COMPARATIVE ANALYSIS BETWEEN MERRA AND UPDATED MEPDG CLIMATE DATABASE IN THE STATE OF TENNESSEE

By

Abubakr Mohamed Salah Ibrahem Ziedan

Mbakisya Onyango
Associate Professor of Civil Engineering
(Chair)

Joseph Owino
Professor of Civil Engineering
(Committee Member)

Ignatius Fomunung
Professor of Civil Engineering
(Committee Member)

Weidong Wu
Assistant Professor of Civil Engineering
(Committee Member)

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Abubakr Mohamed Salah Ibrahem Ziedan

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ABSTRACT

The Mechanistic-Empirical Pavement Design Guide (MEPDG) addresses climate effects on pavement design in a comprehensive way, which allows for investigating the effect of climate inputs on pavement performance. However, it requires detailed climate inputs, which might not be available for most of the state DOT. The Updated AASHTOWare climate database encompasses twelve stations in the state of Tennessee, which might not well represent all climatic regions in the state of Tennessee. This study compares and evaluates the performance of pavements in Tennessee using Modern-Era Retrospective Analysis for Research and Applications (MERRA) and the updated AASHTOWare databases as a source of MEPDG climate data inputs.

A comparative analysis between these two climate data sources using eight LTPP sites in Tennessee was conducted. It was found that using MERRA as a climate data source for the state of Tennessee will offer better geographic coverage and therefore more precise distress predictions are expected.

DEDICATION

This thesis is dedicated to those who were with me throughout my journey, with support, encourage and knowledge.

To my sweet and loving parents, whose affection love and prayers were with me every day and night.

To the soul of my aunt Suaad who passed away during this journey.

To all of friends for their support and help.

To Muayed Alfatih and Yaseen.

To Roaa.

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LIST OF ABBREVIATIONS

AADTT	Average Annual Daily Truck Traffic
AASHTO	American Association of State Highway and Transportation Officials.
AASHTOWare	MEPDG Design Software
ASOS	Automated Surface Observation System
AWOS	Automated Weather Observation System
AWS	Automated Weather Stations
CMS	Climatic-Materials-Structural Model
COO	Cooperative Observer Program
CRCP	Continuously Reinforced Concrete Pavement
CRREL	United States Army Cold Regions Research and Engineering Laboratory
EICM	Enhanced Integrated Climate Model
HDF	Hourly Distribution Factors
JPCP	Jointed Plain Concrete Pavement
IRI	International Roughness Index
LTPP	Long-Term Pavement Performance
MAF	Monthly Distribution Factors
MEPDG	Mechanistic-Empirical Pavement Design Guide
MERRA	Modern-Era Retrospective Analysis for Research and Applications
NALS	Normalized Axle Load Spectra
NARR	North American Regional Reanalysis
NASA	National Aeronautics and Space Administration
OWS	Operating Weather Station
TDOT	Tennessee Department of Transportation
TTC	Truck Traffic Classification
USCRN	United States Climate Reference Network
VCD	Vehicle Class Distribution
VWS	Virtual Weather Station

CHAPTER I

INTRODUCTION

Climate and environmental factors have direct short and long term impacts on material characteristics and pavement performance. Material characteristics are affected by the environmental factors in several aspects, for example, asphalt modulus may vary from 100,000 psi in hot weather to 2 or 3 million psi in cold weather. Frozen soil could increase resilient modulus values by 20 to 120 times the resilient modulus of unfrozen soil, and high moisture content is associated with lower resilient modulus for unbound materials. Pavement performance and deflections of both flexible and rigid pavements are similarly profoundly influenced by temperature and moisture. In climates with high-temperature fluctuations, very cold temperatures result in transverse cracks in asphalt pavements, while high temperature leads to an increase in the deflections and rutting (Byram et al.; Huang). Concrete blowup, deflections near joints and slab cracks, are effects of temperature changes in concrete pavements (Huang). These distresses are indicators of the impact of environmental factors on pavements, which necessitates their consideration on pavement design. Environmental factors also can affect pavement ride quality and serviceability (Applied Research Associates).

Most state departments of transportation in the US use AASHTO-1993 pavement design guide for pavement design. This guide was developed by the American Association of State Highway and Transportation Officials (AASHTO) in 1960's. The latest version of this guide was last updated in 1993. The AASHTO-1993 guide is an empirical design method based on AASHO road test that was conducted between 1958 to 1960 (Huang). This design approach does not sufficiently address climate factors; it uses drainage factors to account for moisture effect in the design process. The new pavement design method, Mechanistic-Empirical Pavement Design Guide (MEPDG), was introduced to provide a deeper understanding of pavement performance (Applied Research Associates).

MEPDG is a mechanistic-empirical based pavement design method developed to replace the current AASHTO-1993 pavement design method to overcome many limitations in the AASHTO-1993 design guide such as, heavier traffic loadings, new rehabilitation methods, new axle types and configurations, different hot asphalt concrete mixes, and different climate conditions. MEPDG design philosophy provides to pavement engineers many advantages like: it offers variety of material and design options, reduces pavements early failures, increases pavement longevity, addresses new and rehabilitating design methods, provides hierarchal level of design inputs that allows more flexibility, evaluates base erosion under rigid pavements, and considers aging and seasonal effects when estimating pavement performance (Applied Research Associates). MEPDG introduced a hierarchical design method by introducing three levels of inputs for the required material and traffic inputs. The designer selects the appropriate design level according to the importance of the project and the available resources (AASHTO). These three design levels are defined as follows:

- Level-1 inputs: these inputs are measured directly at the design site which provides the highest knowledge of the site conditions but requires a higher cost for data collection and testing.

- Level-2 inputs: these inputs are either obtained from regional values or generated from regression models. Level-2 inputs do not provide the most precise data for the site but costs less than level-1 inputs.
- Level-3 inputs: these are the default inputs that were developed using national values. Level-3 inputs provide the least knowledge about the analyzed sites, but the cost associated with using level-3 inputs is less than cost of using level-1 or level-2 inputs (AASHTO).

Looking at climate particularly, AASHTO-1993 is based on a test that was performed at one location in Illinois, representing only one geographic region, therefore, different climate conditions are not directly considered in AASHTO-1993 design guide, while MEPDG comprehensively addresses this issue by incorporating the Enhanced Integrated Climate Model (EICM) in the pavement design software. EICM is a one-dimensional coupled heat and moisture flow algorithm that simulates changes in the behavior and characteristics of pavement and subgrade materials in conjunction with climate conditions over several years of operation. EICM was developed in 1989; then it was modified and updated in 1997, 1999 and 2004. It contains three major components (Applied Research Associates) :

- The Climatic-Materials-Structural Model (CMS Model);
- The United States Army Cold Regions Research and Engineering Laboratory (CRREL).CRREL Frost Heave and Thaw Settlement Model (CRREL Model);
- The Infiltration and Drainage model.

The EICM model is considered a significant advancement in pavement design and analysis since it can predict the following parameters through the pavement profile:

- Temperature, Resilient Modulus adjustment factors.
- Pore water pressure and water content.
- Frost and thaw depths.
- Frost heave and drainage performance.

These predicted values are used to define material characteristics, structural response and pavement performance for both flexible and rigid pavement.

According to mechanistic-empirical design guide of new and rehabilitated pavement structures, for EICM to be able to predict these values, EICM needs information that can be classified in five categories (Applied Research Associates):

1. General information:
    - Base/Subgrade Construction completion month and year.
    - Pavement Construction completion month and year.
    - Existing Pavement Construction completion month and year (for rehabilitation only.
    - Traffic opening date.
    - Design type.
2. Weather-related information:
    - Hourly air temperature which is used to calculate longwave radiation by heat balance equation in EICM. It is also used to define the freeze-thaw cycles.
    - Hourly precipitation which is used for calculating infiltration for rehabilitated pavement and aging process. Moreover, precipitation happens in months when the mean temperature of that month is less than freezing temperature is modeled by EICM as snow.

- Hourly wind speed is used for calculation of convection heat transfer coefficient at the pavement surface.
- Hourly sunshine percentage (cloud cover) is used for calculating heat balance on pavement surface.
- Hourly relative humidity has a significant impact on drying shrinkage in Continuously Reinforced Concrete Pavement (CRCP) and Jointed Plain Concrete Pavement (JPCP) and determining the initial crack width of CRCP.

3. Groundwater table depth.
4. Drainage and surface properties:
   - Surface Shortwave Absorptivity
   - Infiltration
   - Drainage Path Length
   - Pavement Cross Slope
5. Pavement surface and materials:
   - Layer Thicknesses.
   - Thermal Conductivity, K and Heat Capacity Q for AC and PCC layers.
   - Surface Shortwave Absorptivity for Asphalt Materials.
   - Mass-Volume Parameters for unbound layers which include maximum dry density, optimum gravimetric moisture content, and specific gravity.
   - Dry Thermal Conductivity and Dry Heat Capacity for unbound layers.

The most challenging information to obtain is weather-related information since it needs hourly data for long periods of time and there is a limited availability of weather stations. MEPDG design software (MEPDG AASHTOWare) requires latitude, longitude, and elevation of the design site to create virtual weather station by interpolating the necessary data based on the distance and elevation difference. MEPDG AASHTOWare automatically selects the nearest six stations, or the user can select the desired number of stations to be used to interpolate climate data. However, maximizing the number of the sites is preferred since some data may be missing. After the user selects the stations, EICM model interpolates the values and creates virtual weather station (AASHTO; Applied Research Associates).

The previous version of MEPDG AASHTOWare used to obtain climate data from ground weather stations located near the project site. MEPDG AASHTOWare had about 800 stations located all over the US. Most of these stations have about 60 to 66 months of data which is enough for calculation purposes, which requires 24 months of actual data to be performed (Applied Research Associates).

The current MEPDG AASHTOWare version weather-related data was updated using North American Regional Reanalysis (NARR) database which raised the number of the available station to about 1200 in US and 300 in Canada. This update made climate data available for more extended periods. Nevertheless, the geographic distribution of these stations is a challenge facing state departments of transportation (Brink et al.).

The problem with the available climate data in MEPDG AASHTOWare is the limited geographical distribution representation since the number of the weather stations in each state does not represent all climate regions ((Truax et al.), (Johanneck),(Yang et al.)).

