Impact of Climate Change on Pavement Structural Performance in the United States

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Abstract

This study uses climate projections from multiple models and for different climate regions to investigate how climate change may impact the transportation infrastructure in the United States. Climate data from both an ensemble of 19 different climate models at both RCP8.5 and RCP4.5 as well as three individual prediction models at the same Representative Concentration Pathways (RCP) levels is used. These models are integrated into the AASHTOWare Pavement ME software to predict the pavement performance. Comparisons are made between the predicted performance with respect to typical pavement distresses using both historical climate data as well as climate projection data. Though there is substantial variation for different prediction models in terms of the magnitude of the impact, the consistency in results suggest that projected climate changes are highly likely to result in greater distresses and/or earlier failure of the pavement. This finding is consistent across all the climate zones studied, but varies in magnitude of 2-9% for fatigue cracking and 9-40% for AC rutting at the end of 20 years depending on the climate region of the pavement section and prediction model used. This study also compares the impacts incorporating temperature only projections with temperature and precipitation projections. In this respect, the sections considered in this study do not show any substantial difference in the pavement performance when the precipitation data from the climate predictions are also considered in the climate inputs into AASHTOWare Pavement ME software.

Keywords: Climate Change, AASHTOWare Pavement ME software, Pavement performance, CMIP5; Impact Assessment

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC, 2014) indicates that climate change poses a major risk to human life, nature, and the built environment. One component of the built environment that may be particularly prone to these impacts is the physical network of roads, bridges, railroad, and hydraulic structures that ensure efficient, safe, and reliable movement of people, goods, and services, i.e., transportation infrastructure. The components of this system are particularly prone to climate since they are constantly exposed to the natural environment. When these components fail they may cause substantial loss of user productivity as repairs can often take days to months depending on the magnitude of the disruption. Even when full closures are not needed for repairs, the losses can be substantial with work zones contributing to nearly 17% of non-weather related congestion in the US (Chin et al., 2004). Considering that roads and highways allowed Americans to travel more than 3 trillion vehicle trip in the year 2015 (USDOT, 2015), the nation's roadway infrastructure is clearly a major contributor to the development of the US economy.

In 2008, the National Cooperative Highway Research Program (NCHRP) evaluated how climate change might introduce hazards to transportation infrastructure. These hazards were described in broad terms across all transportation modes, but encompassed a range of potential impacts from increased shipping seasons in cold weather ports to operational challenges due increased coastal and inland flooding events (Humphrey, 2008). With respect to pavements this report suggested that future increases in very hot days and heat waves may lead to concerns with pavement integrity. They also recognized that changes in subgrade moisture levels (either by changes to the water table depth or through precipitation) could alter the bearing capacity and thus performance of this infrastructure, and conclude that the typical design scope for pavements (10-20 years), may help to mitigate these impacts.

While the findings from the NCHRP are enlightening, they do not quantify the potential impacts from moisture and temperature changes on pavement performance. Reviews of other studies on climate change impacts reveals some gaps in accurately quantifying the impacts using distresses directly. For example, Anderson et al. (2015) quantify the potential impact to Arizona transportation infrastructure using the number of projected days above 38°C. This approach is not addressing the fact that pavements are designed with materials specific to the location in which they are placed and thus the number of days above a single fixed temperature does not indicate the impacts fairly across areas that are already climatologically diverse. In addition, Anderson et al. (2015) do not account for the interactive impacts of soil conditions, traffic, and structure. In another study involving the state of Texas, researchers recognized the difference in materials across regions, but did not project how an increase in temperature might affect performance with respect to the continuation of historical trends (Cambridge Systematics, 2015).

Chinowsky and Arndt (2012) developed an economic dynamic-stressor model based on empirical performance impacts from precipitation and temperature). These models reflect, but do not predict the precise impact of climate change on materials. This approach has been codified into a planning system and used extensively to assess the economic impacts of climate change on pavement infrastructure (Schweikert et al., 2014). A limitation in these network level analyses is that they ignore the actual engineering details of the infrastructure. They essentially overlay climate variables in terms of changes in temperature and/or precipitation on top of the existing infrastructure and identify where the two (infrastructure and climate change) intersect. Such an approach does not account for the fact that the pavement performance is a cumulation of many interactive factors (materials, structures traffic, and climate).

An engineering analysis was completed by Daniel et al. (2014) to evaluate the impact of climate change on the performance of New England pavements. Climate prediction data was incorporated into the pavement design process and results were compared with design/analysis completed using the historical data. The study concluded that climate change predictions may have a substantial effect on pavement distresses, specifically that pavement life may decrease from between 16 years to 4 years and maintenance cost may also increase by 100%. Meagher et al. (2012) used climate change projections from the North American Regional Climate Change Assessment Program to evaluate designs of flexible pavements in New England. In this study the authors used only temperature data and found that changes in alligator cracking for secondary and interstate pavements was negligible but for the increase ranged from 4% to 16% depending on the precise location. Other studies have concluded that rutting and pavement failure occurs much earlier than anticipated leading to the frequent new construction and maintenance of roadway infrastructure (Harvey et al., 2004, Mills et al., 2009, Mndawe et al., 2013).

Most of these studies mentioned above focus on temperature data alone from the climate prediction models to study the impact of climate change on the pavement performance. However, two recent studies used changes in precipitation levels along with temperature data from climate prediction models and reported that climate change shows significant impact on the pavement life (Heitzman, 2011, Mndawe et al., 2015). These studies integrate both temperature and precipitation data, but do not indicate whether one or the other factors has a greater impact. Very little data is found isolating the impact of precipitation. Many of the studies that exist echo that of Gaspard et al. (2007), which studied pavements performance after Hurricane Katrina and found that pavements submerged during the hurricane were weaker than the ones that were not. In case of flexible pavements, the damage observed is more than the damage observed for rigid pavements.

Overall, existing evidence suggests that climate change will impact the performance and maintenance of the pavement infrastructure. However, there are some limitations in the existing literature:

1. Most of the existing studies are limited to one pavement structure, location, and/or one climate region. Even taken collectively the literature uses dissimilar models and other underlying assumptions making it impossible to gain a comprehensive view of impacts,
2. Most current studies focus on one or maybe two climate models and do not include different potential emission scenarios in the analysis, thus it becomes very difficult to infer or ascertain the certainty/uncertainty in the predicted outcome, and
3. Current studies do not identify the relative significance of projected temperature versus precipitation on predicted pavement performance.

The primary objective of the research is to predict the performance of freeway sections in different climate regions across the United States and for different climate models and in so doing address the gaps in the literature. Then, using these results in conjunction with performance predicted using historical climate data, quantify the impact of incorporating projected climate data.

2. Methodology

The overall approach followed in this study is shown in Fig. 1. As seen in this figure the methodology involves conducting multiple pavement performance predictions using the, AASHTOWare Pavement ME software, to predict and compare the long-term behaviors of pavements under either historical or projected climate scenarios. Simulations using the historical database are referred to as the baseline cases, while those using the climate model data are referred to as the future cases. As detailed below, these future cases include representative concentration pathways (RCPs) 8.5 and 4.5 and multiple sections of real in-service pavements. In total sixteen different future climate cases are considered;

- Average of 19 models at RCP8.5 with temperature and with temperature + precipitation,
- Average of 19 models at RCP4.5 with temperature and with temperature + precipitation,
- MIROC-ESM at RCP8.5 and RCP4.5 with temperature and with temperature + precipitation,
- CCSM4 at RCP8.5 and RCP4.5 with temperature and with temperature + precipitation, and
- MRI-CGCM3 at RCP8.5 and RCP4.5 with temperature and with temperature + precipitation.

