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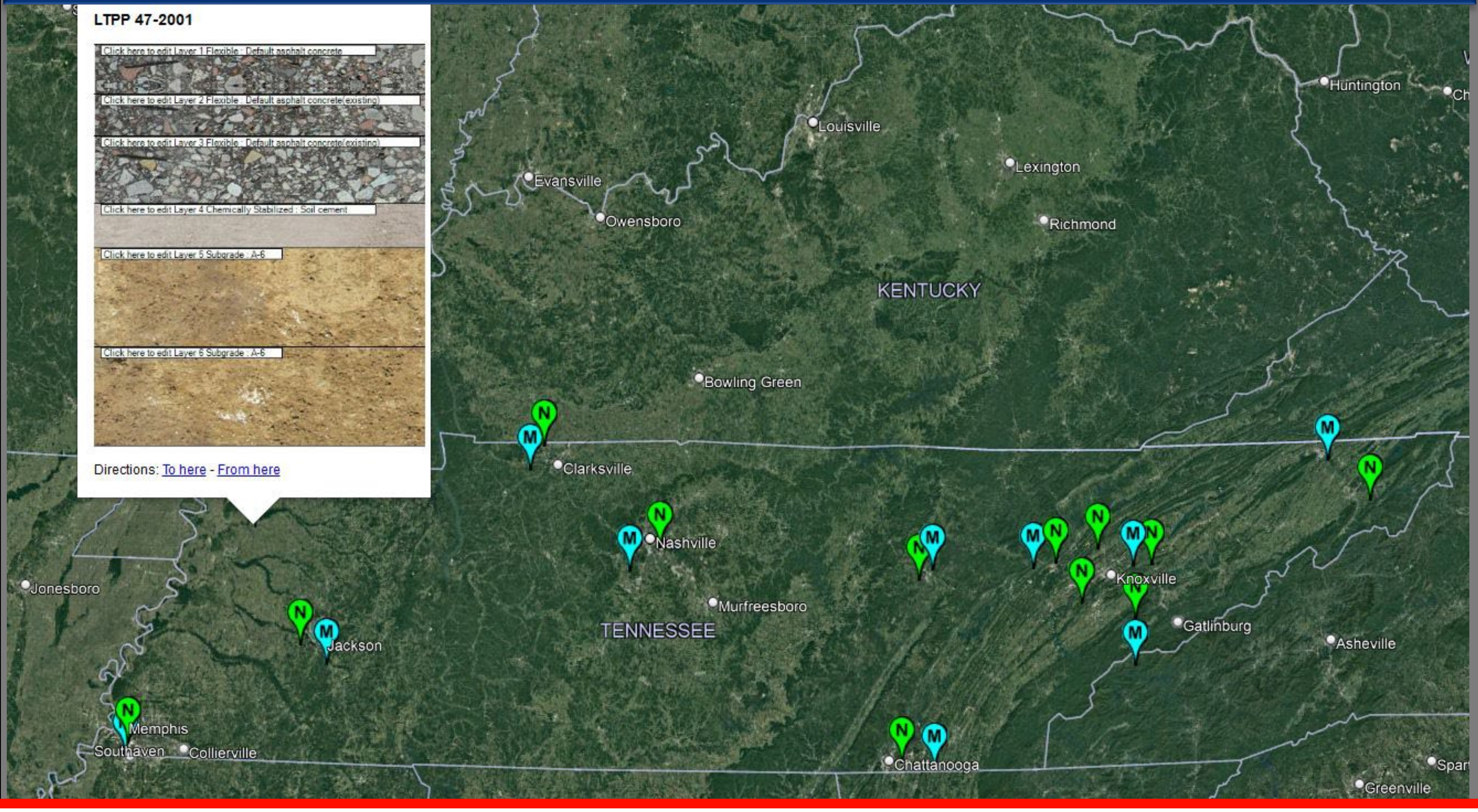

MEPDG Climate Data Input for the State of Tennessee

Final Report

Research Final Report from University of Tennessee at Chattanooga | Mbakisya Onyango (PI), Joseph Owino (Co-PI), Weidong Wu (Co-PI) and Kelvin Msechu (GA) | May 31, 2022

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THE UNIVERSITY OF TENNESSEE CHATTANOOGA

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16. Abstract

The Pavement Mechanistic Empirical Design (PMED) method was developed to address shortcomings experienced on the AASHTO Guide for Design of Pavement Structures (1993) including environmental/climate considerations. However, the implementation of PMED requires a large number of design inputs that characterize materials, traffic, and climatic conditions. This project was conducted to address the PMED climate input data for the state of Tennessee. Two climatic data sources were considered, North American Regional Reanalysis (NARR), and Modern-Era Retrospective Analysis for Research and Application (MERRA). First, the sensitivity analysis using 2^k factorial design method considering lower and higher extremes of each climatic input and water table was performed to determine climatic inputs sensitive to pavement distresses. Then, Virtual Weather stations (VWSs) were created, and their predicted performance was analyzed in comparison to the existing stations. Lastly, the performance analysis of NARR and MERRA climatic data sources considered pavement distress predictions, and surface layer optimization. On sensitivity analysis of the EICM model, temperature was the most sensitive climatic input in PMED distress predictions, while humidity had no effect to pavement distress predictions. Performance evaluation of PMED VWSs indicated a significant difference in some of the predicted distresses when comparing PMED VWSs and MERRA stations at identical locations. The performance analysis of NARR and MERRA climatic data sources using surface layer optimization, indicated that MERRA optimized surface layer thicknesses were not significantly different from the original surfaces, while NARR and input Levels 2 and 3 thicknesses were significantly different from the original layer thicknesses.

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Executive Summary

This research was conducted by the University of Tennessee at Chattanooga (UTC) in collaboration with Tennessee Department of Transportation (TDOT) to select the most appropriate climatic data input source for Pavement Mechanistic Empirical Design (PMED). Two climatic data sources were considered, North American Regional Reanalysis (NARR), and Modern-Era Retrospective Analysis for Research and Application (MERRA).

The research team spent time first to understand the operation of the climatic model function of the Pavement Mechanistic-Empirical Design (PMED) software, by evaluating (i) the sensitivity of the PMED software to climatic input changes, and (ii) performance of the Virtual Weather Station (VWS) tool that is used to create virtual stations by data interpolation from existing weather stations. Secondly, the research team assessed the performance of the two climatic data files, NARR, and MERRA, using the LTPP and TDOT sites to compare predicted distresses, and to optimize the surface layer thickness.

The sensitivity analysis utilized 2^k factorial design method with lower and higher extremes of each climatic input (temperature, windspeed, relative humidity, percent sunshine), and water table depth. A total of 32 hourly climatic data files were created with 36.5 years of hourly climatic data. Each of the 32 climatic files represented a combination of the climatic input and water table depth extremes (lower and higher). Three Long Term Pavement Performance (LTPP) sites with different pavement cross section profiles, material properties, and traffic data were used for analysis in the PMED software with the 32 climatic files as climatic stations. Results indicated that temperature was the most sensitive climatic input affecting all the predicted distresses on all pavement types. The depth of water table was the most sensitive input to the pavement section with surface layer and unbound base (stone base) layer. Wind speed affected most of the pavement distress outputs, while relative humidity had negligible effect to the predicted pavement distresses.

To evaluate the performance of the PMED VWS tool, MERRA climatic stations were used as the climatic data source for VWS interpolation and results comparison because of their good geographic coverage. The VWS interpolation considered eight MERRA climatic stations to create a PEMD VWS at the center of the eight stations, where there is an existing MERRA station. The comparison was between the PMED VWS and the existing MERRA station at the same location. Using this method forty-nine (49) PMED VWSs were created throughout the state of Tennessee. In each PMED VWS station, climatic data files were generated and were compared to the existing MERRA station climatic data files at the same location. Furthermore, five LTPP sites were used with the forty-nine (49) PMED VWSs climatic data files and forty-nine (49) MERRA climatic data files as inputs to predict pavement distresses. Results, on the climatic data summaries, showed a significant difference between predicted and actual average annual number of freeze/thaw cycles and number of wet days. Distress predictions showed a significant difference in jointed plain concrete pavement (JPCP) transverse cracking for rigid pavement sections, and bottom-up cracking, AC permanent deformation, and total pavement deformation within the flexible pavement sections. Other predicted distresses showed no significant difference. This finding led the team to not recommend the use PMED VWS tool because of failure to significantly replicate results at the same location with MERRA station.

This study used pavement distress prediction, and surface layer optimization to evaluate the performance of NARR and MERRA climatic files. Based on the sensitivity analysis performed and the inconsistencies found on the VWS creation tool on PMED software, this research did not use PMED VWSs, instead a single MERRA or NARR station near the site was used. Pavement distress prediction and layer optimization analysis were divided into three groups based on the traffic input parameters and calibration data used. Group 1 (or Level 1) included level 1 traffic data collected by LTPP and Tennessee local material calibrated parameters, Group 2 (or Level 2) was comprised of Tennessee local traffic inputs and local material calibrated parameters, and Group 3 (or Level 3) included national (default) traffic and material parameters.

Fifty-nine (59) LTPP and TDOT pavement sites in the state of Tennessee were considered for distress predictions. All three Levels showed a significant difference between NARR and MERRA climatic files in the prediction of thermal cracking values. The significant difference in the thermal cracking can be associated with NARR having higher predictions than MERRA. Considering the prediction of AC permanent deformation using both parametric and non-parametric hypothesis tests, Level 2 and Level 3 inputs showed a significant difference between NARR and MERRA climatic files using both tests, while Level 1 showed a significant difference in the median for NARR and MERRA climatic files using the non-parametric test. MERRA showed higher AC permanent deformation predictions than NARR.

Surface layer optimization on flexible pavements was conducted by comparing the original layer thickness to the optimized layer thickness using NARR and MERRA climatic files. On this comparison, NARR optimization with Level 2 and Level 3 inputs showed a significant difference with the parametric test only when comparing the mean AC layer thickness. The surface layer optimization with MERRA climatic files did not show any significant difference with all Levels of analysis. This indicates that the AC surface layer thicknesses optimized using MERRA climatic files are close to the original pavement thicknesses. The research team recommends using MERRA climatic data source over NARR.