Other sources can be used to obtain weather-related data, for example, data from U.S. Climate Research Network; National Weather Service Cooperative Observer Program; Department of Energy Solar Infrared Radiation System station; and Modern-Era Retrospective

Analysis for Research and Applications (MERRA). MERRA is a new source for climate data. It was developed by the National Aeronautics and Space Administration (NASA) for its own needs and provides continuous hourly weather data starting in 1979 on a relatively fine-grained uniform grid. MERRA is based on a reanalysis model that combines computed model fields (e.g., atmospheric temperatures) with ground-, ocean-, atmospheric-, and satellite-based observations that are distributed irregularly in space and time. The result is a uniformly gridded dataset of meteorological data derived from a consistent modeling and analysis system over the entire data history. MERRA data is provided at an hourly temporal resolution and a 0.5 degrees latitude by 0.67 degrees longitude (approximately 31.1 mi by 37.3 mi at mid-latitudes) spatial resolution over the entire globe. MERRA database combines both measured observations and modeled data (Schwartz et al. "Evaluation of Long-Term Pavement Performance (Lttp) Climatic Data for Use in Mechanistic-Empirical Pavement Design Guide (Mepdg) Calibration and Other Pavement Analysis").

MERRA can be considered as a valuable source for climate data inputs for MEPDG since it has an extensive database and excellent spatial coverage. The suitability of using MERRA data as climate data inputs for MEPDG in the State of Tennessee is evaluated in this study in comparison to the MEPDG AASHTOWare climate data.

1.1 Problem Statement

As stated in the introduction, climate and environmental considerations are very important in pavement design. Currently, the state of Tennessee uses AASHTO-93 pavement design guide, however Tennessee Department of Transportation (TDOT) is putting in place all the necessary parameters required for the MEPDG implementation.

Climate and environment are among input parameters required for the MEPDG. The MEPDG AASHTOWare database provides weather or climate stations that can be used for each state. In 2006, the state of Tennessee had only nine stations in AASHTOWare database, which covers only nine out of 95 counties in Tennessee as shown in Figure 1. Figure 1, clearly indicates that there are some parts of the state of Tennessee that lacks a climate/weather station, which may affect the pavement design in this region.

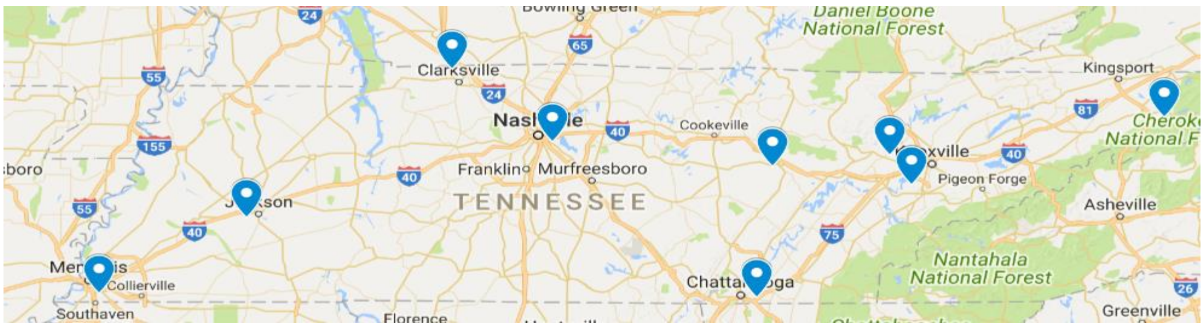

Figure 1 Original MEPDG AASHTOWare Climate Station Locations in the State of Tennessee

The availability of the climate data from these nine stations in 2006-MEPDG climate database varies from 5 years to 10 years for the period 1996 to 2006 as shown in Table 1. It can be noticed that these stations had a limited number of years of climate data which it is not expected to offer good representation for climate data.

Table 1 Original MEPDG AASHTOWare Climate Stations in the State of Tennessee

Station Name	Station Location	First Year	Last Year
Bristol/Jhnsn Cty/Kngsprt	Tri-Cities Regional Tn/Va Airport	1996	2006
Chattanooga	Lovell Field Airport	1996	2006
Clarksville	Outlaw Field Airport	2001	2006
Crossville	Memo-Whiton Field Airport	2000	2006
Jackson	Mckellar-Sipes Regional Airport	1998	2006
Knoxville	Mc Ghee Tyson Airport	1996	2006
Memphis	Memphis International Airport	1999	2006
Nashville	Nashville International Airport	1996	2006
Oak Ridge|	Oak Ridge	1998	2006

As it was mentioned in the introduction, MEPDG climate database was updated in 2016 using North American Regional Reanalysis (NARR) database. This update overcomes the data availability limitations reported in the earlier versions of MEPDG since it offers 37 years of data from 1979 to 2015. The number of the available stations in MEPDG was also raised to about 1200 in US and 300 in Canada (Brink et al.). In this newly updated database, the number of the available stations in the state of Tennessee increased from nine to twelve stations which represent twelve counties introducing three new stations around Knoxville area as shown in Table 2.

Table 2 Updated MEPDG AASHTOWare Climate Stations in the State of Tennessee using NARR Database

Station Name	Station Location	First Year	Last Year
Bristol/Jhnsn Cty/Kngsprt NARR Grid Point	Tri-Cities Regional TN/VA Airport	1979	2015
Chattanooga NARR Grid Point	Lovell Field Airport	1979	2015
Clarksville NARR Grid Point	Outlaw Field Airport	1979	2015
Crossville NARR Grid Point	Memo-Whiton Field Airport	1979	2015
Jackson NARR Grid Point	Mckellar-Sipes Regional Airport	1979	2015
Knoxville NARR Grid Point	Mc Ghee Tyson Airport	1979	2015
Knoxville NARR Grid Point	Mc Ghee Tyson Airport	1979	2015
Knoxville NARR Grid Point	Mc Ghee Tyson Airport	1979	2015
Knoxville NARR Grid Point	Mc Ghee Tyson Airport	1979	2015
Memphis NARR Grid Point	Memphis International Airport	1979	2015
Nashville NARR Grid Point	Nashville International Airport	1979	2015
Oak Ridge NARR Grid Point	Oak Ridge	1979	2015

However, this update is still faced with the limited geographical distribution of these twelve stations since the added three stations are all around the Knoxville area as shown in Figure 2. This climate data may not well represent the climate in the state of Tennessee. The existence of data gaps in the state and elevation differences affects the accuracy of interpolated data.

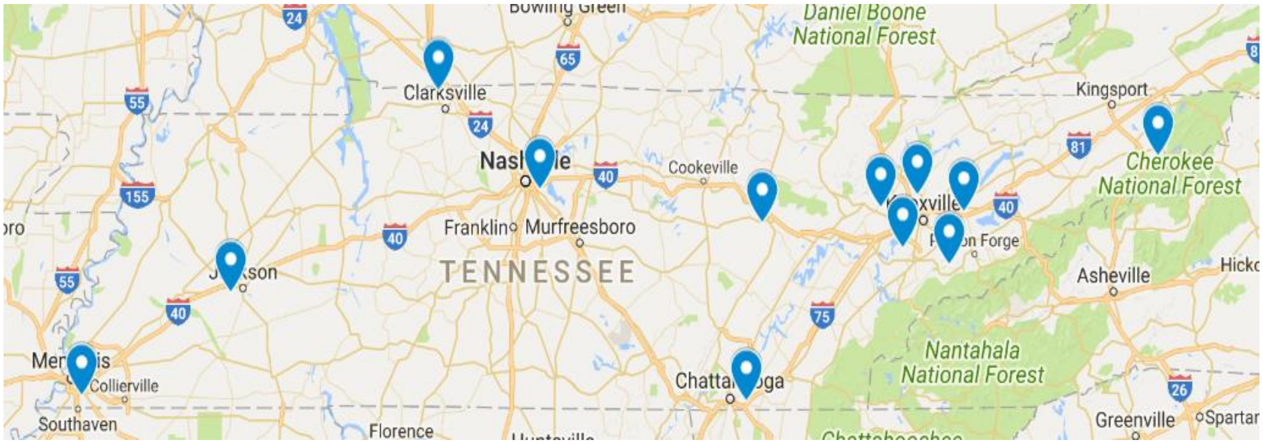

Figure 2 Updated MEPDG AASHTOWARE Climate Stations Locations in the State of Tennessee using NARR Database

1.2 Objective

The objective of this study is to evaluate and compare the performance of pavements in Tennessee using MERRA and the updated AASHTOWare databases as a source of climate data inputs for MEPDG. This analysis used eight Long-Term Pavement Performance (LTPP) sites in Tennessee.

CHAPTER II

LITERATURE REVIEW

Many states across the US face difficulties with climate data inputs for MEPDG, which led to various types of research and studies conducted in different states with objectives that address climate issues in MEPDG. Some of these studies discuss the effect of using accurate climate data on MEPDG predictions, and others investigate different methods to improve the available climate database or using other sources of climate data as inputs.

In 2010, Johanneck and Khazanovich studied the impacts of climate in MEPDG predictions by predicting the performance of 610 composite pavement sections with Asphalt Concrete (AC) over Portland Cement Concrete (PCC) nationwide using MEPDG AASHTOWare version 1.0. This study indicated that climate inputs have major influences on pavement performance, and the quality of MEPDG weather stations varies from one station to another since MEPDG allows low-quality data to be used. Another important finding from this analysis was that by observing PCC transverse cracking, it was noticed that there were many discrepancies. Therefore, checking and cleaning of low-quality climate data was recommended by authors (Johanneck and Khazanovich).

In studying the effects of the climate inputs in the State of Louisiana, the state was split into two parts by a line at latitude 30.6º. The northern part has higher elevations, higher temperature fluctuations, and deeper water table while the southern part is a coastal area with lower temperature fluctuations and shallower water table. Twenty sites were selected for the analysis, ten from each part of Louisiana to study the effect of climate inputs on MEPDG. The ten sites in each part were chosen with different pavement structures to negate the impact of the pavement structure. The climate inputs were developed by using VWS by interpolation from nearest two or three weather stations. The effects of the climate on rutting and fatigue cracking were studied by applying a T-test analysis with a null hypothesis that the average errors of the MEPDG for the two groups of projects are equal, and the alternative hypothesis H1 is that the average errors of the MEPDG for the two groups of projects are unequal. It was found that MEPDG overestimates rutting in the southern part of Louisiana while it underestimates fatigue cracking in the north of the State of Louisiana (Yang et al.).