Performance projections for the baseline and each of the sixteen future cases were carried out using five different interstate locations; I-10 in Arizona (I10-AZ), I-90 in Montana (I90-MT), I-95 in Maine (I95-ME), I-64 in Virginia (I64-VA), and I-65 in Indiana (I65-IN). These locations have bene chosen to represent different climate regions and because the respective states have calibrated the AASHTOWare Pavement ME models for their state/region. The analysis period in each simulation was 20 years in deference to standard practice.

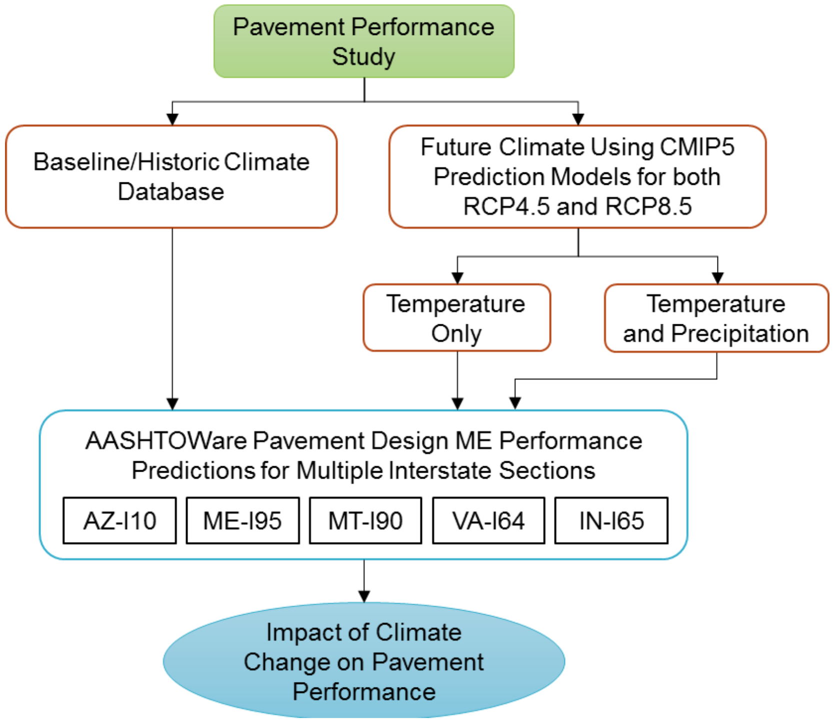


Fig. 1. *Framework for assessing the impact of climate change on the pavement performance.*

The present (baseline) scenario was evaluated by using the climate files that exist within the Pavement ME software. Future scenarios are evaluated using the average of a multi-model ensemble of 19 different 12 km downscaled Global Climate Models (GCMs) as well as three of the individual models from this ensemble (Brekke et al., 2013). Table 1 shows 19 models used for ensemble climate projections in this study. The models chosen participated in the CMIP5 project and had both RCP8.5 and RCP4.5 downscaled data. During the Coupled Model Intercomparison Project Phase 5 (CMIP5), the IPCC established RCPs approach to consider future climate change in terms of policy decisions (IPCC, 2007). The RCPs are four greenhouse gas concentration trajectories, but the two most often used are; 1) RCP8.5, which corresponds to a high greenhouse emissions pathway and is the upper limit of all RCPs (Riahi et al., 2011) and 2) RCP4.5, which is a scenario that assumes radiative forcing stabilizes by 2100 (Thomson et al., 2011). These two scenarios are chosen to encompass ranges of likely future scenarios where RCP8.5 assumes essentially no abatement of emissions and RCP 4.5 assumes intervention policies that result in greenhouse gas emissions reducing near mid-century. Many climate scientists agree that pathways below 4.5 are now unlikely (Knutti and Seldacek, 2013, Schleussner et al., 2014, Makin et al., 2015) and so RCP4.5 serves as a lower bound estimate of climate change outcomes while RCP8.5 serves as an upper bound estimate.

Table 1 *Climate prediction models considered for extracting temperature and precipitation data from CMIP5 database.*

Modeling Center (or Group)	Institute ID	Model Name
Commonwealth Scientific and Industrial Research Organization (CSIRO) and Bureau of Meteorology (BOM), Australia	CSIRO-BOM	ACCESS1.0
Beijing Climate Center, China Meteorological Administration	BCC	BCC-CSM1.1
Canadian Centre for Climate Modeling and Analysis	CCCMA	CanESM2
National Center for Atmospheric Research	NCAR	**CCSM4**
Community Earth System Model Contributors	NSF-DOE-NCAR	CESM1(BGC)
Centre National de Recherches Météorologiques / Centre Européen de Recherche et Formation Avancée en Calcul Scientifique	CNRM-CERFACS	CNRM-CM5
Commonwealth Scientific and Industrial Research Organization in collaboration with Queensland Climate Change Centre of Excellence	CSIRO-QCCCE	CSIRO-Mk3.6.0
NOAA Geophysical Fluid Dynamics Laboratory	NOAA GFDL	GFDL-ESM2G GFDL-ESM2M
Institute for Numerical Mathematics	INM	INM-CM4
Institute Pierre-Simon Laplace	IPSL	IPSL-CM5A-LR IPSL-CM5A-MR
Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute, and National Institute for Environmental Studies	MIROC	**MIROC-ESM** MIROC-ESM-CHEM MIROC5
Max Planck Institute for Meteorology	MPI-M	MPI-ESM-LR MPI-ESM-MR
Meteorological Research Institute	MRI	**MRI-CGCM3**
Norwegian Climate Centre	NCC	NORESM1-ME

For each model, the daily maximum and minimum temperatures and average monthly precipitation data were extracted. Climate files for each model were downloaded from the Climate Analytics website. There, downscaling of temperatures were performed per the daily bias-correction and constructed (BCCA) analogs method (Brekke et al., 2013), while precipitation data was downscaled per the Bias-Correction Spatial Disaggregation (BCSD) method (Maurer et al., 2007). Although projections are available spanning the period from current day through 2100 only the period from 2040 through 2060 was considered in this study to evaluate the impact of climate change in future for a span of approximate pavement design life. This timeframe was chosen to estimate the mid-century impacts and encompass a period of time where impacts (if they existed) would be evident. Also, beyond mid-century, the uncertainty inherent in the GCMs becomes very large and therefore meaningful conclusions become more difficult to attain. The data itself was downloaded from the archives of the Climate Analytics Group (Brekke et al., 2013). The three models chosen for individual predictions were MIROC-ESM, CCSM4, MRI-CGCM3. These three models were chosen for specific reasons. The first was that they fell into different clusters of GCMs based on their simulation fields as defined by Knutti et al. (2013). The second was that after study of individual model predictions in several different geographical locations, these three models were found to approximate high-temperature, median-temperature, and low-temperature growth scenarios. This finding generally agreed with those from others as well (Adaptwest, 2016). It may be argued that these models do not accurately reflect North American conditions, since for example the MRI model originates in Japan. However, here the approach suggested by climatologists and articulated by Knutti et al. (2013) is adopted wherein each individual model is itself a representative sample of a future scenario given uncertainties and limitations in observations, imprecise or imperfect understanding of all individual and interactive physical mechanisms, and limited computational resources. As such the ensemble, itself (inclusive of all models), serves as the first order approximation of future uncertainty and any individual model that aligns at one end or the other of the ensemble can be extracted to bracket the outcomes.