Key Findings

The following were the key findings that were observed in this research:

- From the sensitivity analysis of the EICM model, temperature appeared to be the most sensitive climatic input in PMED distress predictions.
- Performance evaluation of the PMED VWSs showed statistically significant differences on some of the climatic summaries and distresses predicted when comparing the PMED VWSs and the existing MERRA stations at the same location. This led to the research team not recommending the use of PMED VWS creation tool until it is updated.
- On comparing distresses predicted using NARR and MERRA climatic flies, the analysis of all three input levels showed a significant difference when comparing distress values of thermal cracking and AC permanent deformation (AC rutting).
- AC surface layer optimization showed a significant difference between the original surface layer thicknesses and optimized layers when using NARR climatic files with Level 2, and Level 3 inputs, NARR climatic files predicted relatively thicker layers than the original layer thicknesses.

- AC Surface layer optimization using MERRA climatic files showed no significant difference to the original thicknesses at all three levels of analysis.

Key Recommendations

- Close attention should be paid to the climatic inputs on selection of climatic files to use in PMED software. This study revealed that temperature is the most sensitive input, therefore closer attention should be put on the mean annual air temperature value. If possible, the value of the mean annual air temperature should be compared to values presented by weather channels for that design location.
- The use of PMED VWS creation tool should be avoided as much as possible as it may lead to results that are significantly different from a real/actual weather station data. This conclusion was reached by comparing MERRA data and PMED VWS at the same location and some of the results were significantly different.
- Based on spatial coverage, and up-to-date climatic data, MERRA is recommended for use in the pavement design and analysis for Tennessee pavements.
- On selecting weather stations, TDOT should consider the use of the nearest available weather station and should avoid creating virtual weather stations unless the current PMED VWS model is updated.

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Glossary of Key Terms and Acronyms

AADTT	Average Annual Daily Truck Traffic
AASHTO	American Association of State Highway and Transportation Officials
AC	Asphalt Concrete
AWS	Automated Weather Stations
EICM	Enhanced Integrated Climatic Module
HCD	Hourly Climatic Data
HMA	Hot Mixed Asphalt
IRI	International Roughness Index
JPCP	Jointed Plain Concrete Pavement
LTPP	Long Term Pavement Performance
MEPDG	Mechanistic-Empirical Pavement Design Guide
MERRA	Modern-Era Retrospective Analysis for Research and Application
NARR	North American Regional Reanalysis
NASA	National Aeronautics and Space Administration
OWS	Operating Weather Station
PCC	Plain Cement Concrete
PMED	Pavement Mechanistic-Empirical Design
SEE	Standard Error of the Estimate
TDOT	Tennessee Department of Transportation
USGS	United States Geological Survey
VWS	Virtual Weather Station
VWSs	Virtual Weather Stations

Chapter 1 Introduction

Pavement design procedures have evolved through the years from the use of rule of thumb to empirical designs and currently, to mechanistic-empirical (M-E) design. The ultimate pavement design goal is towards mechanistic design approach. Researching and implementing the design methods through the years, have driven improvements in the design procedures. Over the years, results from various pavement research activities have revealed factors that affect pavement longevity, material performance, and traffic characteristics. The AASHTO Guide for Design of Pavement Structures (1993), for instance, considered drainage factors in the design process, but other climatic related parameters were seldomly considered. This is among the reasons that led to Pavement M-E Design (PMED) method, which considers detailed design inputs in material characteristics, traffic loading, and climate (*1;2;3*). The advancement in computational capabilities is an added advantage to the successful development of mechanistic-empirical design methods.

The data input requirement in the PMED is large, hence it calls for a robust software to design the pavement and predict its performance. AASHTO developed a PMED software, AASHTOWare, to aid in the pavement design process. PMED software contains different models that predict the behavior and performance of a pavement under various conditions. The prediction models are calibrated to reflect the desired design conditions, with respect to materials, traffic, and climate. The software allows the user to enter data in three hierarchical levels: Level 1 represents actual data obtained from the design site, Level 2 represents local/regional data derived from regression analysis of existing information representing a general occurrence of a state or a region, and Level 3 uses national average data representing a general occurrence over a wider area, mostly covering a nation (*3; 4*). Level 1 data is of the highest quality but the hardest and most expensive to obtain as compared to other levels. In the absence of Level 1 data, Level 2 is recommended for use. Level 3 data are the default values and readily available in the software but has the lowest reliability level.

The implementation of PMED by state DOTs require local calibration of model input parameters and establishing local (Level 2) design inputs. TDOT already has the local calibrated material parameters and traffic inputs. This study was commissioned to establish PMED climatic data inputs for the state of Tennessee. Two climatic data sources were considered in the study, the North American Regional Reanalysis (NARR), and Modern-Era Retrospective Analysis for Research and Application (MERRA). NARR uses climate data from available weather stations in the state, while MERRA, developed by the National Aeronautics and Space Administration (NASA), uses spatial stations that covers the whole state and provides continuous hourly weather data since 1985.

1.1 Problem Statement

AASHTO Guide for Design of Pavement Structures (1993), empirical design method, does not adequately consider the effects of climate on the long-term pavement performance. Various research works have acknowledged the influence of climate on pavements. The effects of temperature variation, for instance, have seldom been accounted for in the empirical design methods. For example, the dynamic modulus of asphalt concrete (AC), and resilient modulus of soil, change seasonally due to the influence of temperature. The dynamic modulus of AC is high in cold temperatures to about 2 to 3 million psi, and lower with warm temperature to about 100,000 psi. Similarly, frozen soils resilient modulus increases 20 to 120 times when compared to its unfrozen state. In very cold weather conditions, thermal cracking is the most prevalent distress in asphalt concrete pavements, while hotter weather leads to rutting and deflection. Furthermore, concrete pavements experience blow-up, deflections near joints, and mid-span cracks as a result of temperature variation (*4*).

The variations in climatic conditions, shift the focus of climatic consideration from merely drainage factors to inclusion of all possible climatic factors. PMED uses an Enhanced Integrated Climatic Model (EICM) to account for climatic condition on pavement design. EICM evaluates the effects on pavement due to air temperature, wind speed, precipitation, humidity, percent sunshine and level/depth of water table (*3*).

In 2017 eight LTPP sites in Tennessee were used to analyze the climatic effects by comparing the updated MEPDG climate data and MERRA. In this study, MERRA climate data estimated higher distress values, possibly because it considered more robust climate data than the updated MEPDG, which used NARR climate data, and had twelve weather stations in the state (*5*). These findings indicated that using MERRA's database as the climate input could address climate effects on pavements much better than the updated MEPDG which had 12 weather stations in the state of Tennessee, five of which were located in the Knoxville area. A study that will consider more than eight data points or locations will provide a better analysis of the two climate databases and give TDOT confidence in the selected database and their differences.

TDOT, like other state DOTs, is moving towards the implementation of PMED by calibrating the input parameters and design factors. In its PMED implementation plan, TDOT has already characterized PMED material, and traffic inputs. This research project evaluated the effect of the two climate databases MERRA, and NARR, for pavement design in Tennessee. The results will form part of the PMED implementation plan by confidently selecting the most appropriate climate data input source for Tennessee pavements.

1.1.1 Objective of the Research

The objectives of this research project were to:

- Evaluate the suitability of NARR, and MERRA climate data sources, among other inputs, to design pavements and predict distresses on selected pavement sections in Tennessee.
- Analyze and compare distresses predicted by NARR, and MERRA climate data sources.
- Establish regionwide (Level 2) climate data source for design of Tennessee pavements.

1.1.2 Scope of Work and deliverables

To understand the consideration of climatic data sources on PMED, and select an appropriate database for Tennessee, an extensive literature search was conducted on journals, and reports from state DOTs. This included a detailed study of the NCHRP Project 1-37A Part 2 Chapter 3 final report, and PMED AASHTOWare (*3*). Pavement sites with complete input data were selected as candidates for analysis, this included 48-hour count stations and LTPP sites in the state of Tennessee. These candidate sites required pavement structure, traffic, and material inputs. PMED software was used to predict distresses caused by using NARR, and MERRA climatic data sources. A statistical analysis was utilized to evaluate the pavement performance of the selected sites using the two climatic data sources. Finally, layer optimization was performed using the two climatic data sources and the results were compared to the original pavement thicknesses to determine the climatic data source that adequately represents the condition of the pavements.

This report provides pavement performance and analysis using NARR, and MERRA climatic data sources for the state of Tennessee. The report contains five (5) chapters. Chapter 1 Introduces the project, stating objectives, and scope of the work. Chapter 2 is comprised of literature review on the Enhanced Integrated Climate Model (EICM), Virtual Weather Station (VWS) creation and performance, practices on climatic files quality check, and analysis of PMED climatic data sources. Chapter 3 discusses the methodology used for sensitivity analysis of EICM, assessment of PMED Virtual Weather Stations (VWSs), and comparative analysis of NARR, and MERRA climatic data presented as distress prediction, and layer optimization. Chapter 4 presents and discusses results on EICM sensitivity to climatic inputs, the performance of PMED virtual weather station model, and the comparative analysis of NARR, and MERRA distress prediction and layer optimization. Finally, Chapter 5 concludes the study and reports research findings and recommendations.

Chapter 2 Literature Review

The Pavement M-E Design method requires numerous design inputs in materials, traffic, and climate data. The state of Tennessee in its PMED implementation process has already calibrated local material input parameters, and traffic inputs. This study evaluates the PMED climate input databases/sources that will satisfactorily predict the performance of designed pavements and can be used to design new pavements in Tennessee. PMED uses an Enhanced Integrated Climatic Model (EICM) to evaluate the influence of climatic conditions on pavement design. EICM allows pavement design to include the effects of air temperature, wind speed, precipitation, humidity, percent sunshine, and level/depth of water table (*1*). There have been numerous studies on climate data inputs on PMED software for performance prediction (*5;17;26*). This literature review summarizes studies on the PMED software climate model (EICM), EICM sensitivity analysis, PMED climatic files selection practices, PMED performance with EICM's Virtual Weather Stations, climatic file quality check methods, and PMED default climatic data sources.

