered as the MEPDG cannot provide a prediction for them.

RESULTS

The prediction of pavement performance is presented as pavement distress including longitudinal cracking, fatigue cracking, transverse cracking, asphalt course (AC) rutting, total rutting and IRI. The sensitivity of these distresses at 40 years after trafficking is calculated as a consequence of a 5% increase in climatic inputs (Table 4). Predicted transverse cracking for three roads and predicted longitudinal cracking in Washington and Minnesota is small enough to be negligible and thus it does not appear in the results.

TABLE 4 Result of Sensitivity Analysis

	Longitudinal Cracking (ft/mi)	Fatigue Cracking (%)			Subtotal AC Rutting (in)			Total Rutting (in)			IRI (in/mi)		
	VA	WA	MN	VA	WA	MN	VA	WA	MN	VA	WA	MN	VA
T +	16.2	2.4	1.7	1.5	5.4	4.4	4.2	1.2	2.0	1.6	0.0	0.2	0.2
P +	0.8	0.0	0.2	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
W +	-1.3	-0.2	-0.2	-0.1	-0.5	-0.4	-0.3	-0.2	-0.2	-0.1	0.0	0.0	0.0
S +	2.0	0.2	0.2	0.2	0.2	0.5	0.4	0.1	0.2	0.1	0.0	0.0	0.0
G +	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TV +	16.9	1.2	1.1	1.2	2.4	2.7	3.3	0.6	1.4	1.2	0.3	0.2	0.4

(T = temperature, P = precipitation, W = wind speed, S = percent sunshine, G = ground water level, and TV = temperature variation)

The longitudinal and transverse cracking is sometimes predicted to be negligible, either under current or future climate. It indicates the pavement which experienced this may have reasonable resistance to longitudinal and transverse cracking. However, this does not mean that those factors are not sensitive to climatic variations on other roads.

A general observation is that temperature changes (both the T+ and TV+) were the most influential climatic factors (Figure 2). The sensitivity occurring in TV+ was usually smaller than that of T+. However, it seems that the sensitivity of longitudinal cracking and the IRI to TV+ were greater compared that to T+ (Table 4). This may be due to the fact that a greater seasonal temperature variation results in higher seasonal tensile stress and thermal contraction, thus the pavement undergoes more deterioration.

Although longitudinal cracking was only predicted to occur on the road in Virginia, it can still be observed in Table 4 that among all distresses longitudinal cracking was the most influenced by a 5% increase in all climatic inputs. This has also been observed by other researchers (*2, 22*) and leads to the discussion on the longitudinal cracking model in the MEPDG. From experience, longitudinal cracking is more likely to occur on thick asphalt pavements but the prediction in MEPDG appears to the contrary (*22*). In spite of this, both T+ and TV+ resulted in significant developments in longitudinal cracking. Although the sensitivity of AC rutting in Virginia to T+ was greater than that it was to TV+, the sensitivity of longitudinal cracking to TV+ was noticeably greater than it was to T+. This may be because TV+ creates (extreme) cold weather and induces greater thermal tensile stress that leads to more longitudinal cracking.

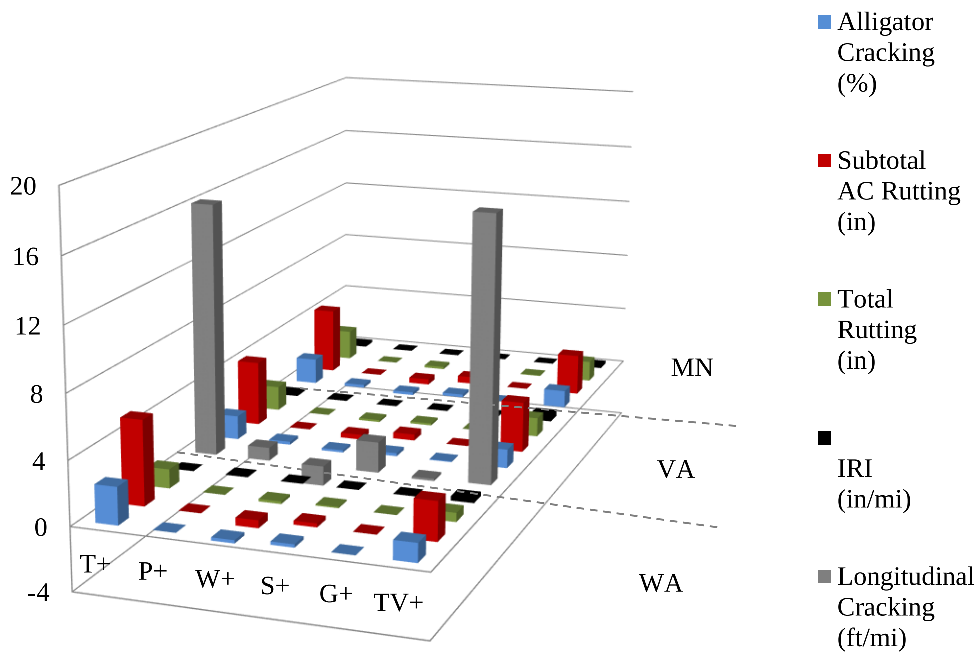

FIGURE 2 Results of Sensitivity Analysis.