2.1. Performance Prediction Process in AASHTOWare Pavement ME Software

In this study AASHTOWare Pavement ME software is the primary analysis tool to assess the impacts of climate on pavement performance. There is substantial literature on the development of this model and interested readers are referred to the final reports of the NCHRP 1-37A research project for more details (ARA, 2004a, b, Pierce and McGovern, 2014, Darter et al., 2014). In short, the models incorporate four primary categories of inputs for the analysis process; material properties (soils and paving materials), structural design, traffic (both loads and numbers), and climate. These inputs are specific to the pavement or location being evaluated. In this study, the structural details and inputs were obtained from actual in-service pavements using the Long-Term Pavement Performance (LTPP) program database. Traffic levels for these sections were estimated from National Highway Planning Network (NHPN) database (NHPN, 2015). Soil data was obtained from the NCHRP 9-23B database (Witczak et al. 2006), and other relevant inputs were taken from state agencies. With respect to climate, the software uses hourly air temperature, wind speed, percent sunshine, precipitation, and relative humidity for analysis purposes. These data are stored in climate files that are read by the software at the time of analysis. These climate files generally contain five to ten years of climate data beginning around the mid 1990's. For analysis, the climate data is assumed to remain stationary throughout the entire design life and thus when analysis period exceed the extent of the climate record, the software simply reuses the same climate data repeatedly. The relevant details of these sections are shown in Table 2.

Table 2. *Pavement Design ME input parameters used for the interstate flexible pavement sections*

Input Type	Variable	AZ _I10	ME_I95	MT_I90	VA_I64	IN_I65
Traffic	AADTT[1]	7089	4860	2543	17750	11800
	Lanes	2	2	2	2	2
	Speed (mph)	75	75	65	70	70
Climate	Elevation (m)	455	15	1350	190	240
	Location	Phoenix, AZ	Portland, ME	Bozeman, MT	Charlottesville, VA	Indianapolis, IN
Layer 1- AC	Thickness (cm)	35.3	23.6	19.8	21.6	25.4
	Density (kg/m^3)	2370	2370	2370	2370	2370
	P_{be} (%)[2]	4.6	5	4.5	5.8	5
	Va (%)[3]	5.3	5	4.9	5.6	7
	Asphalt	AC 40	AC 20	PG70-28	AC 20	AC 20
Layer 2- Aggregate Base	Thickness (cm)	15.2	83.8	83.8	13	11.7
	Modulus (MPa)	210	210	210	210	210

Subgrade	Modulus (MPa)	115	115	80	80	90

[1]AADTT = Two way annual average daily truck traffic, [2]P_{be} = Effective asphalt cement content by mass, [3]V_a = Air void content

The software estimates the pavement performance by individually predicting the initiation and growth of several key distresses. The predictions essentially involve a three-step process. First, layered elastic models are used to predict the stresses and strains in the pavement structure due to surface loads. These predictions are performed for all relevant combinations of axle load, axle type, wheel location, and season/sub-season that exist over the course of design life. Next, the response strains are used in semi-empirical performance models to estimate the amount of damage that occurs due to the loads. For fatigue, the damage from each axle load, axle type, wheel location, and sub-season combination is quantified using the ratio of the number of cycles applied at that combination to the number of cycles that would result in pavement failure. The cumulative damage is obtained by mathematically summing the individual damage factors in accordance with the linear accumulation law. Other definitions of damage exist for rutting (with flexible pavements), transverse cracking in rigid pavements, and faulting in rigid pavements. One important factor that needs to be mentioned, and was considered in this study is that the performance models were calibrated to the local/regional conditions. Studies have shown that there is a large difference in the damage prediction from between real pavements and predicted pavements when only the national calibration factors are used (Banerjee et al., 2009 and Banerjee et al., 2010). Finally, the damage is linked to distress via empirical functions calibrated to actual field performance.

Since the initial development of this method, several studies have been conducted at both national and state levels to calibrate and validate the performance models used therein. (Von Quintus and Moulthrop, 2007, Momin, 2011, Daniel et al., 2012, Kim et al., 2013, Pierce and McGovern, 2014, Smith and Nair, 2015, Tian, 2016, Banerjee et al., 2010). In this study, local design calibration factors (from the respective states) were input in the project files during the analysis process to provide the most accurate analysis results possible. This study uses the AASHTOWare Pavement ME software due to its relatively widespread usage, its national scope at the development phase, and because calibration factors are available for many different-locations. The outputs of interest for flexible pavement analysis are the fatigue cracking and rutting, while transverse cracking and faulting are the primary distresses for rigid pavements.

It should be mentioned here, that while the Pavement ME software explicitly considers the interactive factors that affect pavement performance, scientific proof that this method provides the most accurate estimation of pavement performance does not exist. In fact, there is a strong argument that can be for empirical models, like the ones used by Chinowsky and Arndt (2012) and Schweikert et al. (2014) that have been calibrated on large sets of data. Often the statistical rigor with which these methods assess performance exceeds that of mechanistic-empirical models (Banerjee et al. 2009, 2010). Thus, while it is the authors' opinion that the ME model provides a more accurate assessment of climatological changes on pavement since it explicitly separates material selection and climate (empirical models most often implicitly group material decisions and climate together), this belief is not rigorously confirmed.

2.2. Processing Climate Projections

The future climate projections included daily maximum and minimum temperatures and monthly precipitation geospatially arranged in 12 km square blocks for the years 2006-2100. A

MATLAB script was developed to automate the data extraction for only the years 2040-2060 and to perform geospatial interpolation for the block that was closest to the relevant weather station. Once the daily maximum and minimum temperature and monthly precipitation were extracted, the historical weather data was then obtained from the climate databases held in the AASHTOWare Pavement ME software. Since this analysis requires hourly temperature and precipitation data, and not just daily maximums and minimums or monthly averages, additional processing was needed.

The Modified Imposed Offset Morphing Method (M-IOMM) was adopted (Belcher et al. 2005, Sailor, 2014) to create the future projected hourly data. The standard IOMM method shifts and stretches given hourly temperature data based on the predicted monthly mean temperature. In this study, since projected daily maximum and minimum temperature values are available the IOMM was modified. Historical data was first extracted and from this data the 20 years of daily temperature variation was obtained. To create the hourly climate data file for the future cases from this data the following procedure was used for each pavement section and for each of the 16 future cases in this study.