2.1 Enhanced Integrated Climatic Model (EICM)

EICM is a one-dimensional program that uses hourly climatic data (HCD) including temperature, wind speed, percent sunshine, humidity, and precipitation to model and predict heat and moisture flow on the pavement layers and subgrade throughout the design life/years of service (*1; 6*). The heat and moisture profiles directly impact distress development and the mechanistic properties of pavement materials. EICM is comprised of three major components/models: climate-material structure model, infiltration-drainage model (ID model), and Frost-heave and settlement model (CRREL model). The first two models were developed at Texas A & M University and the third at the United States Army Cold Regions Research and Engineering Laboratory. The EICM considers a complete pavement structure and subgrade profile in predicting pavement and subgrade water content, frost-heave, frost and thaw depth, pore water pressure, temperature, and resilient modulus adjustment factors for the entire pavement structural design life (1; 6). The following requirements are considered when collecting hourly climatic data and depth of water table, as used in the EICM model (*7*):

1. Hourly climatic data (HCD) includes air temperature (degrees Fahrenheit), wind speed (miles per hour), percent sunshine (0% for cloudy and 100% for clear), precipitation (inches), and relative humidity (percent).
2. Depth of water table (ft.) input represents the moisture condition on which the pavement structure is to be designed/constructed. Depth of water table input on PMED is either an annual value or seasonal values that represent the site's characteristics. Level 2 data for water depth can be obtained from geotechnical/geological investigations conducted on the road section that is to be analyzed or designed. Level 3 data that represent county values can be obtained from Agricultural services or other trusted county coring services (*3*).

EICM is dependent on hourly climatic data for its operation. PMED software allows the pavement designer to select a weather station that best represents the location of pavement design. In cases where no weather station is available near the design site, the software allows interpolation of existing stations to create a Virtual Weather Station (VWS) at the design site. For better quality results, it is recommended to use more weather stations to create a VWS (*3*).

2.2 EICM Sensitivity Analysis

The sensitivity analysis in EICM provides a closer look at the effects and performance of the model at various climatic conditions. The sensitivity analysis gives the designer the awareness of the importance of quality of data used. Poor quality data, especially for the sensitive inputs, will eventually lead to poor pavement designs.

Several studies (*8;9;11;12*) have been performed on the EICM model to understand the performance of pavement sections under different climatic conditions. The studies also aimed at determining the level of sensitivity of each of the EICM inputs had in the design.

In 2005 a study was conducted in the state of New Jersey, to understand the performance and sensitivity of the EICM model. The study considered 24 test sections for analysis. It was reported that flexible pavements were more sensitive to seasonal variation than rigid pavements. The study further evaluated 2 flexible pavements to compare measured and predicted parameters in a 2-year period. The study considered moisture content, ground water depth, pavement temperature, air temperature, rainfall, and frost-thaw depth. The comparison analysis between the measured and EICM predicted temperature and moisture content suggested variation that was statistically significant (*8*).

In 2008 a sensitivity analysis study was performed using the MEPDG software, to assess the impact of climatic inputs on flexible pavements in southern Canada. The analysis predicted the distresses of six Long Term Pavement Performance (LTPP) sites with low traffic volumes. From the analysis, climatic changes showed a significant impact on pavement rutting, longitudinal, and alligator cracking predictions while showing negligible effects on transverse cracking. Higher temperature values resulted to an increase in rutting predictions (*9*).

In 2013 a One-At-a-Time (OAT) climatic input sensitivity analysis was performed for rigid and flexible pavements in Maryland. The OAT sensitivity analysis suggested that the average annual temperature, and average temperature range to be the most sensitive climatic data input parameters for both flexible, and rigid pavements. Percent sunshine and windspeed variations showed little sensitivity in the OAT analysis, while relative humidity and precipitation showed very little sensitivity. The most sensitive distress to climatic input variations in hot mixed asphalt (HMA) were asphalt rutting, total rutting, and longitudinal cracking. For Jointed Plain Concrete Pavement (JPCP), slab cracking was the most sensitive distress to climatic changes (*10*).

In 2014, another study was conducted to investigate the sufficiency and accuracy of Canadian climatic files on the MEPDG software for flexible pavement design. The climatic data was collected by Transportation Association of Canada. The comparison of the freezing index and frost depth was between computed values from the MEPDG and those that were available in other Canadian climatic databases. 201 climatic files from a typical pavement cross section were used. Results indicated a large extent of inconsistency in the permafrost zone. Findings showed that MEPDG software alligator and transverse cracking models were not sensitive to climatic changes; permafrost zone sections predicted significantly higher longitudinal cracking compared to other climatic zones. It was also observed that the rutting model used in the MEPDG was sensitive to climate changes (*11*).

In 2017, researchers conducted a sensitivity study in the state of Michigan using PMED to predict flexible pavement distresses due to climatic inputs. The study selected six representative, geographically distributed sites in Michigan. The findings showed that temperature changes had a significant effect on the prediction of flexible pavement performance whereas other climatic inputs had a lower impact on the predictions. Rutting and the international roughness index (IRI) increased with increase in temperature and percent sunshine, whereas the likelihood for fatigue cracking decreased. Fatigue cracking predictions increased as wind speed or precipitation were increased whereby rutting and IRI predictions decreased. Ambient relative humidity had a negligible effect on the flexible pavements' distress predictions. The study concluded that temperature was the most sensitive climatic input followed by wind speed which affected thermal cracking, AC rutting, total rutting and IRI predictions. Percent sunshine was the third most sensitive parameter, affecting thermal cracking, top-down cracking, and bottom-up cracking predictions. The EICM showed less sensitivity to relative humidity and precipitation (*12*).

In 2020 a 2^k factorial sensitivity analysis was performed on EICM with Tennessee as the case study. The factorial sensitivity analysis considered the maximum and minimum values of five climatic inputs as defined in the PMED software (example percent sunshine maximum = 100%, and minimum = 0%). The factors considered were temperature, windspeed, relative humidity, percent sunshine, and depth of water table. Three pavement sections from LTPP sites were adopted for the analysis. Pavement sections selected represent different flexible pavement sections with different traffic inputs. The study showed that temperature was the most sensitive climatic input affecting all flexible pavement distresses, followed by wind speed, and depth of water table. Percent sunshine showed negligible sensitivity to the pavement performance predictions while relative humidity showed no sensitivity on the predicted distresses using PMED's EICM (*13*).

2.3 EICM Climatic File Selection Practices

A comparative analysis, sponsored by Mississippi Department of Transportation, was performed between MEPDG climate data and a climatic data file created from a combination of other data sources. The team created a new historic climate file with its hourly data obtained from a total 23 Automated Surface Observation System (ASOS) and Automated Weather Observation System (AWOS). The analysis was conducted to compare the impact of MEPDG climate data and historic climate input on jointed Portland Cement Concrete (PCC), thick HMA and thin HMA. Comparing the actual pavement distresses to those predicted by MEPDG climate data and the new historic climate data, it was observed that the MEPDG climate data predicted larger distresses compared to the historic climate data. This observation is mainly due to the few MEPDG climatic data availability (*7; 14*).

Louisiana Department of Transportation and Development built accurate historic and future MEPDG climate input files. The state of Louisiana was divided into nine climate zones. The team applied climate science to improve the depth and length of climate data by using ASOS and the Cooperative Observer Program to generate historical climate file from 1970 to 2010 (40 years). To fill the gap, an interpolation in space and time method was employed to create a historic climate file for each parish. The future climatic files created applied projected changes in climate based on global and regional models from the 40-year historic climate data. From the process, each of the 64 parishes had one future climate file containing a complete dataset from 2010 to 2050 that can be used in predicting future performances reflecting long-term climate trends (*7*).

A comparative analysis was conducted between MERRA and updated MEPDG climate database using eight LTPP sites in the state of Tennessee using PMED AASHTOWare. The Updated MEPDG climate database had only twelve stations in the state, which had less geographic coverage compared to MERRA stations. The distresses predicted by the updated MEPDG weather stations were compared to those predicted using MERRA stations, while keeping other input parameters (traffic and material) constant. The deviations in predictions led to the suggested use of MERRA climate data input as it offers better geographic coverage, thus making it a more robust climate database (*5*).

A study aimed at increasing the number of Michigan's climatic stations beyond the existing 24 weather stations was conducted by the Michigan department of transportation. The team used data from 15 potential ASOS/AWOS stations to fill in the gaps in the PMED climate data. The quality and quantity of the new climatic files were checked for adequacy and consistency by comparing them to the existing data format. The combination of the climatic data files resulted in the increase of climate stations from 24 to 39 at the end of 2014 with the average climatic data length extended from 7.6 to 15.2 years (*15*).

In 2019 an impact assessment was conducted on an existing Fort Worth, Texas, pavement design to evaluate the influence of climate change on pavements for a 20-year service life. The evaluation considered rutting and international roughness index (IRI) for the pavement analysis period. The Texas DOT trigger values for maintenance are 100 in/mile for IRI and 0.4 inches for AC rutting. Evaluation of distresses with historic data gave longer period-to-failure compared to the global model data. Through comparison of these results, it was seen that for the case of IRI and rutting, the maintenance was suggested to be done earlier for the global model (CRCM-CCSM) data compared to what was suggested by the historic data (*16*).

2.4 PMED Performance with EICM's Virtual Weather Station

PMED software allows the user to create Virtual Weather Stations (VWSs) in instances where no nearby weather station is available near the design/analysis site. The VWS is simply a product of interpolation of data from other existing weather stations (*4*). The EICM model uses an inverse square ($1/R^2$) method in the interpolation to create VWS. The inverse square method also referred to as the gravity model, creates VWS by using a weighing criterion. Weather stations closer to the point of VWS creation point are weighted more and hence contribute more to the values of the final data. Figure 2-1 shows an illustration of VWS creation considering five-weather station at distance R from the location/point of the VWS (*17*).