Li et al. assessed the accuracy of the virtual weather stations climate data generated by EICM by comparing this data to data collected by LTPP using Automated Weather Stations (AWS). The generated values of maximum monthly temperature, minimum monthly temperature, mean monthly temperature, mean annual temperature, monthly precipitation, annual precipitation and number of freeze and thaw cycles were compared to data obtained from 42 Automated Weather Stations (AWS) data. Two cases were used to generate the climate data using EICM. In the first case, VWS data was generated by interpolation from the nearest six stations while in the second case VWS data was generated by interpolation from the nearest station only. It was found that the data generated by MEPDG is reasonably accurate, but the deviation between VWS and AWS does not follow a normal distribution pattern. Also, using many nearby stations for interpolating climate data leads to more accurate results. Another important finding that the elevation difference between the analyzed site and the nearby stations has considerable effects on the accuracy of interpolated VWS while the distance between project location and selected stations for interpolating climate data does not affect VWS significantly (Li et al.). The impact of generated climate data on pavement performance was also investigated in this study. A site located in Fayetteville, Arkansas was selected for this purpose using Average Annual Daily Truck Traffic (AADTT) of 10000, 20-year design life and pavement structure which was designed using AASHTO-1993 for both flexible and rigid pavements. The impact was studied by changing the average temperature by (±3ºF) and monthly precipitation by 7.2 in. It was found that AC rutting was the most sensitive to changes in climate data while International Roughness Index (IRI) was the least sensitive to changes in climate data (Li et al.).

Johanneck in 2011 modeled the thermal behavior of concrete and composite pavements using EICM and validated EICM predictions of thermal gradients through the slabs using temperature data from Minnesota Department of Transportation (MnRoad). It was concluded that "evaluation of the material thermal inputs should be a part of a process of local calibration and adaptation of the MEPDG"(Johanneck).

Breakah et al. examined the effects of using accurate climatic conditions on MEPDG considering the State of Iowa as a case study. For the study purposes, the available climate data in the software were compared to the climate data developed from historical data from different counties in Iowa State. MEPDG climate database contains 15 stations while data from 24 counties was obtained from Iowa Environmental Mesonet to represent Iowa State's climate. The predicted distresses indicted that MEPDG climate data predicted lower IRI and lowered thermal cracking compared to locally developed climate data. Higher rutting was predicted by MEPDG climate data but only on the northern part of the state. Almost 10% deviation was noticed for high temperature distresses, and almost 17% deviation was observed in low temperature distresses. These differences between MEPDG and local developed climate data predictions specify the importance of accurate climate data from MEPDG application (Breakah et al.).

Saha et al. evaluated the effects of the Canadian climate condition on MEPDG predictions for flexible pavement performance. To achieve the objective, the authors studied the following: frost depth and freezing index computed by MEPDG and the sensitivity of the MEPDG-predicted performance indicators for flexible pavements to the climate in Canada. Data from 222 climatic stations collected by Transportation Association of Canada for MEPDG implementation was used in this study. It was concluded that discrepancies were detected when frost depth and freezing index computed using the MEPDG were compared to other Canadian databases. Also, it was found that alligator and transverse cracking models in the MEPDG were not sensitive to climate changes across Canada while higher longitudinal cracking is expected in the permafrost zone. Small variations in IRI and rutting values were noticed (Saha et al.).

The State of Michigan is comprised of 24 weather stations that are available in MEPDG, which do not cover all geographic regions. This is considered as a challenge because the sites in the climate database have limited available data, and the data is not updated. Yang et al. studied the applicability of using the Automated Surface Observation System and the Automated Weather Observation System (ASOS/AWOS) to increase the number of stations in Michigan and to update the data of the existing stations. Procedures for quality check, quantity check, missing data filling and inaccurate data correction was developed and applied in this study, so Michigan increased the number of the available weather stations to 39 with an average length of data of 15.2 years instead of 7.5 years (Yang et al.).

The State of Mississippi faced challenges similar to Michigan State with only 12 stations in Mississippi available in MEPDG climate database which represent ten counties across the state. Mississippi faced these challenges by developing historic climate database using hourly data from 23 ASOS and AWOS, and the daily data from over 100 Cooperative Observer

Program (COOP) that contains 40 years of climate that represent 82 counties in Mississippi. This historic data was used to develop 40 years of future climate inputs for nine climate zones that represent different climate conditions in Mississippi. Sensitivity analysis was performed to investigate the climate inputs effects on pavement performance on both flexible and rigid pavements in Mississippi State. Rutting and ride quality were selected for this study to determine the sensitivity of flexible pavements while faulting and ride quality were selected for rigid pavements. It was found that using MEPDG default climate inputs overestimate the future distresses (Truax et al.).

The State of Iowa had 15 stations included in the MEPDG climate database that comprised about 10-years of data. These 10-years of available data are repeated to simulate the climate in the design life of the pavement. An additional challenge was to know the sufficient data length that enables the designer to model the climate for whole pavement design life. Heitzman examined MEPDG assumption that 15-20 years of climate data is enough to represent the climate in Iowa State. It was found that the climate data in Iowa has high fluctuations in a period of 10-years, so historical data will not model the climate accurately, virtual climate database is required to project future climates and predict future pavement performance accurately (Heitzman).

Byram et al. investigated MEPDG flexible pavement performance predictions sensitivity to climate using Spearman's rank correlation test and hierarchical regression analysis. This analysis was conducted at two levels: Regional Level considering 12-sites from Arkansas and National Level considering 18-sites across the US. In both levels, the same method was followed by changing the climate inputs while all other inputs remain constant for all sites. Many important findings were specified by this analysis which includes defining temperature as the most significant factor for the EICM, and it has the strongest correlation with pavement distresses and less fatigue cracking and rutting are expected in cold weather. Also, it was also noticed that moisture has less impact on flexible pavement performance than temperature. Another major output of this study was that IRI doesn`t highly influence by climate alone (Byram et al.).

Another study examined alternative sources of climate data that can be used as climate inputs for MEPDG like “Evaluation of LTPP Climatic Data for Use in Mechanistic-Empirical Pavement Design Guide Calibration and Other Pavement Analysis” and Alternative Source of Climate Data for Mechanistic-Empirical Pavement Performance Prediction by Schwartz and his group. (Schwartz et al. "Alternative Source of Climate Data for Mechanistic–Empirical Pavement Performance Prediction") This research evaluated MERRA climate as alternative sources of climate data for MEPDG application. The study compared MEPDG predictions for 20 locations distributed across the contiguous United States using climate data from different sources like Ground-based climate data which is built in (MEPDG), United States Climate Reference Network (USCRN) and NASA's MERRA. USCRN data were eliminated from the MEPDG performance comparison because it does not include wind speed and cloud cover data which are essential for the MEPDG models, so the predicted performance of flexible and rigid pavements was compared using MEPDG data and MERRA data. From the results of this study, it was observed that MERRA climate data estimates higher distresses than predicted by MEPDG weather data. For rigid pavement, there was no clear trend for deviations between MERRA and MEPDG weather forecasts. However, it was found that using MERRA as a source of climate data for MEPDG can predict acceptable results for engineering design for both flexible pavement and rigid pavements. The study addressed several benefits of using MERRA as a source of climate data including better spatial coverage; better frequency, continuity, consistency, and quality; focus on physically real quantities; rich and versatile data set, and data enhancement with time (Schwartz et al. "Alternative Source of Climate Data for Mechanistic–Empirical Pavement Performance Prediction").

LTPP team conducted a study with several objectives such as: study current and emerging requirements in climate data collection for transportation applications such as MEPDG, develop a methodology for integrating temporal changes in position and measurement characteristics of Operating Weather Station (OWS) into the calculation of climate indices, and apply this new methodology to update the climate statistics in the LTPP database. But these objectives were ignored when the research team discovered MERRA and the focus was shifted to evaluate whether MERRA is a feasible alternative to conventional ground-based climate data sources. Statistical and sensitivity tests were performed on MERRA data to compare it to the best existing ground climate data in assessing its suitability for MEPDG purposes. This study performed quality checks on the available 851 weather station for MEPDG; only 21 sites met the required quality criteria while MERRA data satisfied all quality requirements. 12 sites nationwide were selected for a comparative study between MEPDG weather database and MERRA. The following conclusions were major findings by LTPP research team (Schwartz et al. "Evaluation of Long-Term Pavement Performance (Lttp) Climatic Data for Use in Mechanistic-Empirical Pavement Design Guide (Mepdg) Calibration and Other Pavement Analysis").

- Both flexible and rigid pavements were affected by the average annual temperature and average annual temperature range values.
- The performance of both flexible and rigid pavements is not sensitive to Precipitation.

- Asphalt rutting, total rutting, and longitudinal cracking were the flexible pavement distresses that were most affected by climate.
- The variances between MEPDG predicted distresses using AWS versus MERRA versus virtual weather station (VWS) versus OWS weather data sources don't follow a certain trend which was interpreted as an acceptable level of agreement between MERRA and VWS/OWS

Based on these conclusions LTPP recommended MERRA as a source for climate data for many applications like MEPDG and bridge management. Additionally, MERRA's close spacing of its modeled stations eliminates the need for improved weather data interpolation and VWS. More extensive research on MERRA applications was recommended by the research team in different areas like comparing MEPDG pavement performance predictions using ground truth, OWS, and MERRA climate data, evaluation of the correctness of MEPDG surface shortwave radiation (SSR) calculations and establishing an appropriate ground truth for climate data.

Chapter III

METHODOLOGY

The objective of this study is to evaluate and compare the performance of pavements in the state of Tennessee using MERRA and the updated MEPDG AASHTOWare climate databases as source of climate data inputs for MEPDG. In this study, two scenarios are developed. In the first scenario, climate inputs are defined from MEPDG climate inputs by interpolating the climate inputs from the nearest six stations available in MEPDG AASHTOWare climate database, while in the second scenario, the climate data is defined from MERRA database. Same traffic and materials inputs are used for both scenarios for a 20 year design period.

Eight LTTP sites in the state of Tennessee are used in this study to compare the pavement performance using MERRA and the updated MEPDG AASHTOWare climate databases as source of climate data inputs for MEPDG. The eight LTPP site are located across the four TDOT regions and represent different traffic and climate conditions since some of these sites represent interstates while the others represent state routes as shown in Figure 3. The MERRA climate input station used for each site of these eight LTPP sites was obtained from LTPP infopave database.