The sensitivity of rutting, especially AC rutting, was found to be high for all three pavements. The sensitivity to TV+ was usually smaller than to T+, probably because more extreme hot-weather hours were generated by T+ when dramatic amounts of AC rutting occurred. Furthermore, the prediction showed that changes of permanent deformation in subgrade and unbound granular layers were negligible.

Fatigue cracking, although less related to climate, did exhibit sensitivity to climatic inputs. Again, T+ and TV+ were the climatic factors with the greatest influence on fatigue cracking, and the sensitivity to T+ is greater.

IRI was predicted to experience little influence as the result of the 5% increase to all climatic inputs. This suggests that IRI is not sensitive to climatic factors. Similar observations have been made by Kim et al. (*2*). However, it seems likely that increasing precipitation can increase the road roughness according to experience (*22*). Interestingly, IRI tended to be more sensitive to TV+ than to T+, while for other distresses the sensitivity was usually reversed. It is known that IRI is consequence of the development of other distresses, including rutting, fatigue cracking and thermal cracking (*6*). Thus when other distresses are less, IRI should also be less.

After the prediction of pavement performance, the pavement service life was calculated. IRI, longitudinal cracking, transverse cracking, fatigue cracking, AC rutting, and total rutting were selected as criteria, which were the outputs of the MEPDG. The threshold values for these criteria are presented in Table 5:

TABLE 5 Thresholds for Pavement Distresses (*6*).

Terminal IRI (in/mi) :	172
AC Surface Down Cracking (Long. Cracking) (ft/mile):	2000
AC Bottom Up Cracking (Fatigue Cracking) (%):	25
AC Thermal Fracture (Transverse Cracking) (ft/mi):	1000
Permanent Deformation (AC Only) (in):	0.25
Permanent Deformation (Total Pavement) (in):	0.75

The results from Washington included 40 years of service life, which was the design life of the pavement. During this period, no predicted distresses in Washington reached their threshold values prior to 40 years. This occurred because the structure or/and material input for the MEPDG for the road in Washington was too conservative.

Results from Minnesota suggested that the most critical distress for the assumed pavement was IRI. It can be observed in Figure 3a that pavement service life was most affected by T+ and TV+, though the impact was not very significant. This is because IRI is not sensitive to climatic factors in the MEPDG, due to how IRI is calculated.

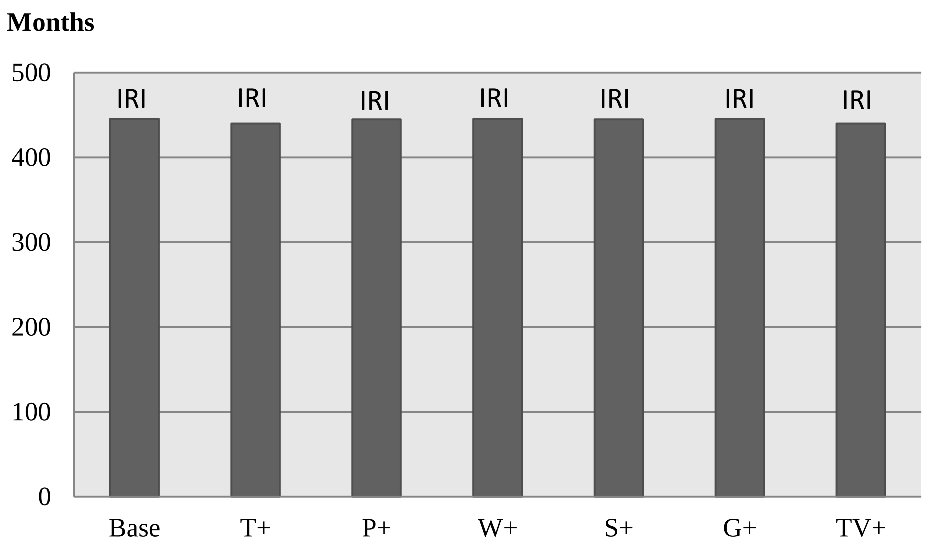

FIGURE 3a Pavement Service Life, Minnesota. *(T = temperature, P = precipitation, W = wind speed, S = percent sunshine, G = ground water level, and TV = temperature variation)*