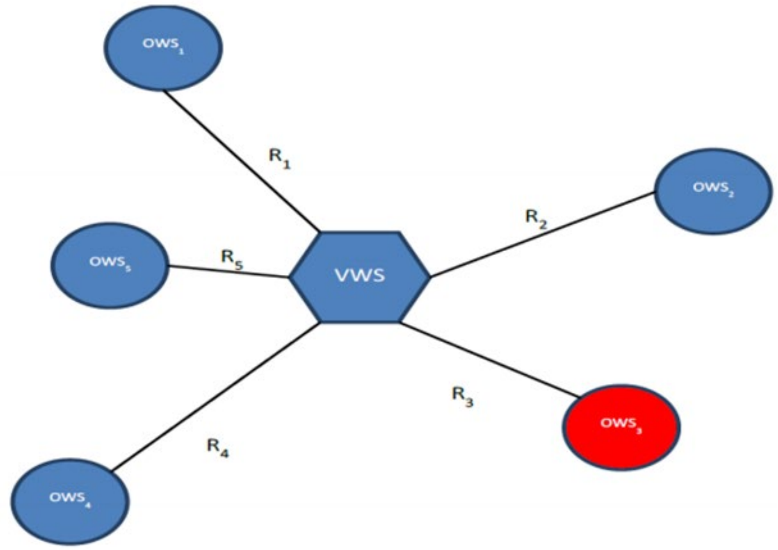


Figure 2-1 Gravity Model Interpolation

Equation 2.1 shows the gravity model and its required parameters. V represents the final interpolated data obtained at time m. V_{mi} represent the climatic data of station i at time m, R represents the distance between station i to the VWS creation point and n represents the number of stations considered in the VWS creation (*17*).

$$V_m = \frac{\sum_{i=1}^{n} \frac{V_{mi}}{R_i^2}}{\sum_{i=1}^{n} \frac{1}{R_i^2}} \tag{2.1}$$

A study was conducted to determine the accuracy of climatic data obtained from MEPDG created VWS to predict transverse cracking. The comparison considered two scenarios, (i) one weather station close to the area of pavement analysis, and (ii) five weather station to create a VWS. The five-weather stations used in the creation of VWS did not consider the weather station used in scenario one. For pavement analysis a composite pavement section with a 2-inch asphalt layer and 7-inch Jointed Plain Concrete Pavement (JPCP) layer was used in 12 non-mountainous location in the United States. The predicted transverse cracking showed similarities in some cases and dramatic differences in other cases when scenarios one and two were compared. From the observation, using of VWS was associated with a possibility of inaccuracies in predictions, and VWS quality was stated to depend on the quality of the climatic stations used for their creation (*18*).

A study was conducted to verify VWSs using LTPP's Automated Weather Stations (AWSs) as climatic data source. Two cases were compared: case (i) considered all AWSs in creation of VWS, and case (ii) considered the nearest individual AWS. The climatic parameters considered in the comparison included absolute difference of maximum and minimum temperature values, mean temperature, and precipitation. In both cases the absolute difference data did not follow a normal distribution pattern. The plots of AWS versus VWS parameters showed that precipitation and minimum temperature values were widely scattered from the line of equity. Further evaluation was performed on mean temperature, precipitation, and number of freeze and thaw cycles. Precipitation from VWS data was under predicted, and the number of freeze and thaw cycles over predicted (*19*).

A comparison of pavement distresses generated by VWSs, and actual weather stations was conducted using MEPDG version 1. Two scenarios were considered: (i) using existing nearby actual weather stations in creation of VWS, and (ii) used nearby actual weather stations with an elevation difference of +/- 500 ft in creation of VWS. The analyses of these two scenarios followed two approaches. The first approach considered the difference between the two scenarios and the actual weather stations, and the second approach considered the percent difference between the scenarios and the actual weather stations. For the first approach, both scenarios of VWSs showed no significant difference in terms of IRI, alligator cracking, and transverse cracking predictions. A significant difference was observed with transverse cracking, AC rutting, and total rutting predictions when considering all weather stations for scenario 1. The second approach showed a significant difference on the annual rainfall and freeze/thaw cycles (*20*).

MEPDG version 1.1 was used to evaluate the performance of VWSs by comparing their pavement predicted distresses with those predicted using existing weather stations. The study used six weather stations in the creation of a VWS while considering three pavement distresses for comparison: IRI, AC rutting, and total rutting. From the results, IRI values showed consistence between the VWSs and the existing weather stations, while both AC rutting, and total rutting predictions were found to be inconsistent. Furthermore, it was pointed out that the causes of the inconsistence were the distance between weather stations, the elevation differences among stations, and the low quality and inconsistent data files used to create the VWS. The maximum variation of AC rutting when using VWS was up to 1.6 times the values predicted by the existing weather stations (*11*).

From this review, it can be concluded that the use of VWSs in pavement analysis and design can lead to inconsistent or unrealistic outputs. The use of VWSs should be carefully considered or completely avoided to prevent the possibilities of over- or under-designing pavements.

2.5 Climatic File Quality Checks Methods

2.5.1 Quality Check Methods

A VWS data quality check was performed by comparing its distress predictions with those predicted on a nearby actual weather station. The method involved creating a virtual weather station using five actual weather stations and comparing its distress predictions with those from the closest actual weather station (which is not among the five stations). Difference or similarity in predictions reflected the quality of the data (*1*).

Computer programs were used for climatic file quality checks to flag data that are erroneous, identifying outliers, unrecognized strings, unreasonable hourly temperature changes, missing hours, days and months of data, and historical recorded temperature range, that indicated errors or poor-quality data (1;*15;21*)

Other researchers set criteria for quality checks, which is used to certify the correct data format from other sources (for example non-numerical formatting may be used to designate missing data). Non-realistic data values, such as negative precipitation and wind speed, percent sunshine and relative humidity range (being less than 0% or greater than 100%), and temperature differences of more than 50 °F for adjacent recorded hourly temperatures, were considered inadequate or of low quality (*17*).

A study conducted with Michigan's climatic data files, checked the quantity and quality of the existing files, along with the sensitivity of each weather variable. Quality checks of the data were done by establishing minimum and maximum limits for the data. Apart from the existing data in the PMED software, additional sources of data were used such as data from AWOS/ASOS and MDOT RWIS to achieve their research objective (*22*).

2.5.2 Obtaining Quality Climatic Files

Elimination/Correction of erroneous and incomplete data files.

Various researchers obtained quality climatic data files by eliminating data containing erroneous or missing information. Canadian researchers (*11*) eliminated 16 incomplete climatic files from 222 files that did not meet the minimum requirement (24-month climate data records of complete hourly data) to implement in the MEPDG software. Other researchers used National Climate Data Center (NCDE) and eliminated incomplete climate data stations from 851 stations to 610 stations with complete data (*1*). Obtaining complete climatic data files can be challenging, for example, another research used NCDE to performed a quality check on 851 weather files and eliminated files from sources that did not have correct data format, and had unrealistic data values, leaving 21 weather files that passed the quality check (*17*).

Use of data from consistent sources.

A study conducted by (*17*) compared distresses predicted using data from MERRA and those from ground-based Operating Weather stations (OWS). MERRA data was found to be substantially better than data from OWS and was thus recommended to be used as a climatic data source for the LTPP. Moreover, (*5*) compared the distresses predicted by using climatic data from NARR and those from MERRA, and concluded that the climatic data from MERRA showed greater advantage over NARR data. It can be seen from the literature that MERRA and NARR climatic files have more consistent and reliable data for PMED software than OWS.

Use of other climate sources to fill gaps in missing data.

Other climatic data sources, that passed the checks, such as Automated Surface Observation System (ASOS) / Automated Weather Observation System (AWOS) data, have been used to fill the gaps that existed in the MEPDG database (*15*). OWS data can also be used although it is not as reliable as MERRA and NARR weather files (*17*).

Use of appropriate weather stations in creating Visual Weather Stations.

The use of many nearby weather stations in creation of Visual Weather Station (VWS) is the most favorable method than using a few stations or only one station near by the design site. The quality of a VWS increases as the number of nearby weather stations increases (*19*). It is recommended that weather stations to be used in creating VWS should be in a relative elevation, close distance, and should have similar terrain features as the location at which the VWS is to be created (*17*).

2.6 PMED Default Climatic Data Sources

The AASHTOWare PMED software version 2.6.1 prompts the user to obtain climatic data from two main sources:

I) North American Regional Reanalysis (NARR)

II) Modern-Era Retrospective Analysis for Research and Application (MERRA)

North American Regional Reanalysis (NARR)

The NARR program was initiated by the National Centers for Environmental Prediction (NCEP). NARR is a Regional Reanalysis of North America containing various data such as climatic data (atmospheric dataset) and soil data (land surface hydrology dataset). NARR is a long-term dataset that is dynamically consistent with high frequency and resolution starting from 1979, having a 3-hour output timestep, 32 km horizontal and a 45-layer resolution over North America. The model used in NARR uses different observations to give a long-term weather prediction over North America. The data used to produce a real-world condition include wind speed, temperature and pressure data from surface observations, and moisture data from radiosondes. Other data included in NARR are cloud drift winds (obtained from geostationary satellites), temperature and wind recorded by aircraft, orbiting satellites, dropsondes and pibals (*23;24;25*). NARR has an improved atmospheric circulation; land atmosphere interaction and the atmospheric analysis of precipitation observations are assimilated in detail and at a high quality (*26*).

Modern-Era Retrospective Analysis for Research and Application (MERRA)

MERRA is a reanalysis dataset that was released by NASA in 2010 based on Goddard Earth Observation System (GEOS-5), a data analysis system. MERRA data set is uniformly gridded, created by combining computed model fields with their respective real observations that are regularly distributed in space and time, collected from ground observations, ocean observation, satellite, and atmospheric observations. MERRA has an hourly temporal resolution, 75-layer resolution in the vertical, and a spatial resolution of 0.67° longitude by 0.5° latitude. The hourly temporal resolution provided by MERRA is two-dimensional whereas three dimensional diagnostics are provided on a three-hour basis. This quality of MERRA data makes it a good source for obtaining high quality atmospheric and surface weather data (*17; 24; 26*). MERRA is currently operating at 0.625° longitude by 0.5° latitude spatial resolution previously 0.67° longitude by 0.5° latitude.

Comparison of NARR data and MERRA data

A good similarity was observed by (*17*) when comparing the MEPDG dataset (NARR) with MERRA. It was observed that air temperature, relative humidity, and precipitation had a close similarity whereas percent sunshine and wind speed had a notable difference. The difference in wind speed and percent sunshine were related to measurement/recording techniques. MEPDG software distress predictions were observed to have a higher similarity in locations with a flat terrain than in varying and mountainous terrains. From these observations, MERRA data was recommended as a good source of climatic data for the implementation in the MEPDG software and other infrastructure applications. Furthermore, MERRA data showed advantages over other datasets that were analyzed; MERRA had a denser, more uniform, broader spatial coverage, a better temporal frequency and continuity, and excellent data quality and consistency. It focuses on fundamental physical quantities, is richer and more versatile, has reliability analysis capabilities, and has improved over time. These qualities gives the MERRA dataset great potential as a dataset for the MEPDG implementation (*17*).