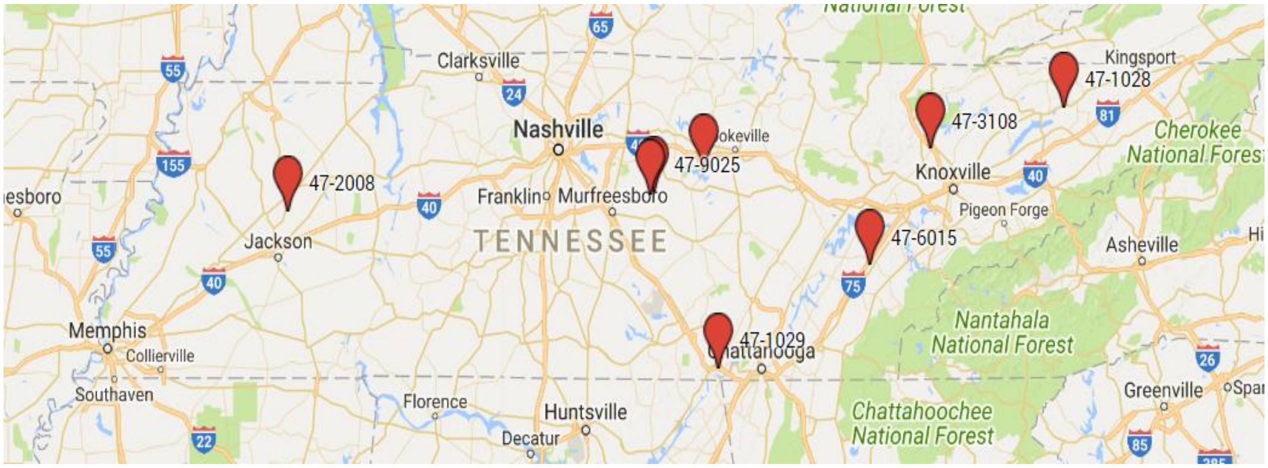

Figure 3 Analyzed Sites Locations

This analysis was limited to eight sites with complete traffic information from the LTPP database as shown in Table 3.

Table 3 Sites Basic Information

#	SHRP_ID	Total lanes	County Name	Route No	Mile Post	Functional Class	AADTT	TTC
1	1028	4	Hawkins	11	8.83	2	720	2
2	1029	4	Marion	28	0.59	2	736	6
3	2008	4	Gibson	43	5.27	2	1058	4
4	3075	2	De Kalb	56	19.08	2	660	13
5	3101	2	Cannon	96	1.92	2	146	12
6	3108	4	Anderson	I-75	123.04	1	7918	1
7	6015	4	Mc Minn	I-75	59.4	1	6720	1
8	9025	2	Cannon	96	3.48	2	136	12

In Table 3, SHRP_ID represents site identification number assigned by LTPP program. AADTT is the initial two-way average annual daily truck traffic. Truck Traffic Classification (TTC) defines a group of roadways with similar normalized axle-load spectra and normalized truck volume distribution. MEPDG has 17- TTC group that were determined by analyzing the traffic data collected on over 180 LTPP test sections (AASHTO).

The analysis was performed on the eight sites using MEPDG AASHTOWare to determine predicted distresses caused by same traffic load using the two climate data sources. The analysis (1) predicted pavement distresses by each climate data source caused by the given traffic loading; (2) optimized the AC layer thickness taking into account the given climatic conditions and (3) using statistical analysis to evaluate the difference between the predicted distresses using the two climate databases.

1.3 Distresses

The MEPDG predicted distresses include International Roughness Index (IRI), permanent deformation, AC bottom-up cracking, AC thermal cracking, and AC top-down fatigue cracking. The MEPDG AASHTOWare version 2.3 was used to estimate these distresses for the eight sites using climate data input for both scenarios.

IRI quantifies the smoothness of pavement. IRI is vital in pavement design since rough pavement leads to higher vehicle operation cost and user discomfort. MEPDG uses empirical equations to estimate IRI as a function of permanent deformation, as well as AC bottom-up cracking, AC thermal cracking, and AC top-down fatigue cracking.

Permanent deformation (total rutting) is defined by MEPDG as the maximum vertical difference in elevation between the transverse profile of the HMA surface and a wire-line across the lane width as shown in Figure 4 (AASHTO).

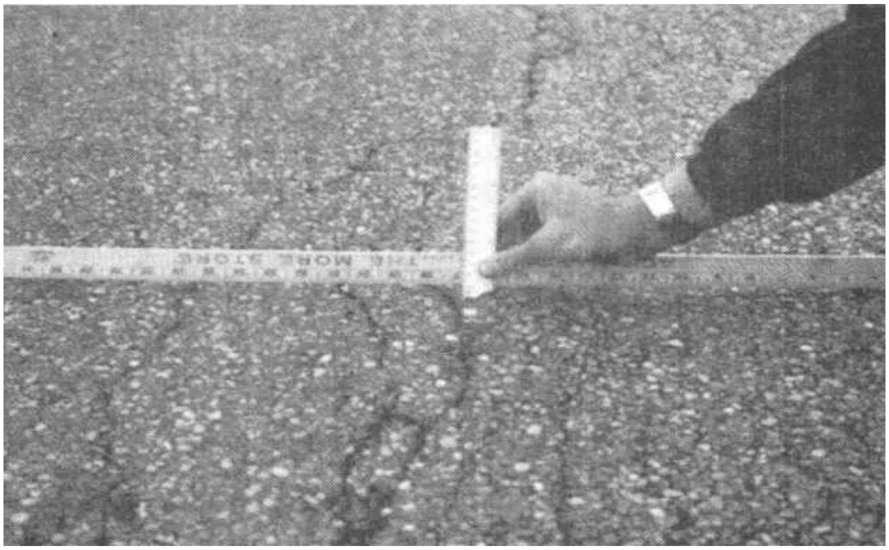

Figure 4 Permanent Deformation taken from (Huang)

AC bottom-up cracking (Alligator Cracking) is a series of interconnected cracks that start at the bottom of the HMA layers as shown in Figure 5 (AASHTO). These cracks starts at the bottom of the asphalt or base layers. Alligator cracking is measured in square feet of surface area. Measuring alligator cracking might be complicated if cracks with different severities took place in one area since each severity level must be measured separately (ASTM-D6433-07).

Figure 5 AC Bottom-Up Cracking taken from (ASTM-D6433-07)

AC thermal cracking (Transverse Cracking) is a non-load related distress form of cracking that is predominantly perpendicular to the pavement centerline and caused by low temperatures or thermal cycling as shown in Figure 6 (AASHTO). These cracks are measured in linear feet (ASTM-D6433-07).

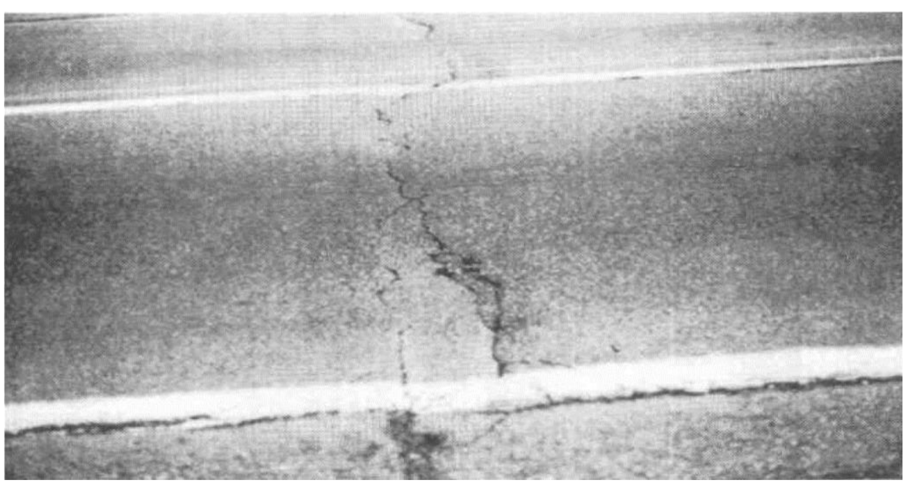

Figure 6 AC Thermal Cracking taken from (Huang)

AC top-down fatigue cracking (Longitudinal Cracking) is another form of load-related cracks which take place mainly parallel to the pavement centerline as shown in Figure 7 (AASHTO). These cracks are measured in linear feet (ASTM-D6433-07).

Figure 7 AC Top-Down Fatigue Cracking taken from (ASTM-D6433-07)

MEPDG introduced a new concept of optimizing AC layer thickness to ensure that the estimated distresses will be within the allowable limits. The optimized AC layer thickness was also calculated for the two scenarios using MEPDG AASHTOWare version 2.3 optimization tool.

1.4 Statistical Analysis

To investigate the significance of the difference, if any, in the predicated distresses between the two climate data sources, a paired T-statistical test with a confidence level of 95% was performed for the distresses that follow normal distribution with the following hypotheses:

Null hypothesis:

There is no difference between distresses predicted using Updated MEPDG and MERRA climate data inputs.

Alternative hypothesis:

There is a difference between distresses predicted using updated MEPDG and MERRA climate data inputs.

For the distresses that do not follow normal distribution, a nonparametric Wilcoxon sum-rank test was used to investigate the significance of the difference between the two sources of the climate data. The confidence level used for this test was 95% and the same hypotheses used for the T-test used for Wilcoxon sum-rank test.

The design criteria used for this study to evaluate these distresses was recommended by the AASHTO manual of practice criteria and shown in Table 4 (AASHTO).

Table 4 Pavement Performance Criteria

Distress	Limit	
	Interstates	Primary Roads
Terminal IRI	160	200
Bottom Up Cracking	10% lane area	20% lane area
Top-Down Cracking (ft./mile)	2000	2000
Transverse Cracking (ft./mile)	500	700
Permanent Deformation (in)	0.4	0.5

The analysis looked at the predicted distresses against the design criteria and also compared the distresses predicted using the two climate data sources. Current pavement condition was not readily available, therefore; a comparison to the actual condition or validation of results was not performed.

CHAPTER IV

ANALYSIS AND RESULTS

MEPDG design method is iterative, and it produces results in terms of distresses and smoothness values and not layer thickness. The MEPDG design approach has three major steps: Evaluation, Analysis, and Strategy Selection as shown in Figure 8.