1. Daily minimum and maximum temperatures (T_{BMin} and T_{BMax}) were extracted from the historic climate database for each day of the 20 Year record.
2. Daily minimum and maximum temperatures (T_{FMin} and T_{FMax}) were extracted from the given projected climate data for each day of the 20 Year record (2040-2060).
3. The difference between the daily maximum and minimum temperatures for each day of the 20 years was calculated for both the historic climate data (T_{BMax}- T_{BMin}) and the predicted climate data (T_{FMax} - T_{FMin}).
4. Predicted hourly temperature (T_{iF}) was calculated using the hourly distribution of historic temperature (T_{iB}) and predicted maximum and minimum temperature, with Equation (1)

$$T_{iF} = \frac{(T_{FMax} - T_{FMin})}{(T_{BMax} - T_{BMin})} \times (T_{iB} - T_{BMin}) + T_{FMin} \quad (1)$$

For the cases where only temperature projections were considered the remaining climate input parameters (Wind Speed, Percent Sunshine, Precipitation and Relative Humidity) were taken from the historic climate files. However, for some cases precipitation projections were also included into the climate file. To create hourly precipitation data, the IOMM approach was adopted by combining the hourly precipitation data from the historical record with the monthly average precipitation rate from the future cases. The following step-by-step procedure was adopted.

1. Cumulative monthly rainfall for the baseline case was extracted and used to calculate an average daily precipitation rate for the respective month.
2. Average daily precipitation of each month was calculated from the historic climate data base.
3. Average daily precipitation of each month (was extracted from the given climate projection.
4. The hourly rainfall for future (was calculated using the Equation (2).

$$R_{iF} = \left(\frac{(R_{FMAvg} - R_{BMAvg})}{R_{BMAvg}} \times R_{iB} \right) + R_{iB} \quad (2)$$

The hourly precipitation data calculated for future years from the above procedure was then input to the temperature modified climate database along with other climate input parameters (Wind Speed, Percent Sunshine, and Relative Humidity) to create a future case climate files. It should be noted that this analysis does not consider certain climate stressors that may affect pavement performance and these are acknowledged. For example, depth to water table changes due to sea level rise (Knott, 2017), soil expansion/contraction due to both long-term and short-term water variations (Lytton, 1994), and extremes in daily temperature variation are not explicitly considered within the analysis framework.

3. Pavement Performance Study Analysis and Results

3.1. Impact on Flexible Pavements

Typical results from the AASHTOWare Pavement ME D simulation process are shown for the Arizona site and for the baseline and RCP8.5 future cases in Fig. 2. The results are compiled for the three distresses of fatigue cracking, rutting in the asphalt concrete (AC) layer only, and total rutting for the entire pavement cross-section. From this figure, it is observed that irrespective of the predictive model, the distresses observed in the pavements are increasing when compared to the baseline. Although it is not shown here, similar observations are made from the other locations and for RCP4.5 cases as well.

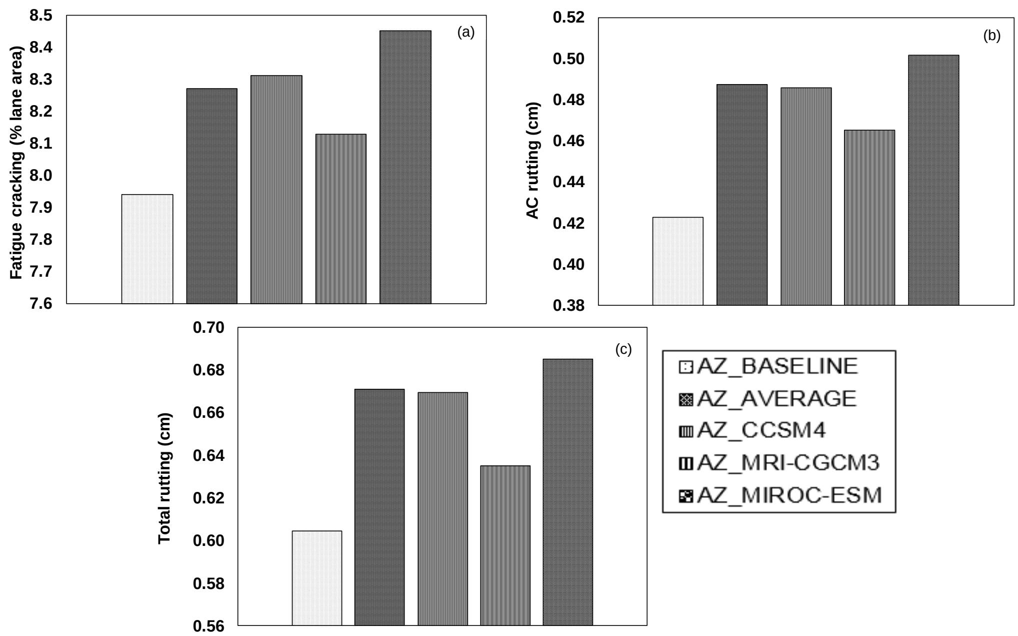


Fig. 2. *Pavement distress comparison across baseline and future climate prediction models for AZ section (a) Fatigue cracking, (b) AC layer rutting and (c) Total rutting.*

To compare each case more effectively a percent difference increase function (*DI*), Equation (3) is defined.

$$DI = \frac{(Future\ scenario\ pavement\ Distress - Baseline\ scenario\ pavement\ distress)}{(Baseline\ scenario\ pavement\ distress)} \times 100 \qquad (3)$$

Using this definition for the data in Fig. 2, the predicted impact of the climate projections is a 2-7% increase in the fatigue cracking, an 8-20% increase in the AC only rutting, and a 5-25% increase in total rutting at the end of the 20-year analysis period depending upon the model considered. The data in Fig. 2 shows that there is considerable uncertainty in the range of predicted effects from temperature change. Thus, it is necessary to consider the impacts of climate change stochastically. Pavement performance results obtained after using different climate projections for both RCP4.5 and RCP8.5 are shown in the form of Box-and-Whisker plots. Climatologists are clear to not assign individual probabilities to the RCP scenarios and thereby consider them all as equally likely outcomes depending on technology as well as government and individual choices. Thus, in this study the results obtained from both scenarios are grouped together in order to estimate the certainty or uncertainty in climate projection impacts. The Box-and-Whisker plots are used to demonstrate this uncertainty. The box is bounded by the first (25^{th} percentile of the results) and third (75^{th} percentile of the results) quartiles of the projections while the median is shown as a horizontal line in the interior of the box. The maximum and minimum values are shown as the error bars extending vertically from the box.

Fig. 3 shows the variation of pavement performance in terms of percentage difference in fatigue cracking, AC rutting and total rutting across the five pavement sections considered in this study for the case where only temperature is adjusted. The first notable observation is that in the case of fatigue cracking, the Montana section (MT) shows very high difference relative to the other sections. However, after careful study it was observed that in the case of MT the fatigue cracking at the end of design life in the baseline scenario is very low (4.5%), which magnifies the true difference. In the most extreme model prediction this fatigue cracking increases to 7.3%, which is still considered a relatively small amount of fatigue cracking. To confirm this observation, the section was analyzed again by changing the pavement thickness so that at the end of the design life the pavement experienced more fatigue crackling in the baseline case. In this case, it is in fact found that the percentage increase in fatigue cracking from the climate models is in line with the rest of the sections. To be able clearly see the percentage increase in fatigue cracking, the rest of the four sections are plotted separately and shown in Fig. 3 (c). In the case of AC rutting and Total rutting, the percentage increase in distress is more stable across all climate locations with fatigue cracking increase ranging from 2-11%, AC layer rutting from 9-45% and total rutting from 5-34% depending on the prediction model and climate location.