Chapter 3 Methodology

The methodology used in this research focused on first understanding the performance of the PMED climatic model (EICM), then comparing the performance of NARR, and MERRA climatic data sources on distress prediction and surface layer optimization. To understand the EICM model, this research used a sensitivity analysis and assessment of virtual weather stations performance. The sensitivity analysis was performed to understand what climatic inputs (temperature, wind speed, percent sunshine, relative humidity, and water table depth) mostly affect the distress predictions. Virtual weather station (VWS) performance study was carried out to confirm the suitability of PMED VWS creation tool for use in the analysis. The methodology and flow of work towards understanding the EICM climatic model and assessing the PMED VWS creation tool is explained in sections 3.1 and 3.2 respectively. Section 3.3 presents the methodology and flow of work towards the NARR and MERRA climatic data analysis and comparisons. All distress predictions used AASHTOWare PMED version 2.5.5 and later repeated on version 2.6.0 and 2.6.1 due to the change of the previously top-down cracking model.

3.1 Sensitivity Analysis of EICM

This analysis was performed to assess the sensitivity of climate inputs in relation to distress prediction, using a full model 2^k factorial design approach. The 2^k factorial design considers maximum and minimum values of events/inputs when assessing their effect on the observed system (*13*). Climatic inputs/variables used for the analysis include, temperature, wind speed, percent sunshine, relative humidity, and water table depth. The results are expected to determine what are the most sensitive climatic inputs to pavement distresses prediction and confirm or refute findings reported by various researchers showing temperature as the most sensitive climatic input.

Table 3.1 shows the high and low values of each climatic input used in the analysis. Precipitation was not included in the analysis due to the failure to replicate its high and low values in the AASHTOWare PMED software.

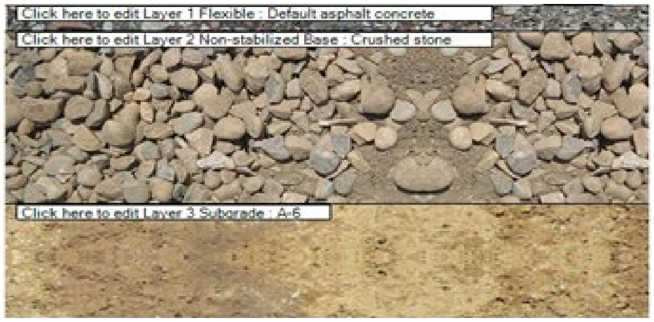
Table 3-1 Input Levels for Design Factors

Input Levels	*High (+)*	*Low (-)*
Temperature (F°) - A	110	32
Wind Speed (miles/hour) - B	60	0
Percent Sunshine (%) - C	100	0
Relative Humidity (%) - D	100	0
Water Table Depth (ft) - E	100	0

Using the five variables in Table 3.1, a combination matrix of total 32 (2^5) lines of high and low combinations was generated (Appendix A). Each combination in the matrix was used as a blueprint in creating 32 climatic files with 36.5 years of hourly climatic data collected.

Each of the created climatic files was used in the AASHTOWare PMED software as a climatic station in analyzing three LTPP flexible pavement sites (Figure 3-1 and Table 3.2) with varying pavement structure, materials, and traffic conditions. Thirty-two (32) analyses per site were performed. ANOVA was used to assess the relationship between the climatic inputs and the distresses predicted. The distresses considered for analysis included asphalt concrete (AC) permanent deformation, total pavement permanent deformation, top-down cracking, bottom-up cracking, and terminal IRI. Table 3.2 shows the layer description for the three LTPP sites used for the analysis, shown on Figure 3.1. Analysis and results are presented in Section 4.1.

LTPP Site 47-1028 LTPP Site 47-3108



LTPP Site 47-3104

Figure 3-1 LTPP Sections for Sensitivity Analysis

Table 3-2 Layer Description for LTPP Sites used in the Sensitivity Analysis

Layer	*LTPP Site 47-1028*	*LTPP Site 47-3108*	*LTPP Site 47-3104*
1	AC Surface (4.3 in.)	AC Surface (2.7 in.)	AC surface (1.3 in.)
2	AC Base (6.2 in.)	AC Base (5.5 in.)	Crushed stone base (8.7 in.)
3	AC Base (5.1 in.)	AC Base (6.1 in.)	Compacted subgrade A-6
4	Crushed stone base (3.8 in.)	Crushed stone base (6.1 in.)	
5	Compacted subgrade A-7-5	Compacted subgrade A-7-6	

3.2 EICM's Virtual Weather Stations (VWSs) assessment

To assess the performance of VWSs, the study used MERRA stations in and bordering the state of Tennessee (*27*). MERRA data was used because of its geographic coverage advantage. Figure 3.2 shows the distribution of forty-nine (49) MERRA climatic stations with reference to the state of Tennessee (Refer to Appendix F for MERRA stations information). The stations are equally spaced, currently operating at 0.625° longitude by 0.5° latitude spatial resolution, which made the analysis easily adaptable.

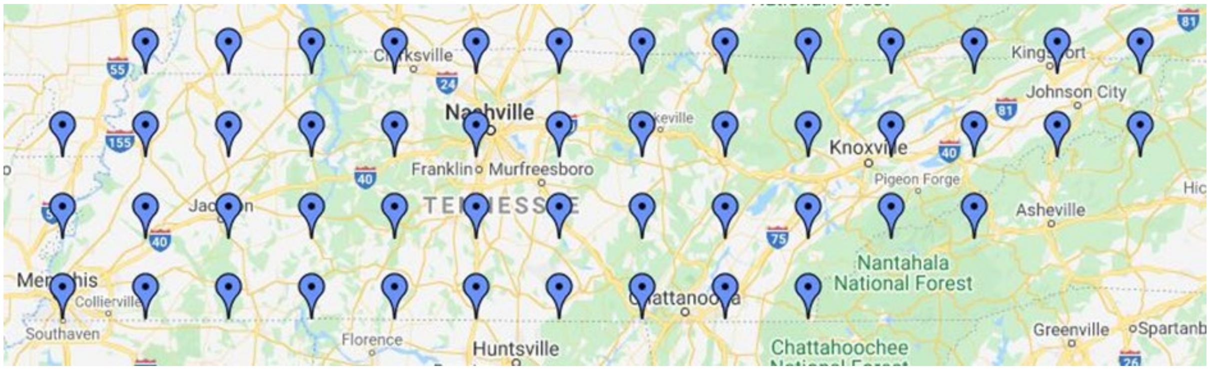


Figure 3-2 MERRA Stations for the State of Tennessee

For creation of VWSs the PMED software VWS creation tool was used. To create a VWS station eight MERRA stations (Figure 3-3) were used at each of the forty-nine (49) MERRA station locations shown on Figure 3-2. For this operation, a total of forty-nine (49) VWSs were created at the same locations as the forty-nine (49) MERRA stations (Refer to Appendix B for the workflow chart). Figure 3-3 shows the eight MERRA stations (in green) used to create a VWS at a yellow pin drop and an actual MERRA station in blue that is used for comparison to the created VWS.

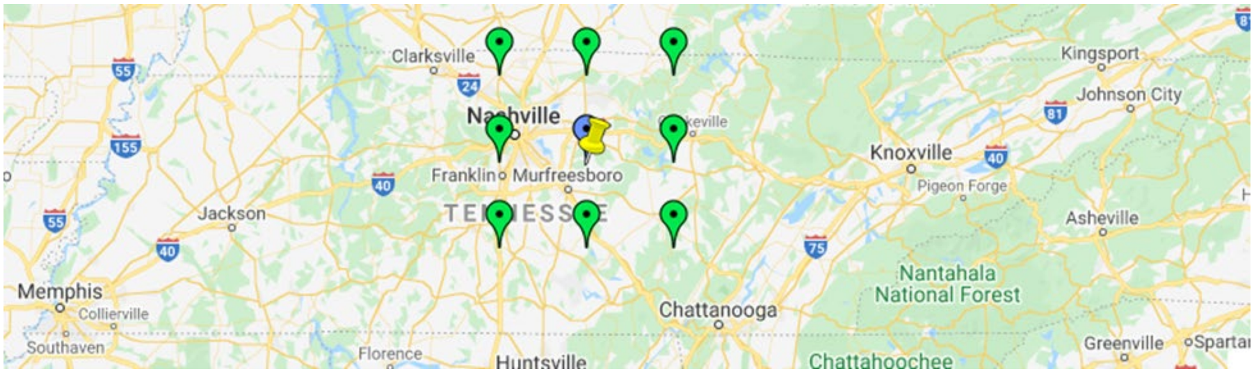


Figure 3-3 Interpolation Methodology Scheme

The comparisons the forty-nine (49) MERRA and forty-nine (49) PMED VWSs stations considered their climatic summary output values and their distress predictions. The climatic summaries comprised of the values of the climatic inputs for both MERRA and PMED VWS stations. For distress prediction, a total of five LTPP sites (Figure 3-4 and Table 3.3) were used in comparing each of the forty-nine (49) MERRA and forty-nine (49) PMED VWS pairs at identical locations (Figure 3-2 and Figure 3.3). The workflow chart of how the task was performed is shown in Appendix C.

For this study, the comparison of MERRA and PMED VWS data at a respective location considered the use of correlation analysis and hypothesis testing. For comparative analysis, the goodness of fit methods, coefficient of linear determination (R^2), and Standard Error of the Estimate (SEE) were used. For hypothesis testing, T-tests & Wilcoxon rank sum tests at a 95% confidence level were used for parametric and non-parametric data respectively. The hypothesis testing considered a null hypothesis stating, “No difference between MERRA and PMED VWS”, and an alternative hypothesis stated otherwise. The analysis and results are presented in Section 4.2.