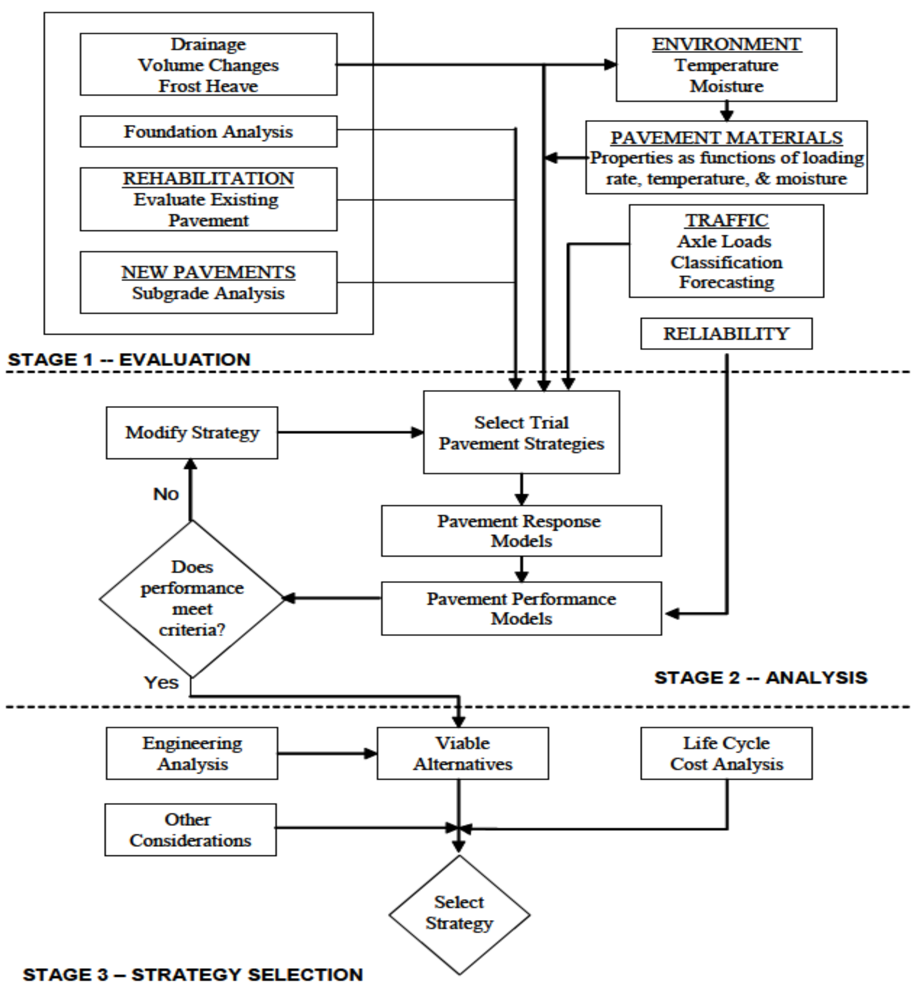

Figure 8 MEPDG Three Steps Design Process taken from (Applied Research Associates)

In the evaluation step, the material, climate, traffic inputs and design criteria are determined. MEPDG AASHTOWare requires various traffic, materials, and climate inputs to forecast the pavement performance during its design life at a specific reliability level (AASHTO).

In the analysis step, the designer selects a trial pavement cross section to perform the first analysis run. This trial cross section can be generated using AASHTO-1993 design guide or any other design method adopted by the agency. Based on this trial pavement design, MEPDG pavement response model calculates Load Related Cracking, Non-Load Related Cracking, Rutting, Faulting, Distortion, and IRI. These distresses are then evaluated against the selected design criteria. If the predicted distresses are within the allowable limits defined by the design criteria, the trial design strategy is considered to be viable strategy, and will be assessed in the last design step, otherwise a new trial design strategy is selected and evaluated (AASHTO; Applied Research Associates).

The Last step is the strategy selection. In this step, the Life Cycle Cost Analysis, and Engineering and Constructability Analysis are applied to the select best strategy from the evaluated design strategies (AASHTO; Applied Research Associates).

As mentioned above in this section, MEPDG requires material properties for each layer of the pavement. Soil classification and gradation, coefficient of lateral earth pressure, dry density, moisture content, Atterberg limits and resilient modulus are required for unbound layer while dynamic modulus, tensile strength, creep compliance, Poisson's ratio, surface shortwave absorptivity, thermal conductivity, heat capacity, coefficient of thermal contraction, effective asphalt content by volume, air voids, aggregate specific gravity and gradation, voids filled with asphalt and unit weight are needed for asphalt layers. These properties can be defined as level-1 using site-specific data or level-2 using regional data or level-3 using national data. Level-3 was used in this study since level-1 or level-2 material inputs were not available (AASHTO; Applied Research Associates).

In the traffic side, MEPDG AASHTOWare requires initial two-way Average Annual Daily Truck Traffic (AADTT), truck percent in the design direction, truck percent in the design lane, operational speed, Normalized Axle Load Spectra (NALS), Normalized Vehicle Class Distribution (VCD), Monthly Distribution Factors (MAF), Hourly Distribution Factors (HDF), axle load configuration, dual tire pressure, tire pressure, and lateral wander of axle load. These traffic inputs are hierarchal (Level 1, 2 and 3). MEPDG recommends using level-3 values for axle load configuration dual tire pressure, tire pressure, and lateral wander of axle load, however, it recommends using level-2 or level-1 traffic inputs for NALS, VCD, MAF, and HDF if they are available. (AASHTO; Applied Research Associates)

In this study, AADTT values were obtained from LTPP Infopave database for the eight sites that were analyzed. The analysis used level-3 values for NALS, VCD, and MAF since these inputs are not available for the state of Tennessee. A linear traffic growth factor of 1.34% was used for this analysis. This growth factor was calculated by averaging the available traffic growth factors for all counties in the state of Tennessee. This growth factor was used for all vehicle classes since no growth factor data is available for each vehicle class. The percent trucks in design direction and percent trucks in design lane were assumed to be 50% and 95% respectively.

As stated in introduction section, MEPDG EICM uses hourly temperature, precipitation, wind speed, relative humidity, and cloud cover to forecast the temperature and moisture content throughout the pavement structure. This data is available in MEPDG AASHTOWare database. It requires the user to enter the longitude, latitude, and elevation of the site then select nearby stations to interpolate the climate properties for the selected sites using virtual weather station concept (AASHTO). MEPDG climate database was updated using North American Regional Reanalysis (NARR) database. This updated database has a 37-years of weather data for years 1979 to 2015 (Brink et al.). This climate database update resolved the previous data availability issues since most of the stations had only 5 to 10 years of climate data (Brink et al.). However, MEPDG AASHTOWare climate database still faces the challenge of limited geographic coverage which results into using stations with high elevation difference which affects the accuracy of the interpolated climate data. In this study, the predicted distresses using MEPDG virtual weather stations climate inputs was compared to the predicted distresses using MERRA climate inputs to evaluate and compare the performance of pavements in Tennessee. Pavement layers, AADTT, growth rate, design life, climate stations and other design inputs used for the analyzed sites in this study are highlighted in section 4.1.

1.5 Design Inputs for the LTTP Sites

This analysis was performed on eight LTPP sites with complete traffic information from the LTPP database as shown in Table 5. These eight LTTP sites are located across the four TDOT regions in the state of Tennessee and represent different traffic and climate conditions since some of these sites represent interstates and others represent state routes.

Table 5 Basic Information for the Analyzed Sites

#	SHRP_ID	Total lanes	County Name	Route No	Functional Class	AADTT	TTC
1	1028	4	Hawkins	11	2	720	2
2	1029	4	Marion	28	2	736	6
3	2008	4	Gibson	43	2	1058	4
4	3075	2	De Kalb	56	2	660	13
5	3101	2	Cannon	96	2	146	12
6	3108	4	Anderson	I-75	1	7918	1
7	6015	4	Mc Minn	I-75	1	6720	1
8	9025	2	Cannon	96	2	136	12

To create a virtual weather station for site 1028 which is located on route No. 11 in Hawkins County, the following nearby stations were selected: Bristol/ Jhnsn CTY/ KNGSPRT, Knoxville, Oak Ridge, London (KY), Asheville (NC), and Jackson (KY). Three stations London (KY), Asheville (NC), and Jackson (KY) are located outside of Tennessee, in North Carolina and Kentucky which are 71.9 Mi., 73.2 Mi., and 84.3 Mi. away from the site, respectively as, shown in Table 6. Site 1028 elevation is 1136 ft. above sea level. The MERRA virtual station elevation is 1416 ft. which is 280 ft. higher than the site but it is located only 14 miles from the site while the selected MEPDG stations had high elevation differences from the analyzed site. These differences ranged between -667 ft. to 981 ft. as shown in Table 6. These high differences in elevation are expected to affect the interpolated climate inputs as it was found in earlier studies (Li et al.).

Table 6 Site 1028 Design Inputs

Site #	1028
Route	11
Latitude, Longitude	-83.12206, 36.38314
Elevation	1136 ft
Two-way AADTT	720
TTC	2
AC Layer Thickness	1 in
Base Layer	A-1-b
Subgrade Layer	A-7-6
Nearby MEPDG climate stations (Distance from site in Miles)	Bristol (49.5), Knoxville (61.9), Oak Ridge (66.6), London (KY) (71.9), Asheville (NC) (73.2), Jackson (KY) (84.3)
MERRA Station (Distance from site in Miles)	Site 1028 (14.4 mi)
Nearby MEPDG climate stations elevation difference (ft.)	Bristol / Jhnsn CTY/ KNGSPRT (-667), Knoxville (-174), Oak Ridge (-223), London (KY) (45), Asheville (NC) (981), Jackson (KY) (194)
MERRA Station elevation	1416 ft

Site 1029 is located on route 28 in Marion County, the selected nearby stations to model the climate in this site were as follows: Chattanooga, Rome (GA), Crossville, Huntsville (AL), Cartersville (GA), and Nashville.

Similarly, it was noticed that some of the nearby stations are located far from the site, and some of them are outside the state of Tennessee, like Rome, Georgia and Huntsville, Alabama stations. The MERRA virtual station used for this site was located 17 miles from the site with about 300 ft. elevation difference as shown in Table 7.

Some of the nearby MEPDG stations have similar elevations like Huntsville (AL) with only one-foot elevation difference, but other stations had a high elevation difference like Crossville with 1237 ft. elevation difference as shown in Table 7.

Site 2008 is located on route 43 in Gibson County. This site has six nearby MEPDG climate stations are as follows Jackson, Blytheville (AR), Paducah (KY), Memphis, Clarksville, and West Memphis (AR). Although MEPDG stations used to interpolate the climate inputs for this site has moderate elevation differences compared to the previous sites, the noticed elevation difference was between -236 ft. and 72 ft. However, the MERRA station which located only 10.7 miles from the site with 12 ft. elevation difference is anticipated to model the climate in this station in a better way than the virtual weather station generated from these nearby stations since these MEPDG climate stations as shown in Table 8.