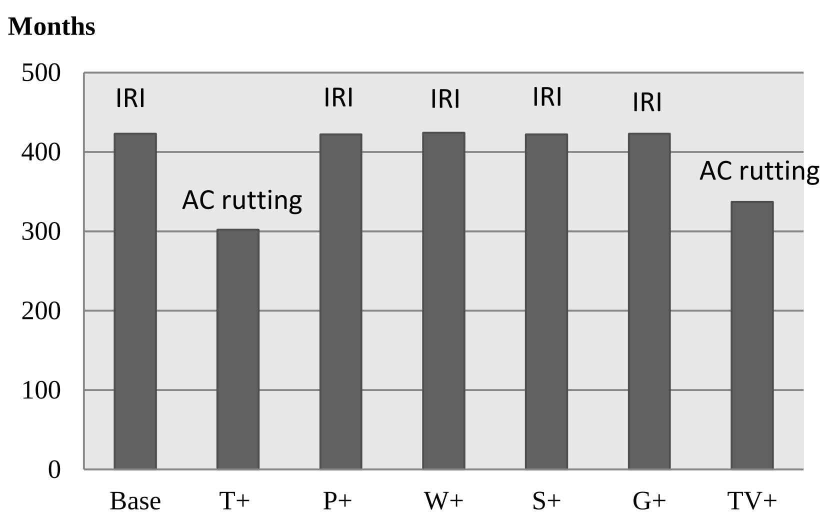

FIGURE 3b Pavement Service Life, Virginia. *(T = temperature, P = precipitation, W = wind speed, S= percent sunshine, G = ground water level, and TV = temperature variation)*

In Virginia, a significant reduction in pavement service life was found. T+ and TV+ (contributing to the development of AC rutting), make AC rutting the critical distress instead of IRI (Figure 3b). Due to T+ and

TV+, pavement service life was predicted to be reduced by 28% and 20%, respectively. This may be a result of the following:

1. As investigated, temperature is influential to rutting, especially AC rutting. An increase in the average annual temperature (+2.9 °F) adds more hot weather when large amounts of AC rutting occur. Similarly, an increased degree in temperature variation is comparatively lower (+1.725 °F) and adds hot weather only during the summer period.
2. The (AC) rutting curve tends to grow slower with constant strain rate during the phase of secondary creep (*23*) compared to the initial densification following the first few years of trafficking. When the propagation of rutting is slow, even a small increase could result in a significant reduction in pavement service life (see Figure 4).

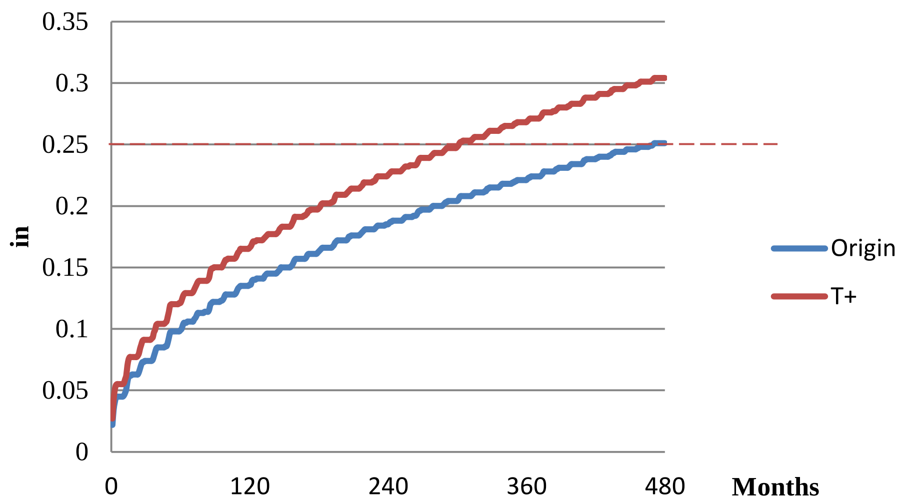

FIGURE 4 Prediction of AC Rutting in Virginia.

CONCLUSION AND DISCUSSION

Based on this study, the following conclusions can be drawn:

1. Temperature is the most influential climatic factor in the MEPDG for the three investigated cases. Temperature (both an increase in the annual average temperature and the seasonal variation) has a significant impact on pavement distresses, including longitudinal cracking fatigue cracking and (AC) rutting. Further investigation is needed to determine if temperature has significant impact on transverse cracking.
2. The pavement service life in Virginia case was found to experience a dramatic reduction (greater than 20%) due to a small (5%) increase in temperature and temperature variation. This occurred when (AC) rutting became a critical distress for the pavement maintenance threshold.

Although the results were based on a number of assumptions and simplifications, this study revealed the significance of the impact of climate change may have on the service life of flexible pavements. These changes may impact the pavement life cycle cost and thus their impact on future maintenance requirement should be investigated. Life-Cycle Costs analysis can help select the most economic mitigation methods and thus aid future road management.

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