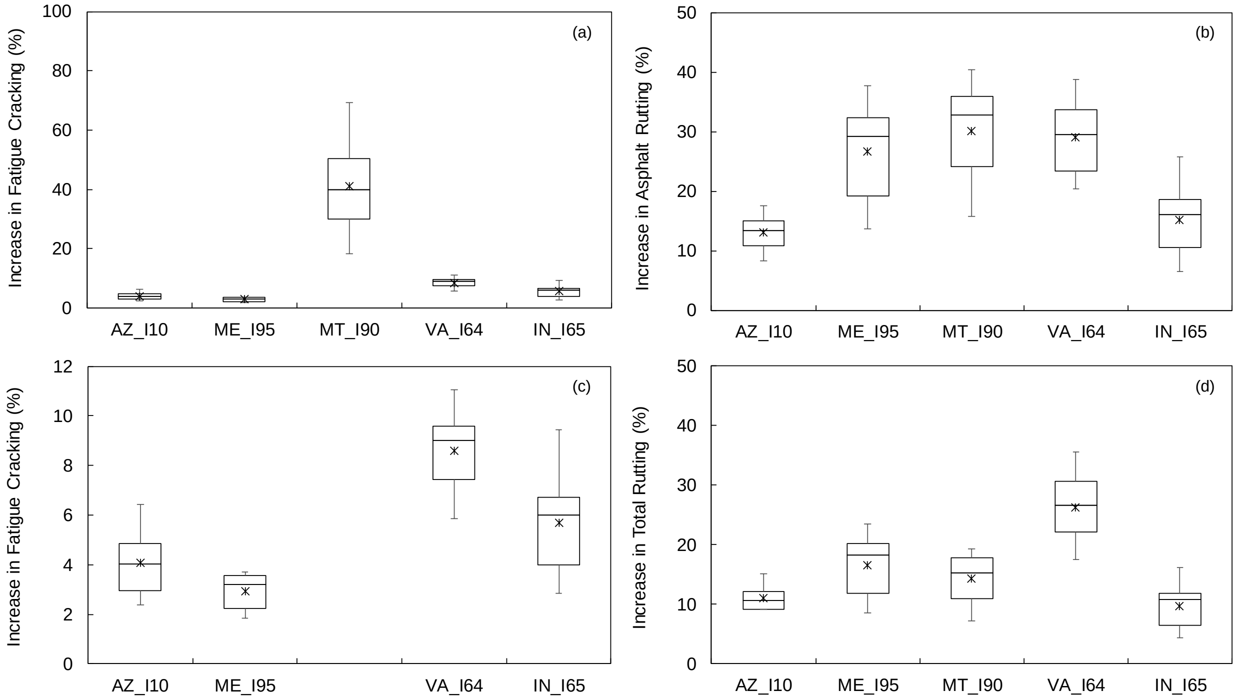


Fig. 3. *Variation of percentage difference across climate prediction models for study locations using only temperature data from predictions for; (a) fatigue cracking, (b) AC layer rutting, (c) fatigue cracking (for 4 locations), and (d) total rutting.*

One important observation made from the results is that the percentage increase in rutting is more when compared to fatigue cracking, which is intuitive as rutting is largely a top of the pavement phenomenon where pavement temperatures due to climate change are expected to be the greatest. Conversely, fatigue cracking (as it is considered in the analysis model) is largely a bottom-up phenomenon where the thermal mass of the pavement structure provides some additional protection against future warming. In addition to percentage increase the figure also shows that the variation of percentage increase (difference between first and third quartiles) in both fatigue cracking and rutting varies across the different climate zones. All locations are showing substantial variation in the results however this variation is observed to be much more for Montana and Virginia as percentage increase in the distresses due to climate change is also high in these regions.

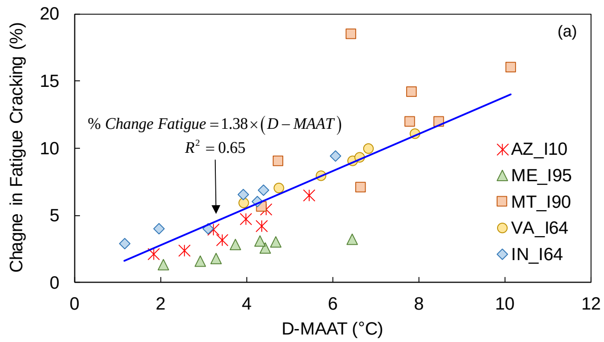
It is found that the impact of temperature changes can be approximated, at a first order level, by observing changes in the mean annual air temperature. For rutting the changes in performance showed greater correlation to the percentage change in mean annual air temperature (*N-MAAT*), Equation (4), than the direct change in temperature, Equation (5).

$$P-MAAT=\frac{\left(MAAT_{Future\ Scenario}-MAAT_{\mathrm{Baseline}\ Scenario}\right)}{\left(MAAT_{\mathrm{Baseline}\ Scenario}\right)}\times 100 \tag{4}$$

$$D-MAAT=\left(MAAT_{Future\ Scenario}-MAAT_{\mathrm{Baseline}\ Scenario}\right) \tag{5}$$

where; *MAAT* = mean annual air temperature, *P-MAAT* = percentage change in *MAAT*, *D-MAAT* = change in *MAAT*, $MAAT_{Future\ Scenario}$ = the *MAAT* from a given climate model, $MAAT_{Baseline\ Scenario}$ = the *MAAT* for the baseline scenario. It is recognized that other climate factors may exist which provide similar or even better correlations. Mallick et al. (2017), for example, adopted the maximum air temperature and its rate of change over time. However, here, only these two climate factors are considered as discussed below.

Fig. 4(a) shows how the predicted asphalt concrete layer rutting increases (as a percentage of the rutting predicted in the baseline scenarios) as a function of *N-MAAT*. The use of this climatic parameter suggests that with rutting it is the increase in temperature relative to the current temperature that will be most likely to cause detrimental performance. It is suspected that type of correlation exists because the materials are already engineered differently in locations with high-temperatures (e.g., the use of mixtures with larger stone and more stone-on-stone contact in Arizona). While material properties are an explicit input to the pavement analysis tool, not all factors are considered and local calibrations implicitly embed many of these differences into the prediction algorithm. Overall the correlation is high (R^2 = 0.88), but there is scatter, which can be attributed to differences in latitude (e.g., angle of incidence with short-wave radiation) and the fact that the correlation variable is a simple function of the annual air temperature change (recall this function is only expected to represent the first order approximation of performance correlation).