It was also noticed that three of the nearby weather stations are located outside of the state of Tennessee like Blytheville and West Memphis which are located in Arkansas and Paducah which is located in Kentucky.

Table 7 Site 1029 Design Inputs

Site #	1029
Route	28
Latitude, Longitude	-85.62516, 35.05654
Elevation	621 ft
Two-way AADTT	736
TTC	6
AC Layer Thickness	3.9 in
Asphalt Base	12.9 in
Unbound (granular) Subbase	A-1-b
Subgrade Layer	A-2-6
Nearby MEPDG stations (Distance from site in Miles)	Chattanooga (24.1), Rome (GA) (55.6), Crossville (68.6), Huntsville (AL) (71.7), Cartersville (GA) (78.1), Nashville (94.6)
MERRA Station (Distance from site in Miles)	Site 1029 (17 mi)
Nearby MEPDG stations elevation difference (ft.)	Chattanooga (50), Rome (GA) (71), Crossville (1237), Huntsville (AL) (1), Cartersville (133), Nashville (-21)
MERRA Station elevation	944 ft

Table 8 Site 2008 Design Inputs

Site #	2008
Route	43
Latitude, Longitude	-88.74789, 35.8587
Elevation	488 ft
Two-way AADTT	1058
TTC	4
AC Layer Thickness	14.4 in
Base Layer	Cement Treated Base
Subgrade Layer	A-7-6
Nearby MEPDG climate stations (Distance from site in Miles)	Jackson (20.9), Blytheville (AR) (60.8), Paducah (KY) (82.7), Memphis (88.7), Clarksville (91), West Memphis (AR) (97.3)
MERRA Station (Distance from site in Mile)	Site 2008 (10.8 mi)
Nearby MEPDG climate stations elevation difference (ft.)	Jackson (-58), Blytheville (AR) (-236), Paducah (KY) (-84), Memphis (-183), Clarksville (72), West Memphis (AR) (-227)
MERRA Station elevation	476 ft.

Site 3075 is located on route 56 in Mc Minn County. The six nearby stations were as follows: Crossville, Nashville, Bowling Green (KY), Chattanooga, Oak Ridge, and Knoxville. These stations are also far from the site, but most of them are within the state of Tennessee except Bowling Green, Kentucky which is outside of the state of Tennessee. The selected MERRA station is 15.5 miles away from the site as shown in Table 9.

These MEPDG stations had high elevation differences having two stations are lower than the analyzed site with more 400 ft. and one site is higher than the analyzed site with more than 800 ft. as shown in Table 9.

Site 3101 is located on route 96 in Cannon County. The six nearby stations were as follows: Nashville, Crossville, Green Bowling (KY), Chattanooga, Clarksville, and Huntsville (AL). Similar to the other analyzed sites, these stations are located quite distant from the analyzed site which will affect the accuracy of the interpolated data. Some of MEPDG nearby climate stations are located outside of Tennessee. On the other hand, the MERRA station is located only 7.9 miles away from the analyzed site as shown in Table 10.

Five of the selected MEPDG stations are lower than the analyzed site. The elevation difference between these stations and the analyzed range between 99 ft. to 245 ft. The last station was higher than the analyzed section by more than 1000 ft. These elevation differences are expected to reduce the accuracy of the predicted climate inputs for this site.

Site 3108 is located on I-75 in Anderson County. This site is located within less than one mile from Oak Ridge MEPDG climate station, so it was used to represent the climate on this site. The MERRA station used for this site was located 13.1 miles away as shown in Table 11. For this site, both MEPDG and MERRA are expected to model the climate accurately since both are located close to the site so no need to use virtual weather station.

Site 6015 is located on I-75 in Mc Minn County. The six nearby stations were as follows: Knoxville, Oak Ridge, Crossville, Knoxville, Knoxville and Chattanooga. All of the nearby stations are located in the state of Tennessee. The selected MERRA station is located 9.7 miles away from the analyzed site.

Elevation differences were noticed between these MEPDG stations and the selected site. One of these stations had similar elevation while the other five stations had elevation differences ranged between -99 ft. to 845 ft. from the analyzed site.

These elevation differences are anticipated to affect the accuracy of the interpolated data as shown in Table 12.

Table 9 Site 3075 Design Inputs

Site #	3075
Route	56
Latitude, Longitude	-85.73592, 36.07004
Elevation	1020 ft.
Two-way AADTT	660
TTC	13
AC Layer Thickness	5 in
Base Layer	Crushed Stone
Subgrade Layer	A-1-a
Nearby MEPDG climate stations (Distance from site in Miles)	Crossville (37.3), Nashville (53.3), Bowling Green (KY) (73.9), Chattanooga (77.7), Oak Ridge (84), Knoxville (99.4)
MERRA Station (Distance from site in Miles)	Site 3075 (15.5 mi)
Nearby MEPDG climate stations elevation difference (ft.)	Crossville (838), Nashville (-420), Bowling Green (KY) (-495), Chattanooga (-349), Oak Ridge (-107), Knoxville (-3)
MERRA Station elevation	669 ft.

Table 10 Site 3101 Design Inputs

Site #	3101
Route	96
Latitude, Longitude	-86.12225, 35.94223
Elevation	770 ft
Two-way AADTT	146
TTC	12
AC Layer Thickness	5 in
Asphalt Treated Base Thickness	3.3 in
Subbase Layer	Crushed Stone
Subgrade Layer	A-7-6
Nearby MEPDG climate stations (Distance from site in Miles)	Nashville (33.9) Crossville (58), Green Bowling (KY) (73.8), Chattanooga (81.4), Clarksville (85.9), Huntsville (AL) (97.1)
MERRA Station (Distance from site in Miles)	Site 3101 (7.9 mi)
Nearby MEPDG climate stations elevation difference (ft.)	Nashville (-170) Crossville (1088), Green Bowling (KY) (-245), Chattanooga (-99), Clarksville (-210), Huntsville (AL) (-148)
MERRA Station elevation	669 ft.

Table 11 Site 3108 Design Inputs

Site #	3108
Route	I-75
Latitude, Longitude	-84.08899, 36.17553
Elevation	947 ft
Two-way AADTT	7918
TTC	1
AC Layer Thickness	8.2 in
Asphalt Treated Base Thickness	6.7 in
Subbase Layer	Crushed Stone
Subgrade Layer	A-7-5
Nearby MEPDG climate stations (Distance from site in Miles)	Oak Ridge (0)
MERRA Station (Distance from site in Miles)	Site 3108 (13.1 mi)
Nearby MEPDG climate stations elevation difference (ft.)	Oak Ridge (-34)
MERRA Station elevation	1039 ft.

Table 12 Site 6015 Design Inputs

Site #	6015
Route	I-75
Latitude, Longitude	-84.52912, 35.58542
Elevation	1012 ft
Two-way AADTT	6720
TTC	1
AC Layer Thickness	4 in
Asphalt Treated Base Thickness	7 in
Base Layer	A-1-b
Subgrade Layer	A-4
Nearby MEPDG climate stations (Distance from site in Mile)	Knoxville (30.1), Oak Ridge (34.5), Crossville (40.1), Knoxville (45.3), Knoxville (46.8) and Chattanooga (53.7)
MERRA Station (Distance from site in Mile)	Site 6015 (9.7 mi)
Nearby MEPDG climate stations elevation difference (ft.)	Knoxville (5), Oak Ridge (-99), Crossville (846), Knoxville (520), Knoxville (195) and Chattanooga (-341)
MERRA Station elevation	948 ft.

Site 9025 is located on route 96 in Cannon County. The six nearby stations were as follows: Nashville, Crossville, Green Bowling (KY), Chattanooga, Clarksville, and Huntsville (AL).

Similar to the other analyzed sites, these stations are located distant from the analyzed site, had high elevation differences and some of MEPDG nearby climate stations are located outside of Tennessee.

Green Bowling (KY) and Huntsville (AL) stations are located in Kentucky and Alabama respectively. Five of these nearby MEPDG climate stations are lower than the analyzed site with elevation difference ranged between 64 ft. to 214 ft. while Crossville station is higher than analyzed site by 1123 ft. as shown in Table 13. On the other hand, the MERRA station is located only 7.9 miles away from the analyzed site with the same elevation as shown in Table 13. This site is very close to site 3101, so they have very similar design inputs.

Table 13 Site 9025 Design Inputs

Site #	9025
Route	96
Latitude, Longitude	-86.09654, 35.95184
Elevation	735 ft
Two-way AADTT	136
TTC	12
AC Layer Thickness	5.9 in
AC Treated Base Thickness	3 in
Subbase Layer	A-1-b
Subgrade Layer	Rock
Nearby MEPDG climate stations (Distance from site in Mile)	Nashville (35) Crossville (56.5), Green Bowling (KY) (73.5), Chattanooga (81), Clarksville (86.7), Huntsville (AL) (98.3)
MERRA Station (Distance from site in Mile)	Site 9025 (6.3 mi)
Nearby MEPDG climate stations elevation difference (ft.)	Nashville (-135), Crossville (1123), Green Bowling (KY) (-210), Chattanooga (-64), Clarksville (-175), Huntsville (AL) (-113)
MERRA Station elevation	735 ft.

Using these mentioned design inputs and a design life of 20 years, two scenarios were developed for each site for comparison purposes. In the first scenario, MEPDG climate inputs were used while in the second scenario MERRA climate inputs were used. All other inputs parameters like traffic and material inputs were the same for both scenarios. The predicted IRI, permanent deformation, AC bottom-up cracking, AC thermal cracking, AC top-down fatigue cracking values, and optimized AC layer thickness were compared for the two scenarios.

The deviation between the predicted distresses between the two scenarios was calculated using equation (1). To investigate the significance of this difference between these scenarios a paired T-statistical test with confidence level of 95% was performed.

$$\text{Deviation (\%)} = \frac{(Distress\ predicted\ by\ MERRA - Distress\ predicted\ by\ MEPDG) * 100}{Distress\ predicted\ by\ MEPDG} \qquad \text{equation (1)}$$

1.6 RESULTS

As mentioned in section 2.1, the objective of this study is to evaluate and compare the performance of pavements in Tennessee using MERRA and the updated AASHTOWare databases as a source of climate data inputs for MEPDG in the state of Tennessee. To achieve this, a comparative analysis was conducted between MERRA and MEPDG climate data input to evaluate the predicted distresses on eight LTPP sites in Tennessee. IRI, bottom-up cracking, top-down cracking, transverse cracking, total rutting depth and AC top-down fatigue cracking were compared between the two climate data sources.