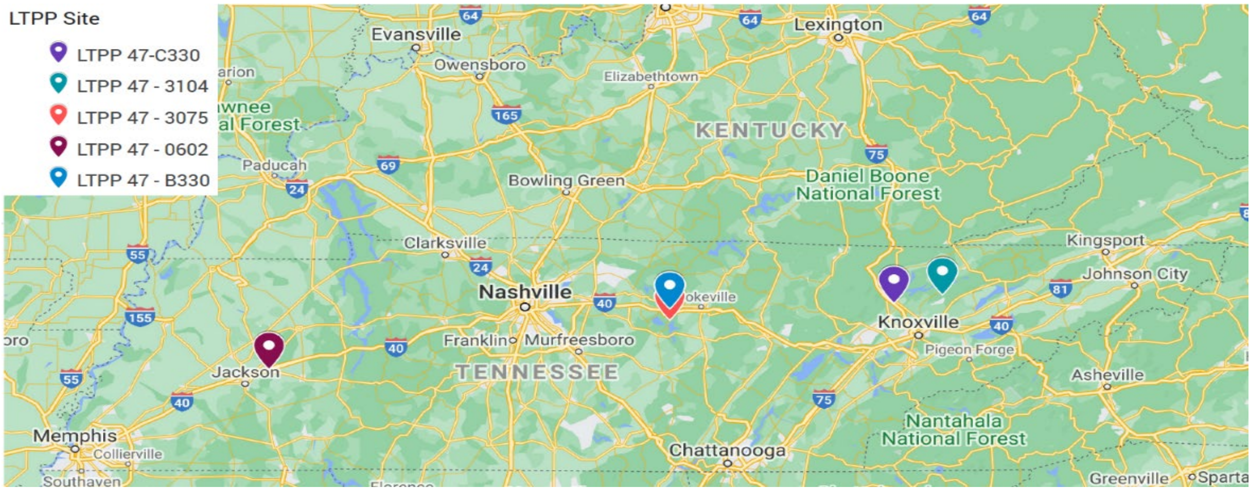


Figure 3-4 LTPP Stations for PMED VWSs Analysis

Table 3-3 Layer Description for LTPP Sites used on PMED VWS Analysis

Layer	*LTPP Site 47-C330*	*LTPP Site 47-3104*	*LTPP Site 47-3075*	*LTPP Site 47-0602*	*LTPP Site 47-B330*
1	AC Surface (5.3 in.)	AC surface (1.3 in.)	AC Surface (5.0 in.)	PCC Surface (8.9 in.)	AC Surface (1.8 in.)
2	AC Base (5.7 in.)	Crushed stone base (8.7 in.)	Crushed stone base (9.2 in.)	Chemical stabilized base (6.0 in.)	AC Base (3.2 in.)
3	Crushed stone subbase (6.0 in.)	Compacted subgrade A-4	Compacted subgrade A-4	Compacted subgrade A-4	Crushed stone subbase (9.2 in.)
4	Compacted subgrade A-6				Compacted subgrade A-5

3.3 Comparative Analysis of NARR and MERRA

Comparative analysis was performed to assess the suitability of NARR and MERRA climatic data sources for designing pavements using PMED software. This included two scenarios, distress prediction and layer optimization using each of the data sources near the site (LTPP and TDOT). A comparative analysis of predicted pavement distresses and surface layer optimization used the climatic data sources (NARR, and MERRA), materials, and traffic data at different hierarchical levels as shown on Table 3.4. The levels were determined according to available data/information at the respective LTPP/TDOT site. Level 3 represents the default values available on the PMED software.

Table 3-4 Input Levels for Pavement Distress Prediction

PMED Input	*Input Hierarchal Level*
Local Distress Model Calibration Factors	Level 2
	Level 3
Materials Properties	Level 2
	Level 3
Traffic	Level 1
	Level 2
	Level 3
Climate	Level 2
	Level 3

3.3.1 Data Sources for Distress Prediction

Different types of data were obtained from different sources as required for PMED pavement distress prediction. Data needed for PMED analysis included traffic volumes, traffic adjustment factors, materials inputs, pavement profile/structure, and water table depth.

Local Distress Model Calibration factors.

Local Calibration factors for distress prediction models (Level 2) used in this research were obtained from the research titled "Local Calibration of Mechanistic-Empirical Pavement Design in Tennessee" conducted by the University of Tennessee Knoxville. The calibrated distress models included alligator cracking (bottom-up), longitudinal cracking (top-down), and rutting (*28*). Top-down calibration factors were not adopted for this research because the latest PMED software version 2.6.1 used in this research had a new top-down prediction model that was not locally calibrated, hence default values were used for this model.

Traffic Volume Adjustment factors

Level 2 traffic volume adjustment factors used in this research were obtained from the TDOT research titled "Traffic Data Input for Mechanistic Empirical Pavement Design Guide (MEPDG) for Tennessee" conducted by the University of Tennessee at Chattanooga. A traffic growth rate of 1.34 % with a linear growth function was adopted for the state of Tennessee (30).

Material Properties and Pavement Profiles

Level 2 material properties and pavement profiles were obtained from LTPP InfoPave website and as provided by TDOT staff. In the case of missing data, the PMED default (Level 3) data were used.

Climatic Model Data Source

The climatic data used in this research were obtained from three major sources:

- NARR climatic data was downloaded from the AASHTOWare Pavement ME Design official website (https://me-design.com/MEDesign/ClimaticData.html).
- MERRA climatic data files were downloaded from the LTPP InfoPave website special for (https://infopave.fhwa.dot.gov/Tools/MEPDGInputsFromMERRA#tabByMap).
- Water table depth values (ft), considered as Level 3 data, were obtained from the National Water Information System, Mapper, which is an interactive USGS website that enables

selection of existing test locations for ground water tables and other water related information (https://maps.waterdata.usgs.gov/mapper/index.html).

Pavement Performance Criteria and Reliability Levels

Pavement performance criteria used in this research considered maximum values at the end of design life as recommended in the MEPDG manual of practice (*29*). However, the pavement performance reliability level values used in the analysis adopted the TDOT recommended values as shown on Table 3.5.

Table 3-5 TDOT Pavement Performance Reliability Levels

Functional Classification	*Reliability Level (%)*
Interstate/Freeways	95
Principal Arterials	90
Collectors	90
Local	90

Pavement Sections for Distress Predictions

A total of fifty-nine (59) sites were used for pavement distress predictions, thirty-seven (37) from LTPP sites, and twenty-two (22) from TDOT sites. The distribution of sites in the four Tennessee regions were determined with respect to their pavement types and functional classes are as shown on Table 3.6. In instances where materials and traffic data were not available from LTPP sites or TDOT sites, the PMED default values were used.

Table 3-6 Pavement Sections for Distress Prediction

Region	*Total Sections*	*Flexible Pavement*	*Rigid Pavement*	*Rigid with AC Overlay*	*FC1*	*FC2*	*FC6*	*FC7*	*FC8*
I	17	17	0	0	9	2	2	4	0
II	14	14	0	0	1	13	0	0	0
III	6	4	2	0	1	4	0	1	0
IV	22	8	7	7	12	4	0	5	1
Total	**59**	**43**	**9**	**7**	**23**	**23**	**2**	**10**	**1**

3.3.2 PMED Distress Prediction, and Layer Optimization

Design periods of 20 years, and 30 years were used in distress predictions for flexible, and rigid pavement sites respectively. For each site, pavement material inputs, and distress model calibration factors were kept constant while changing the traffic levels, and climatic data source (NARR or MERRA). As a result, a single pavement site would have six distress prediction sets of results using both NARR or MERRA climatic data sources with respect to the three traffic levels (Level 1, Level 2, and Level 3). Predictions made using Level 1 utilized LTPP traffic volume adjustment factors and growth rates, Level 2 utilized the local generated traffic volume adjustment factors and a 1.34% growth rate, and Level 3 used PMED default traffic values. It should be noted that Level 1 predictions were performed on LTPP sites only and not the TDOT sites due to unavailability of site collected data.

NARR and MERRA Climatic Files

To ensure a better comparison, the existing NARR and MERRA climatic data files were trimmed to have the same duration of hourly climatic data from 01/01/1985 to 06/30/2015. NARR data had a starting date of 01/01/1979 and end date at or as close to 06/30/2015 as possible, while MERRA data had a starting date of 01/01/1985 and end date of 12/31/2020.

Virtual Weather Stations

The analysis of PMED VWSs explained in sections 3.2 and 4.2 indicated that the created VWSs had some climatic summaries and predicted distresses that were significantly different than those from MERRA stations at same locations. Based on this finding, VWSs were not used in the comparative analysis of NARR and MERRA data sources. Instead, all 12 NARR climatic stations in the state of Tennessee and 10 out of forty-nine (49) MERRA climatic stations were used. The state of Tennessee had 12 NARR stations available for use in the PMED software, while MERRA had forty-nine (49) stations. Since the research focused on the climatic influence on distress predictions comparing NARR, and MERRA, the climatic stations considered from both sources were those closest to each other (distance between stations ranging from 6 miles to 20 miles). Figure 3-5 shows, NARR (green markers), and MERRA (blue markers) stations that met the stated selection criteria. All pavement sections were analyzed using a nearby NARR and/or MERRA climatic stations.

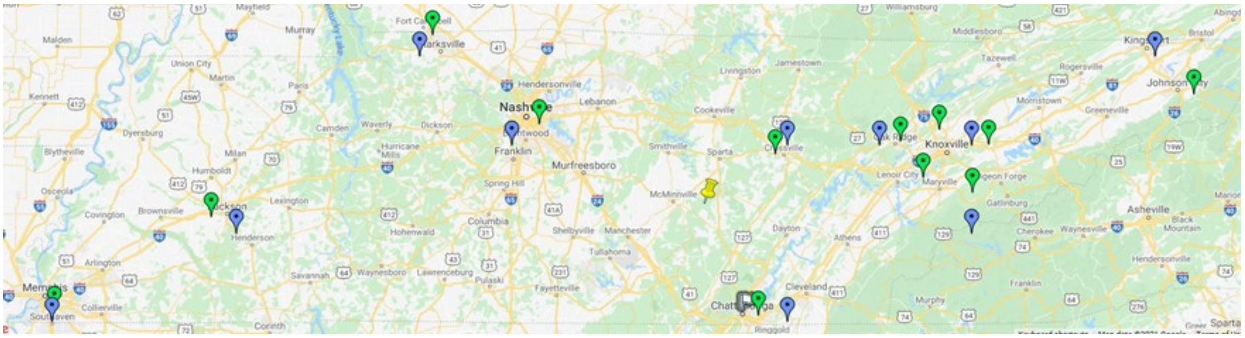


Figure 3-5 NARR and MERRA Stations at Close Vicinity

Pavement distresses analyzed for flexible pavements included terminal IRI, total pavement deformation, bottom-up cracking, thermal cracking, top-down cracking, and AC permanent deformation.

Distresses predicted on rigid pavements included terminal IRI, mean joint faulting, and JPCP transverse cracking. The composite pavements (concrete pavement rehabilitated with asphalt layer) had the following additional distresses: AC permanent deformation, AC bottom-up cracking, AC total transverse cracking, AC thermal cracking, AC top-down cracking, and JPCP transverse cracking.