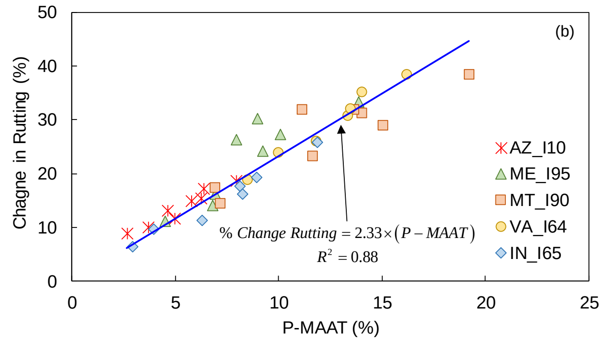


Fig. 4. *Correlation between change in pavement performance and climate indicators; (a) rutting and N-MAAT and (b) fatigue cracking and D-MAAT.*

With fatigue, the greatest correlation was found between the change in predicted cracking and *D-MAAT*, Fig. 4(b). This correlation may be a consequence of the fact that fatigue cracking correlations are more difficult to establish during local calibration and many agencies have relied on national calibration with or without some small adjustments. The lower correlation is also expected in the case of fatigue cracking because of the interactive relationship between cracking, structural configuration, and the level of anticipated pavement. Indeed, it is seen that the Maine simulations deviate from the correlation systematically and this may be attributed to the fact that the Maine pavement is very thick (total structural pavement thickness of 107.4 cm, but carries relatively little traffic. This discrepancy suggests that overdesign of a pavement structure under certain climatic conditions serves as one mitigating strategy against climate change influences on fatigue cracking, but less so with respect to asphalt concrete layer rutting. The Montana pavement, and the existence of the single point that is far above the correlation line (the CCSM4-RCP4.5 scenario) correlation also sheds light on another important aspect of pavement performance that the simple mean annual air temperature based correlations do not capture. As a rule, pavement performance does not degrade uniformly throughout the year. In fact, the performance algorithms embedded into the Pavement ME Design model suggest that pavement distresses grow faster during the warmer months than the cooler months, and that within these months it is the hottest part of the day that exhibits the greatest damage. Thus, predicted changes in not only the mean annual temperature, but also the timing of when projections will tend to be higher (e.g., greater or less warming in the summer versus the winter) will also affect performance.

To prove this effect, the first order approximation between change in fatigue cracking and *D-MAAT* is supplemented with a supposed second effect from the temperature differences between the square of the fifth quintile air temperature differences for July (Δ*Q*5-*July*) from the baseline and future scenario cases is considered. Note, that the fifth quintile air temperature represents the temperature that is greater than 80% of all air temperatures within the month. When incorporating the change in temperature from the fifth quintile from the month July, the correlation for this model begins to look more consistent across the models, see Fig. 5 which shows R^2 increases from 0.59 before including the fifth quintile temperature differences and 0.72 after its inclusion). Note that the x-axis is labeled as "Observed Change in Fatigue Cracking (%)", which are the changes in cracking based on the AASHTOWare predicted fatigue cracking. The y-axis is labeled as "Predicted Change in Fatigue Cracking (%)", which are the values predicted by either of the equations shown on the plot. Again, the relationship is not perfect, but it is not expected to be and the improvement in relationship is simply shows that identifying the impact from projected climate changes must examine not only the mean annual air temperature increases, but also the changes that occur at different times of the year. What is most striking about these correlations are that they suggest that performance is not only positively correlated to the temperature change, but correlated such that differences in performance are magnified with respect to temperature changes (e.g., the slope of the relationships is greater than one).

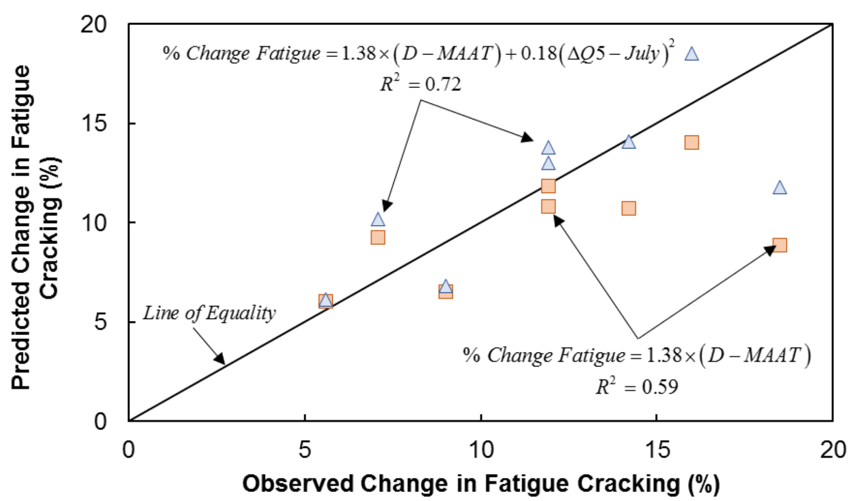


Fig. 5. *Comparison of performance correlation when including Q5 temperature changes.*

These first order approximations have been applied to estimate the potential national impacts from future climate change. Baseline temperatures are extracted for each of the 808 weather stations available in the AASHTOWare Pavement ME Design software for the contiguous US. Climate projects are then extracted from the ensemble of 19 models for each of these locations and averaged. Here, only the average RCP 8.5 case is presented as it shows a slightly above median estimate of the impacts. Fig. 6(a) presents the projected impacts with respect to fatigue cracking and Fig. 6(b) presents those associated with rutting. In both, the values shown are the percentage increase in distress (fatigue cracking or rutting) that could occur if assumptions of climate stationarity continue. As expected the effects are more pronounced in rutting than in fatigue. The overall trend is similar with greater impacts to both fatigue and rutting expected in the northern latitudes (particularly the upper mid-west and northeast areas). Some small pockets of high impact are projected in the southern Nevada and Idaho-Montana/Idaho-Washington border areas, but this may be due to the presence of micro-climatic regions that are common in the western United States coupled to spatial sparse weather stations and imprecision in the downscaling algorithms, which may not reflect likely future events. In these cases, more careful study with better scaled and more regionally valid models may be needed to draw more accurate conclusions. With fatigue cracking a smaller overall impact is projected and some differences in relative scale are also observed.

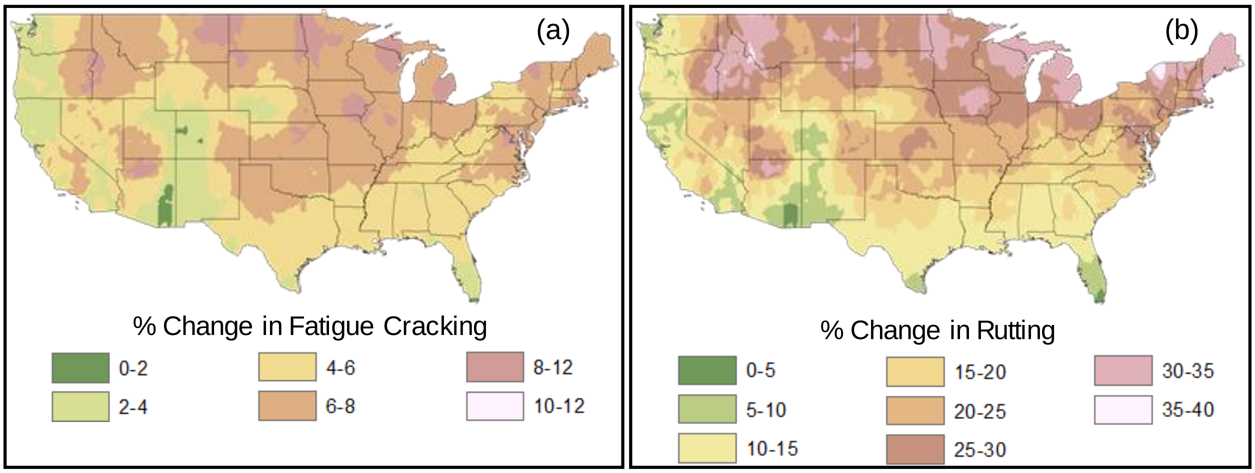


Fig. 6. *Projected national impacts from 2040-2060 climate change projects; (a) fatigue cracking and (b) rutting.*

It should be kept in mind that the maps in Fig. 6 represent only the potential for impacts as they do not consider the extent of the current transportation network, the types of roadways present, and the other second or third order effects that may be present. They also do not account for the real-world processes that go into engineering and maintaining pavements over time. Additional analysis similar to that presented elsewhere that incorporates the extent of the transportation infrastructure in place and/or the volume of traffic carried would be needed, but is beyond the scope of the current study (Espinet, 2016; Mallick et al. 2016; Schweikert et al. 2014).