The calculated IRI values indicate that MERRA estimates slightly higher IRI than MEPDG, about 1% higher as shown in Table 14. The deviations between MEPDG and MERRA is expected to be small because IRI is not very sensitive to climate inputs. Although using updated MEPDG database in this study, these results are similar to previous research outcomes that showed that IRI is the least sensitive distress to climate changes (Byram et al.; Li et al.).

Table 14 IRI Distress Predictions

Site #	Allowable Limit	Predicted distress using Updated MEPDG Climate Database (in/mile)	Predicted distress using MERRA Climate Database (in/mile)	Deviation
1028	200	114.99	116.3	1.14%
1029	200	107.64	108.96	1.23%
2008	200	125.15	125.42	0.22%
3075	200	136.1	137.26	0.85%
3101	200	120.15	120.61	0.38%
3108	160	114.35	115.59	1.08%
6015	160	140.45	142.9	1.74%
9025	200	106.17	106.71	0.51%

Total rut depth values were predicted for the analyzed sites, and the deviation between the predicted values using MERRA and MEPDG climate data sources was calculated for the eight LTPP stations as shown in Table 15. The predicted distresses using MERRA climate database were also higher than the predicted distresses by MEPDG, although both were below the limiting rut depth of 0.5 in. Most of the analyzed sites had a deviation in the range of 8% to 18% between the estimated distresses from the two climate sources. These differences are expected since rutting was reported as the most sensitive distress to climate changes in a previous study compared pavement performance using MERRA and old MEPDG climate database (Schwartz et al. "Alternative Source of Climate Data for Mechanistic–Empirical Pavement Performance Prediction").

These differences are in part due to interpolating climate from far stations with elevation differences that affect the accuracy of the interpolated climate data.

Table 15 Total Rutting Distress Predictions

Site #	Allowable Limit	Predicted distress using Updated MEPDG Climate Database (in)	Predicted distress using MERRA Climate Database (in)	Deviation
1028	0.50	0.16	0.19	18.75%
1029	0.50	0.21	0.23	9.52%
2008	0.50	0.18	0.18	0.00%
3075	0.50	0.34	0.37	8.82%
3101	0.50	0.22	0.24	9.09%
3108	0.40	0.26	0.29	11.54%
6015	0.40	0.31	0.36	16.13%
9025	0.50	0.08	0.09	12.50%

The predicted AC bottom-up fatigue cracking distress followed almost a trend similar to IRI output as shown in Table 16.

MERRA climate inputs estimated higher distresses of about 1% for most of the sites. Only one site had a deviation of 49%. This high deviation for this site was not expected since AC bottom-up fatigue is not sensitive to climate inputs as reported in previous study in Canada using locally collected climate data (Saha et al.).

Site 3075 is located on route 56 in Mc Minn County with AADTT of 660. For this particular site, the climate inputs were interpolated from MEPDG stations with high elevation differences such as Crossville station which is 838 ft. higher site-3075 and Bowling Green (KY) station which is 495 ft. lower than site-3075. Two of MEPDG stations are lower than the analyzed site with more 400 ft. while one site is higher than the analyzed site with more than 800 ft. Therefore interpolating climate data from stations with high elevation differences are probably the reason for this high deviation.

Table 16 AC Bottom-Up Fatigue Cracking Distress Predictions

Site #	Allowable Limit	Predicted distress using Updated MEPDG Climate Database (% lane area)	Predicted distress using MERRA Climate Database (% lane area)	Deviation
1028	20	2.05	2.06	0.49%
1029	20	2.04	2.06	0.98%
2008	20	2.04	2.04	0.00%
3075	20	11.67	17.45	49.53%
3101	20	2.02	2.06	1.98%
3108	10	2.11	2.14	1.42%
6015	10	2.12	2.14	0.94%
9025	20	2.00	2.02	1.00%

When comparing the predicted AC thermal cracking using MERRA versus using MEPDG climate database, there was no clear trend noticed as shown in Table 17. For some of the sites both MEPDG and MERRA estimated similar distresses while on other sites there were some differences. On sites 1028 and 3075, MEPDG estimated higher distresses than MERRA which is not expected since previous findings showed that MERRA estimates higher distresses (Schwartz et al. "Evaluation of Long-Term Pavement Performance (Lttp) Climatic Data for Use in Mechanistic-Empirical Pavement Design Guide (Mepdg) Calibration and Other Pavement Analysis").

These unanticipated results are due to elevation differences between these two sites and the available nearby weather stations in MEPDG climate database which affect the accuracy of interpolated virtual weather station as it was reported in previous research (Li et al.). Site-1028 elevation is 1136 ft. above sea level. The MERRA station used for this site elevation is 1416 ft. which is 280 ft. higher than the site but it is located only 14 miles from the site while the selected MEPDG stations had high elevation differences from the analyzed site. These differences ranged between -667 ft. to 981 ft. as shown in Table-6.

Furthermore, it can be noticed that site 3075 AC thermal cracking prediction was also unexpected prediction as its AC bottom-up fatigue cracking prediction.

Table 17 AC Thermal Cracking Distress Predictions

Site #	Allowable Limit	Predicted distress using Updated MEPDG Climate Database (ft/mile)	Predicted distress using MERRA Climate Database (ft/mile)	Deviation
1028	700	26.76	26.38	-1.42%
1029	700	26.2	27.17	3.70%
2008	700	26.55	30.44	14.65%
3075	700	27.17	26.25	-3.39%
3101	700	27.17	30.68	12.92%
3108	500	26.59	27.17	2.18%
6015	500	27.17	27.17	0.00%
9025	700	27.17	27.17	0.00%

The predicted AC top-down fatigue cracking showed high deviations and did not follow any trend as shown in Table 18. These unrealistic predictions are due to some issues with the top down fatigue cracking prediction model in the current version of MEPDG AASHTOWare as reported in previous study that compared pavement performance using MERRA and old MEPDG climate database (Schwartz et al. "Alternative Source of Climate Data for Mechanistic–Empirical Pavement Performance Prediction").

Table 18 AC Top-Down Fatigue Cracking Distress Predictions

Site #	Allowable Limit	Predicted distress using Updated MEPDG Climate Database (ft/mile)	Predicted distress using MERRA Climate Database (ft/mile)	Deviation
1028	2000	263.61	266.08	0.94%
1029	2000	291.46	538.58	84.79%
2008	2000	264.96	265.36	0.15%
3075	2000	2900.95	2949.67	1.68%
3101	2000	1462.9	2081.16	42.26%
3108	2000	279.1	291.7	4.51%
6015	2000	277.5	344.04	23.98%
9025	2000	547.96	969.42	76.91%

The optimized AC layer thickness was calculated using both climate data sources. The optimized AC thickness values were similar for most of the sections as shown in Table 19.

On four out of eight sites, MERRA estimated higher AC layer thickness; this may be attributed to the fact that MERRA has access to more comprehensive climate data which allows better climate modeling for pavement performance. Additionally, the low quality of some MEPDG climate stations which was reported in previous studies might be also a reason for these unexpected results (Johanneck). Furthermore, using these distant stations with different elevations also affect the accuracy of interpolated VWS (Li et al.).

Table 19 AC Layer Optimized Thickness

Site #	MEPDG (inch)	MERRA (inch)
1028	1	1
1029	1	1
2008	7	7
3075	8	8.5
3101	4	5
3108	5	6
6015	4	5.5
9025	5	5

From this comparison, it can be noticed that although the updated MEPDG AASHTOWare climate database solved the data availability concerns with previous versions but using MERRA as climate inputs source is anticipated to provide better climate predictions since MEPDG AASHTOWare still interpolates the climate data from stations that have high elevation differences. These high elevation differences tend to affect the accuracy of the interpolated data. Furthermore, MERRA database has high-quality climate data and a better geographic coverage. This better geographic coverage eliminates the need to use virtual weather station so no further need to use climate stations with high elevation differences.

1.7 Statistical Analysis

To examine the research Null hypothesis that there is no difference between distresses predicted using MEPDG and MERRA climate inputs, paired T-test and Wilcoxon sum-rank test were used. The paired T-test and Wilcoxon sum-rank test were performed on permanent deformation, AC bottom-up cracking, AC thermal cracking, IRI, and AC top-down fatigue cracking distresses. The statistical analysis was performed at a confidence level of 95% with a null hypothesis that there is no difference between distresses predicted using MEPDG and MERRA climate inputs. The alternative hypothesis was there is a difference between distresses predicted using MEPDG and MERRA climate inputs.

According to Quantile-Quantile (Q-Q) plot shown in Figure-9, permanent deformation followed normal distribution. Therefore, T-paired was used to examine the research null hypothesis.

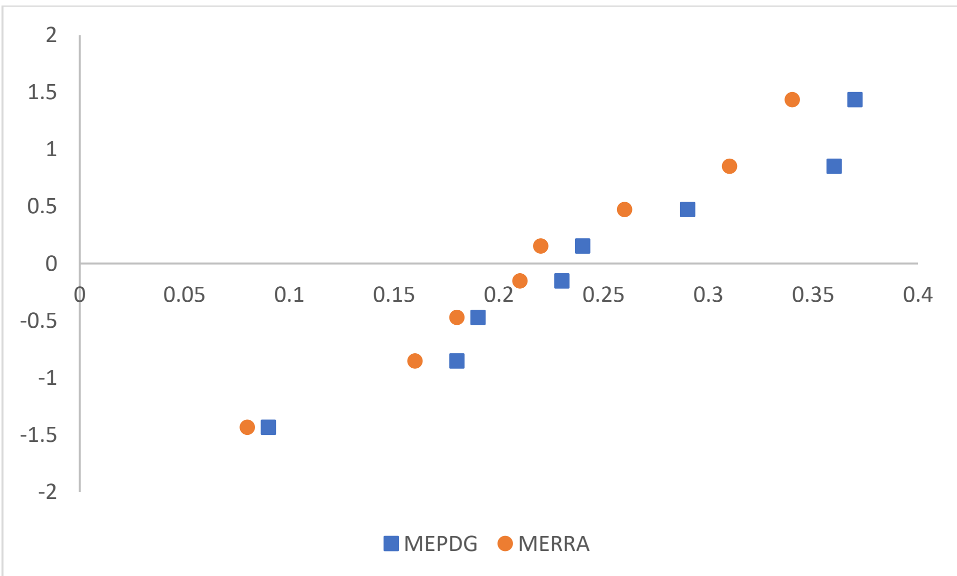

Figure 9 Q-Q Plot for Permanent Deformation

The paired T-test for permanent deformation produced a p-value of 0.003 (<0.05) as shown in Table 20. This result specifies that the null hypothesis is rejected since p-values is less than the significance level. The rejection of the null hypothesis indicates that the differences between MERRA and MEPDG predictions for permanent deformation are statistically significant.