Layer optimization was performed on the pavement sites to determine the optimal surface layer thicknesses using the PMED software. The optimization inputs are similar to those for distress prediction, materials, pavement structure, climatic data inputs, and traffic levels. In instances where optimization failed due to very large distress values, adjustments were made on the AC pavement binder type, and in extreme cases where adjustments failed, further adjustments were made on the performance by reducing the reliability levels.

3.3.3 Statistical Analysis MERRA versus NARR

Statistical analysis was performed using both the NARR, and MERRA predicted pavement distresses and their optimized layer thicknesses while considering all three traffic levels. Statistical analysis was performed to check the correlation and significance difference in the predicted distresses, and layer thickness optimization amongst the two climatic data sources. (Refer to Appendix D, and Appendix E for the distress comparison and layer optimization workflow chart, respectively).

To check the correlation of the predicted distresses, and optimized layer thicknesses, the goodness of fit was used considering the coefficient of linear determination (R^2) and Standard Error of the Estimate (SEE). Table 3.7 shows the categories of correlation coefficient (R^2) and the strength of correlation. Following the assessment of the goodness of fit statistics, a check was performed to determine the normality of the data, and which statistical test to use. For the comparison of non-parametric data, the Wilcoxon rank sum test was used, and T-test was used for parametric data.

Table 3-7 Categories of Correlation Strength

Value of correlation coefficient (R^2)	*Strength of Correlation*
1	Perfect
0.9 - 1	Very strong
0.8 – 0.9	Strong
0.6 – 0.8	Moderate
0.5 – 0.6	Weak
< 0.5	Very weak

A comparison was made between NARR, and MERRA predicted distresses for each of the three analyzed traffic levels with the following hypothesis:

H_0 : There is no difference between NARR and MERRA predicted distresses.

H_A: There is a difference between NARR and MERRA predicted distresses.

Similar comparisons were performed for layer thickness optimization with the following hypothesis:

H_0 : There is no difference between NARR/MERRA optimized layer and original layer thicknesses.

H_A: There is a difference between NARR/MERRA optimized layer and original layer thicknesses.

Chapter 4 presents the data analysis and discussion of results as per methodology explained in this chapter.

Chapter 4 Results and Discussion

This chapter presents results and discussion as per methodology described in Chapter 3. It includes the sensitivity analysis of EICM using 2^k factorial design to generate 32 climatic data files with high and low climatic inputs. Three LTPP sites were used in the sensitivity analysis to evaluate sensitivity of predicted distresses to climatic inputs using the 32 climatic data files.

PMED VWS tool was used to create VWSs climatic data files using MERRA climatic data stations available in the state of Tennessee. Both MERRA and PMED VWSs climatic data files at the same location were used to predict pavement distresses. The comparison of the predicted distresses in general indicated that distresses predicted using PMED VWSs were significantly different from those predicted using MERRA climatic files at the same locations.

NARR and MERRA climatic data inputs were further analyzed using 12 NARR stations in the state of Tennessee and 10 nearby MERRA stations. Distresses predicted using NARR and MERRA climatic data files were compared. Furthermore, surface layer thicknesses were optimized using NARR and MERRA climatic data files and compared to original surface layer thicknesses. In the following sections, results and discussion are presented.

4.1 EICM Sensitivity Analysis

The 2^k factorial design was conducted to determine the sensitivity of climatic inputs on distress predictions using three LTPP sites (Figure 3-1). Since the design considered five (k = 5) climatic inputs, 32 (2^5) climatic files were generated with combinations of high and low values from each of the climatic inputs (temperature, wind speed, percent sunshine, relative humidity, and water table depth). Appendix A shows the combination of levels (high and low) of each of the 32 generated climatic files, and Table 3-1 shows the low and high levels used for each climatic input. The generated climatic files had a total length of 36.5 years of hourly climatic data. The 36.5 years of hourly climatic data was chosen to match the NARR climatic data file length. All generated climatic files were then used in the PMED software as climatic input files to evaluate the distress predictions of the three LTPP sites (LTPP 47-3108, LTPP 47-1028, and LTPP 47-3104, refer to Table 3-2 and Figure 3-1 for site pavement cross-section information).

Tables 4-1, 4-2, and 4-3 show climatic input interactions and pavement distresses affected for LTPP sites 47-3108, 47-1028 and 47-3104 respectively. The numbers included in the parentheses on all distresses refer to the order in which that particular climatic input or interactions of climatic inputs affected that particular pavement distress (number 1 referring to the climatic input with most effect on the predicted distresses, and number 7 with the lowest effect on predicted distresses).

From Table 4-1, the sensitivity analysis of the LTPP-section 47-3108 using the 32 generated climatic files, temperature inputs were observed to affect most distresses than other climatic inputs. For all distresses, only bottom-up cracking was mostly affected by windspeed followed by temperature. The following were the pavement distresses along with the three climatic inputs that mostly affected LTPP site 47-3108:

- AC only permanent deformation predictions were mostly affected by temperature, wind speed, and the interaction effects between temperature and windspeed in that order.

- Total pavement permanent deformation predictions were mostly affected by temperature, and wind speed in that order.
- Top-down cracking predictions were mostly affected by temperature, interaction effects of temperature and depth of water table, and the depth of water table in that order.
- Bottom-up cracking predictions were mostly affected by wind speed, temperature, and the interaction effects between temperature and windspeed in that order.
- Total fatigue cracking predictions were mostly affected by temperature, interaction effects of temperature and depth of water table, and the depth of water table in that order.
- Terminal IRI predictions were mostly affected by temperature, wind speed, and interaction effects of temperature and depth of water table in that order.
- Thermal Cracking predictions were only affected by temperature.
- Relative humidity and percent sunshine had no effect on the predicted distresses.

Table 4-1 Distress Results of Climatic Input Data Interactions LTPP 47-3108

	Temperature	*Wind speed*	*Percent Sunshine*	*Relative humidity*	*Depth of water table*
Temperature	PDAC (1), PDTP (1), TD (1), BU (2), TFC (1), IRI (1), TC (1)	PDAC (2), TD (6), BU (3), IRI (5)			TD (2), BU (6), TFC (2), IRI (3)
Wind speed	PDAC (2), TD (6), BU (3), IRI (5)	PDAC (3), PDTP (2), TD (7), BU (1), TFC (4), IRI (2)			TD (4), BU (5)
Percent Sunshine					
Relative humidity					
Depth of water table	TD (2), BU (6), TFC (2), IRI (3)	TD (4), BU (5)			TD (3), BU (4), TFC (3), IRI (4)

NOTE Distresses analyzed: Terminal IRI = IRI; Thermal Cracking = TC; Bottom-up cracking = BU; Top-down cracking = TD; Permanent deformation AC only = PDAC; Permanent deformation total pavement = PDTP and Total fatigue cracking = TFC.

The sensitivity analysis of LTPP section 47-1028 show temperature as the climatic input that affected all pavement distresses the most, followed by wind speed. The following are summaries of pavement distresses along with the three climatic inputs that mostly affected LTPP site 47-1028:

- Total transverse cracking predictions were mostly affected by temperature, wind speed, and the interaction effects between temperature and wind speed in that order.
- AC only permanent deformation predictions were mostly affected by temperature, wind speed, and the interaction effects between temperature and wind speed in that order.
- Total pavement permanent deformation predictions were mostly affected by temperature, wind speed, and the depth of water table in that order.

- Top-down cracking predictions were mostly affected by temperature, wind speed, and the interaction effects between temperature and wind speed in that order.
- Bottom-up cracking predictions were mostly affected by temperature, wind speed, and the interaction effects between temperature and wind speed in that order.
- Total fatigue cracking predictions were mostly affected by temperature, wind speed, and the interaction effects between temperature and wind speed in that order.
- Terminal IRI predictions were mostly affected by temperature, wind speed, and interaction effects of temperature and depth of water table in that order.
- Thermal Cracking predictions were only affected by temperature.
- Relative humidity had no effect on the predicted distresses.

Table 4-2 Distress Results of Climatic Input Data Interactions LTPP 47-1028

	Temperature	*Wind speed*	*Percent Sunshine*	*Relative humidity*	*Depth of water table*
Temperature	TTC (1), PDAC (1), PDTP (1), TD (1), BU (1), TFC (1), IRI (1), TC (1)	TTC (3), PDAC (3), TD (3), BU (3), TFC (3)	TD (6), BU (4)		PDAC (4), PDTP (4) BU (5), TFC (4), IRI (3)
Wind speed	TTC (3), PDAC (3), TD (3), BU (3), TFC (3)	TTC (2), PDAC (2), PDTP (2), TD (2), BU (2), TFC (2), IRI (2)	TD (5)		
Percent Sunshine	TD (6), BU (4)	TD (5)	TD (4), IRI (5)		
Relative humidity					
Depth of water table	PDAC (4), PDTP (4) BU (5), TFC (4), IRI (3)				PDAC (3), PDTP (3), BU (6), TFC (5), IRI (4),

NOTE Distresses analyzed: Terminal IRI = IRI; Thermal Cracking = TC; Bottom-up cracking = BU; Top-down cracking = TD; Permanent deformation AC only = PDAC; Permanent deformation total pavement = PDTP; Total fatigue cracking = TFC and Total transverse cracking = TTC.

Sensitivity analysis on pavement 47-3104 showed different results compared to the two previous LTPP sites. This difference can be attributed to the pavement cross section. LTPP 47-3104 consisted of unbound base and a thin surface layer unlike the other two sections with multiple layers of both asphalt bound bases and unbound crushed stone layers.

On this site, more effects of depth of water table were observed than the precious sites. The effects of temperature were thus not as dominating as the previous two sites. In many distresses the influence of depth of water table prevailed. The following were the summaries of the pavement distresses along with the three climatic inputs that mostly affected LTPP site 47-3104:

- AC only permanent deformation predictions were mostly affected by temperature, wind speed, and depth of water table in that order.

- Total pavement permanent deformation predictions were mostly affected by depth of water table, interaction effects of temperature and depth of water table, and wind speed in that order.
- Top-down cracking predictions were mostly affected by depth of water table, the interaction effects of temperature and depth of water table, and temperature in that order.
- Bottom-up cracking predictions were mostly affected by temperature, wind speed, and percent sunshine in that order.
- Terminal IRI predictions were mostly affected by depth of water table, the interaction effects of temperature and depth of water table, and wind speed in that order.
- Thermal Cracking predictions were only affected by temperature.
- Relative humidity had no effect on the predicted distresses.