Similar comparisons were made from the results when both projected temperature and projected precipitation data were included, see Fig. 7. The trends observed in this case are also in line with the temperature only case. Comparing Fig. 5 and Fig. 7 it is observed that the inclusion of the precipitation data does not substantially affect the pavement distresses for all the climate locations. The key exception to this case is the fatigue cracking in the MT location. While the average percentage change in the fatigue cracking and AC rutting with the incorporation of precipitation projections into the analysis was only about 1-2% for the other locations (and mainly in VA_I64 and ME_I95), the difference for the MT case is approximately 16-18%. The reason for such a striking difference largely lies in the small amount of cracking that was observed for the MT pavement (baseline cracking = 4.3%). Thus, while the percentage change is high, the actual differences between the cases is small. Among the remaining four pavement locations Maine is showing a higher difference in the increase of fatigue crackling when precipitation prediction data is also used from the prediction models. Even though it is not shown in the graphs similar observations are made with respect to AC rutting.

As with the temperature effects, these changes can be approximated at the first order by using simply the projected change in precipitation. In this case, the percentage change in mean annual precipitation (P-MAP), Equation (6), is used to track climatic changes.

$$P - MAP = \frac{\left(MAP_{Future\ Scenario} - MAP_{\mathrm{Baseline}\ Scenario}\right)}{\left(MAP_{\mathrm{Baseline}\ Scenario}\right)} \times 100 \qquad (6)$$

where; *MAP* = mean annual precipitation, $MAP_{Future\ Scenario}$ = the *MAP* from a given climate model, $MAP_{Baseline\ Scenario}$ = the *MAP* for the baseline scenario.

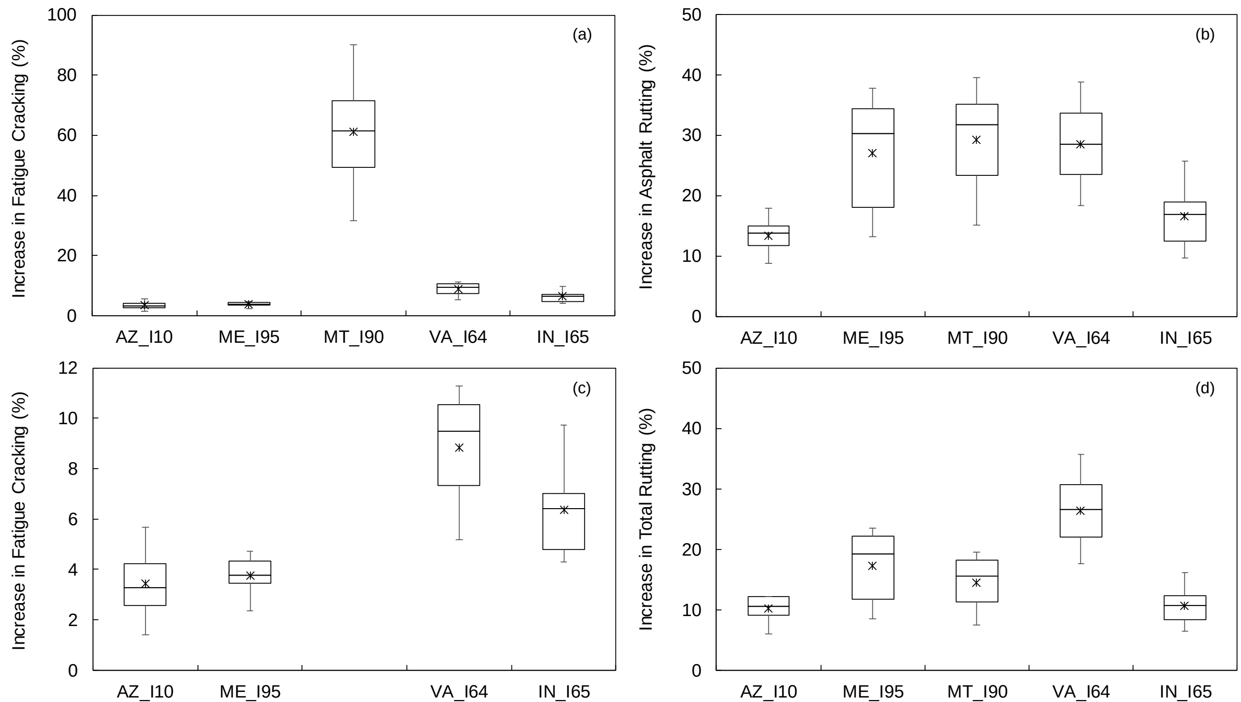


Fig. 7. *Variation of percentage difference across climate prediction models for study locations using both temperature and precipitation data from predictions for; (a) fatigue cracking, (b) AC layer rutting, (c) fatigue cracking (for 4 locations), and (d) total rutting.*

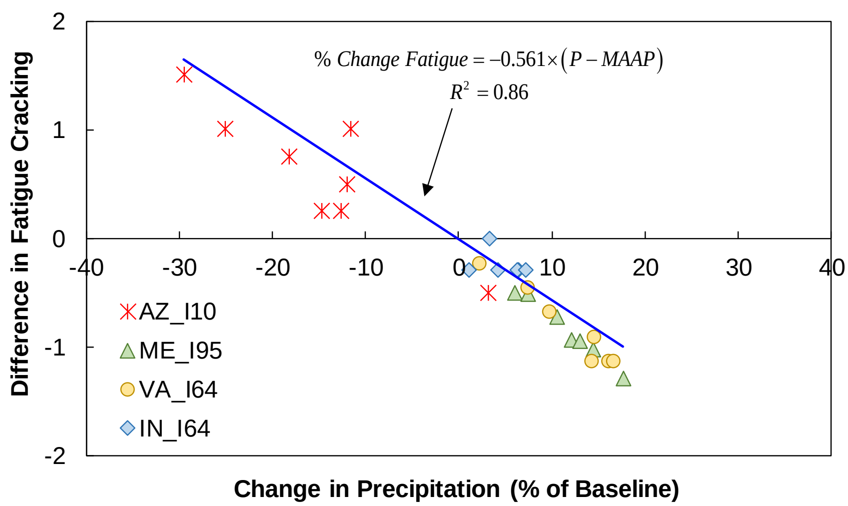


Fig. 8. *Correlation between change in fatigue cracking and P-MAP and fatigue cracking.*

The change in fatigue cracking and asphalt concrete rutting with precipitation inputs are assessed by comparing the resultant distresses from predictions that include both temperature and precipitation changes with those from the same predictions using only temperature. Results of the analysis are summarized for the fatigue cracking in Fig. 8. As expected the effect of changing precipitation inputs is considerably smaller than changes in temperature. In general scenarios that predict less precipitation (e.g., P-MAP less than zero) results in less fatigue cracking. This result occurs because with less precipitation the base ad subgrade layers have a higher modulus and thus the pavement flexes less. Rutting of both the asphalt layer and total pavement show very little change (on the order of hundredths of a millimeter) and so no correlation is found. This finding is not entirely unexpected since surface infiltration is a very minor component in the overall moisture movement calculations embedded into the pavement analysis algorithms.