These differences are expected since permanent deformation is very sensitive to climate inputs as reported in previous studies (Schwartz et al. "Alternative Source of Climate Data for Mechanistic–Empirical Pavement Performance Prediction").

Table 20 Paired T-test Results for Permanent Deformation

Observations	8
P(T<=t) two-tail	0.003

According to AC bottom-up cracking Q-Q plot, populations underlying those samples cannot assumed to be normally distributed, therefore, nonparametric Wilcoxon rank sum test is used to conduct the hypothesis test. The Wilcoxon test results show that AC bottom-up cracking p-value was 0.315 (>0.05) which means failure to reject the null hypothesis since p-value is greater than significance level. This result shows the differences in predictions between the two sources are statistically insignificant as shown in Table 21.

This result is expected since AC bottom-up fatigue is not sensitive to climate inputs as found in earlier studies (Saha et al.).

Table 21 Wilcoxon Rank Sum Test for AC Bottom-Up Cracking

Observations	8
P-value	0.315

The AC thermal cracking Q-Q plots were similar to AC bottom-up cracking Q-Q plots, therefore Wilcoxon rank sum test was used. Wilcoxon rank sum test resulted a p-value of 0.287 (>0.05). This value indicates that there is no significant difference between the two predicted distresses from the two sources since this p-value fails to reject the null hypothesis as shown in Table 22.

This result indicate that thermal cracking distress in the state of Tennessee is not very sensitive to climate inputs. This finding is similar to results found in a previous study in Canada (Saha et al.).

Table 22 Wilcoxon Rank Sum Test for AC Thermal Cracking

Observations	8
P-value	0.287

According to Quantile-Quantile (Q-Q) plot shown in Figure-10, IRI distresses assumed to follow normal distribution and a paired T-test was performed to investigate the hypothesis of the research.

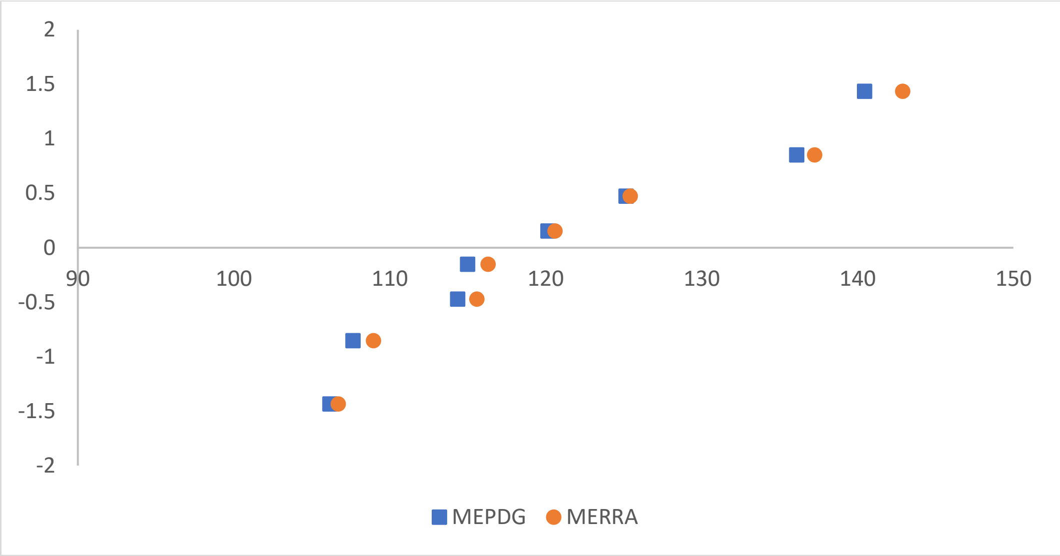

Figure 10 IRI Q-Q Plot

The paired T-test results showed a P-value of 0.003 (<0.05) which means rejection of the null hypothesis, therefore these two sources are expected to predict significantly different IRI distresses as shown in Table 23.

These results are different from some of the previous findings that stated that IRI is the least sensitive distress to climate inputs, therefore, these different predictions may be attributed to MEPDG climate database low geographical distribution, meaning using distant stations with differences in elevation, and the current MEPDG issues in estimating fatigue distress since IRI is calculated as function of area of fatigue cracking (AASHTO; Johanneck; Li et al.; Schwartz et al. "Alternative Source of Climate Data for Mechanistic–Empirical Pavement Performance Prediction").

Table 23 Paired T-test Results for IRI

Observations	8
P(T<=t) two-tail	0.003

The AC top-down fatigue cracking Q-Q plot shows that these distresses do not follow normal distribution. Therefore, Wilcoxon rank sum test was performed. The Wilcoxon rank sum test resulted a p-value of 0.442 (>0.05) as shown in Table 24 which means fail to reject the null hypothesis, so these two sources are expected to predict insignificantly different distresses but these results cannot prove that MEPDG and MERRA climate inputs estimate similar AC top-down fatigue cracking since the current version of MEPDG AASHTOWare has some issues estimating AC top-down fatigue cracking (Schwartz et al. "Alternative Source of Climate Data for Mechanistic–Empirical Pavement Performance Prediction").

Moreover, the high variance values and the difference between the mean values for MEPDG and MERRA also proves that the current version of MEPDG AASHTOWare has some unrealistic estimation for AC top-down fatigue cracking as mentioned earlier in section 4.2 and reported by previous studies (Schwartz et al. "Alternative Source of Climate Data for Mechanistic–Empirical Pavement Performance Prediction")

Table 24 Wilcoxon Rank Sum Test for AC Top-Down Fatigue Cracking

Observations	8
P-value	0.442

CHAPTER V

CONCLUSIONS

The updated MEPDG climate database overcomes the limited climate data availability issue that existed in the previous versions since it offers 37 years of climate data for the period from 1979 to 2015 (Brink et al.), however, it is still challenged with the limited geographic coverage nationwide and particularly in the state of Tennessee. Due to this limited geographic coverage, distant stations with high elevation differences are selected to model the climate data in the analyzed sites which reduces the accuracy of climate data. These high elevation differences generated unexpected results as it was noticed for sites 1028 and 3075.

A comparative study was conducted to evaluate the performance of pavement in the state of Tennessee using MERRA and updated MEPDG climate database as sources of climate data inputs for MEPDG in the state of Tennessee. From this comparative analysis, it was found that MERRA climate inputs estimate higher distresses than MEPDG climate input which is consistent with other findings in the available literature although this study compared MERRA to the updated MEPDG climate database while the other study compared MERRA to the old MEPDG climate database (Schwartz et al. "Evaluation of Long-Term Pavement Performance (Lttp) Climatic Data for Use in Mechanistic-Empirical Pavement Design Guide (Mepdg) Calibration and Other Pavement Analysis").

It was also noticed that although the observed deviations in predicted IRI distress were about 1%, the statistical analysis showed that MERRA and updated MEPDG climate database are expected to provide different IRI predictions. These results indicate that IRI is sensitive to climate inputs. This finding about IRI is in contrast to previous findings in earlier studies that assessed the accuracy of the virtual weather stations climate data using Automated Weather Stations data. This study showed that IRI is not sensitive to climate inputs (Li et al.). Therefore investigation for more sites is recommended in this area to examine if the climate in the state of Tennessee affects the IRI predictions or there are different reasons for these results.

The observed deviation between the predicted rutting distresses between the two scenarios was higher than 10% for most of the analyzed sites. This high deviation shows that rutting is very sensitive which was proved by the statistical analysis results. These findings in line with previous findings it was reported in earlier study evaluated pavement performance using MERRA and previous MEPDG AASHTOWare climate database (Schwartz et al. "Alternative Source of Climate Data for Mechanistic–Empirical Pavement Performance Prediction"). Asphalt is temperature susceptible material, elastic in cold temperature and viscous in hot temperature, which makes it very sensitive to failure related to temperature change like rutting. Moreover, it shows that although the length of available data for MERRA and updated MEPDG climate database is similar but using distant stations affects the accuracy of climate prediction due to elevation differences.

The noticed high deviation in AC top-down fatigue cracking agrees with the suggestion that the current MEPDG version has some issues in predicting AC top-down fatigue cracking which is currently being studied for improvement as also noticed in previous studies (Schwartz et al. "Alternative Source of Climate Data for Mechanistic–Empirical Pavement Performance Prediction").

These findings show that using MERRA as a climate data source for the state of Tennessee will offer a better geographic coverage and therefore more robust climate predictions are expected since it eliminates the need to interpolate the climate data from other stations. Furthermore, previous studies showed that MERRA has better data reliability and quality than the other available climate resources and NASA is targeting to achieve 10 meters horizontal resolution (Schwartz et al. "Alternative Source of Climate Data for Mechanistic–Empirical Pavement Performance Prediction"). Therefore, the state of Tennessee can use MERRA as a source of climate inputs to enhance the climate database in Tennessee and provide better geographic coverage. A further study that will validate the results using measured distresses and more test sites representing different geographical terrain is recommended.

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VITA

Abubakr Ziedan was born in 1990 in Khartoum, Sudan to the parents of Mohamed Salah and Somia. He is the youngest among one brother and sister. In 2007, he was admitted to the University of Khartoum where he earned his Bachelor of Science (Honors) in Civil Engineering with First Class in 2012. After graduation, Mr. Ziedan worked as Transportation Planner for Public Transport Authority, then as Transportation Modeler for MEFIT Consultants in 2013 and Transportation Engineer at the Ministry of Infrastructures and Transportation, Khartoum, Sudan. At the same time he was working as a part-time teaching assistant for the Department of Civil Engineering at the University of Khartoum. In January 2016, Mr. Ziedan accepted a graduate research assistantship at the University of Tennessee at Chattanooga, where he started to pursue his master's degree in Civil Engineering and Graduated in December 2017.