3.2. Impact on Rigid Pavements

Overall, the analysis of the flexible pavement section demonstrates that temperature projections may have a notable effect on pavement performance, but precipitation (at least in the context of monthly on-average increases) has a less important, but still quantifiable impact. It remains to be seen how these differences may manifest in rigid pavements where precipitation infiltration may be more substantial, but the strength of the paving material may conversely compensate for this infiltration. To study the impact of future precipitation data more clearly, the authors performed an analysis for one rigid section from the ME climate location. The reason for choosing ME in the rigid pavement analysis is due to the observed percentage increase in the fatigue cracking using precipitation data with the flexible pavement. The AASHTOWare Pavement ME analysis was again carried out for a rigid pavement section in ME for four different climate prediction models and the two different RCP scenarios. The distresses considered for the analysis purposes for rigid pavements are mean joint faulting and transverse cracking.

The simulation results for temperature only and temperature and precipitation are plotted together in Fig. 9. From the figure, the first observation is that with increases in both temperature and precipitation, the mean joint faulting is expected to increase relative to the baseline scenario. This effect results because increases in temperature changes the expansion and contraction of the slabs thereby resulting in greater relative slab movement. The second observation is that in the case of transverse cracking, the rigid pavements appear to perform better under climate change scenarios. Rigid pavement cracking is a combined result of both load induced stresses and temperature induced curling of the slab. With the increase of temperature, the shrinkage phenomenon in the slabs might be decreasing and this resultant effect is showing as an improvement in the transverse cracking in rigid pavements. More likely the effect occurs because PCC pavements are inherently prone to negative built in temperature gradients and climate change induced temperature rise mitigates this effect. A negative built in temperature gradient refers to the fact that at construction, the pavement surface tends to be at its warmest possible state (pavements are generally constructed during the hottest parts of the year). Since pavements will set as a planar surface, the result is that for most of the pavement life, the surface is relatively cooler than its planar configuration and so there is a slight (imperceptible to the naked eye) curl to the slab. This curl generates stresses in the pavement slab that in conjunction with traffic loads lead to transverse cracking. The projected temperature increases would result in a greater proportion of the year having temperatures above the temperature at set and thereby reduce the overall impact of this built-in negative temperature gradient.

With respect to the effects of including precipitation projections, the data are not showing any difference in terms of pavement distresses for rigid pavements. In fact, the impact of future precipitation data is showing more in the case of flexible pavements compared to the rigid pavements. This observation is corroborating the study findings observed from the impact of Hurricane Katrina on the roadways (Gaspard et al. 2007).

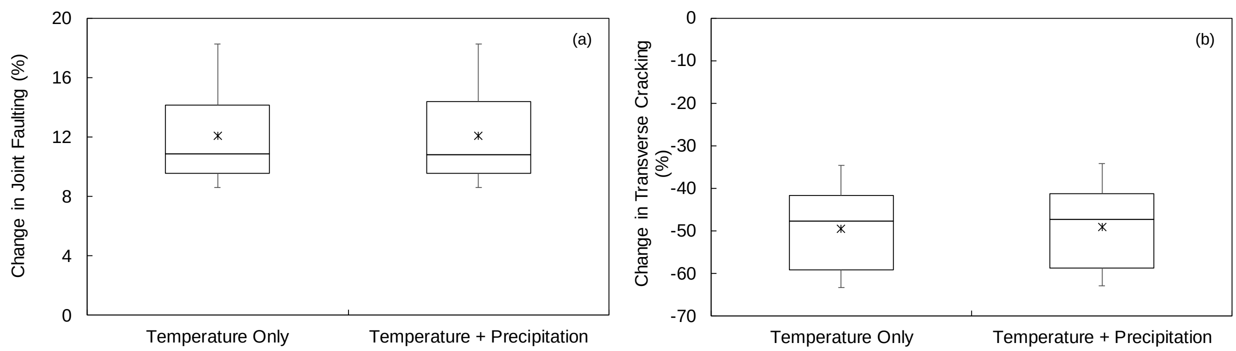


Fig. 9. *Variation of percentage difference across climate prediction models for rigid pavement section in Maine for temperature only, and for temperature and precipitation data from (a) mean joint faulting and (b) transverse cracking.*

4. Conclusions

In this study, the impact of climate change on the pavement performance is assessed using the average from a multi-model ensemble of 19 different CMIP5 climate models and three individual models (MIROC-ESM, CCSM4, and MRI-CGCM3) for both RCP8.5 and RCP4.5 scenarios. The climate projections data is used with the AASHTOWare Pavement ME software to predict the pavement performance. A systematic study for the baseline (AASHTOWare Pavement ME software climate data) and future predictions scenario was conducted for different climate locations using predictions models data. Overall 85 pavement performance simulations were conducted for five different locations and two scenarios. The resultant pavement distresses from the baseline and future scenario are compared and conclusions drawn from these comparisons are provided below.

- Use of climate change projections shows substantial impact on the pavement distress irrespective of the climate location and prediction model data used.
- Though there is a variation in the magnitude of impact due to the climate projections all the projects models are indicting that pavements will experience higher distresses and early failure of the pavements.
- The percentage increase in fatigue cracking (2-9%) is observed to be less compared to the AC rutting (9-40%), as temperature increase in the future will have more impact in terms of AC rutting.
- Impacts from future temperature increases are projected to be greater in the upper Midwest and Northeast regions of the United States.
- Incorporation of precipitation projection data along with temperature projections does not show any substantial difference in the pavement performance.

- Impact of climate change on rigid pavements sections considered in this study shows increase in joint faulting but decreases in transverse cracking.

In short, the study findings suggest, like others, that there may be a substantial impact on the pavement infrastructure due to the climate change. The uncertainty of these projections is large, but the message is consistent. And therefore, it may become increasingly important consider temperatures that deviate from historical norms when analyzing and designing pavements. Contextualizing the specific findings of this research into the broader literature suggests that continued reliance on a static climate record may result in more frequent maintenance and rehabilitation and ultimately greater costs from the transportation infrastructure.

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Highlights

- Pavement performance under climate stationarity policy are predicted
- CMIP5 climate models are extracted
- Performance under climate change is predicted and compared to stationarity cases.
- First order correlations between climate factors and performance are established.
- National impacts are assessed.