Table 4-3 Distress Results of Climatic Input Data Interactions LTPP 47-3104

	Temperature	*Wind speed*	*Percent Sunshine*	*Relative humidity*	*Depth of water table*
Temperature	TC (1), PDAC (1), PDTP (4), TD (3), BU (1), IRI (5)	PDAC (5), PDTP (5), TD (4), BU (4), IRI (4)	BU (5)		PDAC (4), PDTP (2), TD (2), IRI (2)
Wind speed	PDAC (5), PDTP (5), TD (4), BU (4), IRI (4)	PDAC (2), PDTP (3), TD (5), BU (2), IRI (3)	PDAC (7), BU (6)		
Percent Sunshine	BU (5)	PDAC (7), BU (6)	PDAC (6), BU (3), IRI (6)		
Relative humidity					
Depth of water table	PDAC (4), PDTP (2), TD (2), IRI (2)				PDAC (3), PDTP (1), TD (1), IRI (1)

NOTE Distresses analyzed: Terminal IRI = IRI; Thermal Cracking = TC; Bottom-up cracking = BU; Top-down cracking = TD; Permanent deformation AC only = PDAC; and Permanent deformation total pavement = PDTP

In summary:

1. All predicted distresses showed sensitivity to temperature changes.
2. Thermal cracking was affected by temperature inputs only, other climatic inputs showed negligible effect.
3. Wind speed inputs affected most of the distress predictions (second to air temperature). Permanent deformation and bottom-up cracking were affected by wind speed on all three sites.
4. Variation of water table depth mostly affected total pavement rutting and terminal IRI, for all sites, which reflects subgrade failure due to excessive presence of water. LTPP site 47-3104 was the most sensitive to water table depth input affecting total pavement rutting and terminal IRI predictions. This outcome is likely due to site 47-3104 having a thin AC surface layer and crushed stone base on an existing subgrade. This makes the structure more exposed to water table fluctuation effects.

5. Relative humidity showed a negligible influence on all distress prediction results
6. Various distresses showed sensitivity to a combination effect of the climatic inputs (Tables 4.1 to 4.3). The following is a summary of the interacting climatic inputs and the distresses common to the three LTPP sites:
    - Temperature and wind speed affected AC permanent deformation, bottom-up, and top-down cracking.
    - Temperature and water table depth affected terminal IRI, total pavement permanent deformation, and top-down cracking.
    - Temperature and percent sunshine affected bottom-up cracking.
    - Wind speed and percent sunshine affected AC permanent deformation.

From the sensitivity analysis, it was determined that temperature is the most sensitive climatic input, followed by wind speed, and relative humidity had a negligible effect on pavement distress predictions. The findings agree with other researchers (*8;9;10;12*).

Using the three LTPP sections with varying layer thicknesses, materials, and traffic conditions have shown that different pavement sections can be affected differently by climatic inputs. For example, the LTTP 47-3104 structure was mostly affected by water table depth inputs than the other two sites because of its layer structure (AC surface layer on crushed stone base and subgrade). From this observation, and the general climatic input sensitivity analysis, it is recommended for TDOT to carefully select climatic data files and depth of water table data for design and analysis since they have an influence on the pavement performance.

4.2 Performance of Virtual Weather Stations (VWSs)

This section presents the comparative analysis of PMED created VWSs and MERRA climatic data files, to evaluate the performance of PMED VWS creation tool. Eight MERRA stations were used to create a PMED VWS and generate climatic summaries at same location with an existing MERRA station. Forty-nine (49) PMED VWSs and forty-nine (49) MERRA climatic files were used in the analysis. The comparative analysis performed included the climatic summaries and distresses predicted using the two climatic datasets as detailed in the sections below.

4.2.1 Climatic Summary Comparison

Climatic summary was generated by the PMED software as a summary of the climatic values obtained from the respective climatic data file/climatic station(s) selected for pavement design and/or analysis. The PMED software uses the climatic summary outputs as values for its design purposes, therefore the accuracy of these values plays a role in the final PMED results. To check the viability of PMED generated VWSs it was thus important to compare these values to those of known stations (MERRA) at similar locations. The compared climatic inputs include mean annual air temperature, mean annual precipitation, freezing index, mean annual number of freeze/ thaw cycles, and number of wet days.

For analysis, two statistical tools were used, correlation analysis and hypothesis testing. The correlation analysis included the use of R^2 and Standard Error of the Estimate (SEE), while hypothesis testing used T-test and Wilcoxon Rank Sum test for parametric and non-parametric data respectively.

A correlation analysis using R^2 compared the climatic summary output data of PMED VWSs and MERRA stations. It showed a very weak correlation with mean annual precipitation values and a weak correlation with mean annual number of freeze/thaw cycle values as shown in Table 4.4. Mean annual air temperature, freezing index and number of wet days had a moderate correlation. The Standard Error of the Estimate (SEE) values showed freezing index, mean annual number of freeze/thaw cycles, and number of wet days with relatively higher values indicating a higher difference between these compared values from PMED VWSs and MERRA climatic data sources (Table 4.4).

Further analysis of the hypothesis test revealed that only the mean annual air temperature data from both MERRA and PMED VWS followed a normal distribution. The normally distributed data was tested using T-test, while the non-parametric data were tested using the Wilcoxon rank sum test. From the hypothesis testing, a significant difference was observed between mean annual number of freeze/thaw cycles, and number of wet days values ($p < 0.05$). On comparing other climatic summary outputs, mean annual air temperature, mean annual precipitation, and freezing index, had no significant difference. Figure 4-1 show the values of the PMED VWSs average number of freeze/thaw cycles, plotted against the MERRA values ($R^2 = 0.5416$), and Figure 4-2 shows the PMED VWSs plotted against MERRA number of wet days on a common location ID.

Table 4-4 Climatic Summaries Correlation and Hypothesis Testing

Climatic Summary	*R^2*	*SEE*	*P-value*
Mean annual air temperature (°F)	0.654 (Moderate)	1.6252	0.3373
Mean annual precipitation (in)	0.0554 (Very weak)	1.5751	0.5224
Freezing Index (°F - days)	0.6172 (Moderate)	50.2992	0.2111
Mean annual number of freeze/thaw cycles	0.5416 (Weak)	7.3403	0.0005**
Number of wet days	0.6912 (Moderate)	6.4962	2.2e-16**

*NOTE: ** refers to a 0.05 level of significance*

The implication of these results from observing the VWSs climatic summaries generated in the PMED software, showed that a difference in climatic data outputs can arise when VWSs created by the PMED software are used. From this scenario, it has been observed that the climatic values from PMED VWSs created at identical location as MERRA stations had a significant difference ($p < 0.05$) on two out of the five climatic summary outputs. Even those that had no significant difference ($p > 0.05$) the correlations were moderate or weak (Table 4.4). Since eight existing MERRA stations were used to create a PMED VWS at the same location with an existing MERRA station (Figure 3-3), the expectation was, the created VWSs would produce statistically significant data with very strong to perfect correlation for all its outputs. Therefore, it was concluded from this study that PMED VWS creation tool does not in all cases create climatic summary outputs that are close to actual values (MERRA) at identical locations. This observation is crucial and important since the PMED software uses climatic summary outputs in pavement design and analysis. Further effects of these findings are explored when comparing the pavement distresses predicted using these climatic files as reported in section 4.2.2.

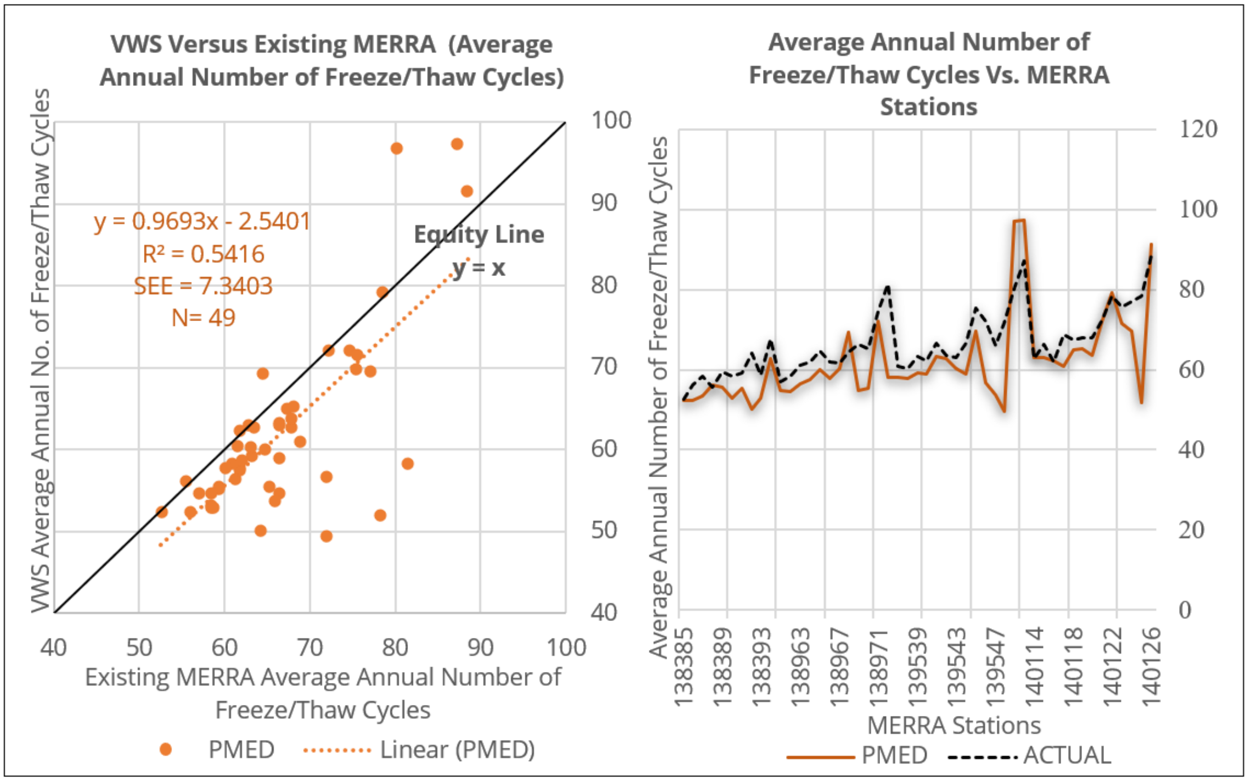


Figure 4-1 PMED VWS versus Exising MERRA Average Annual Number of Freeze/Thaw Cycles

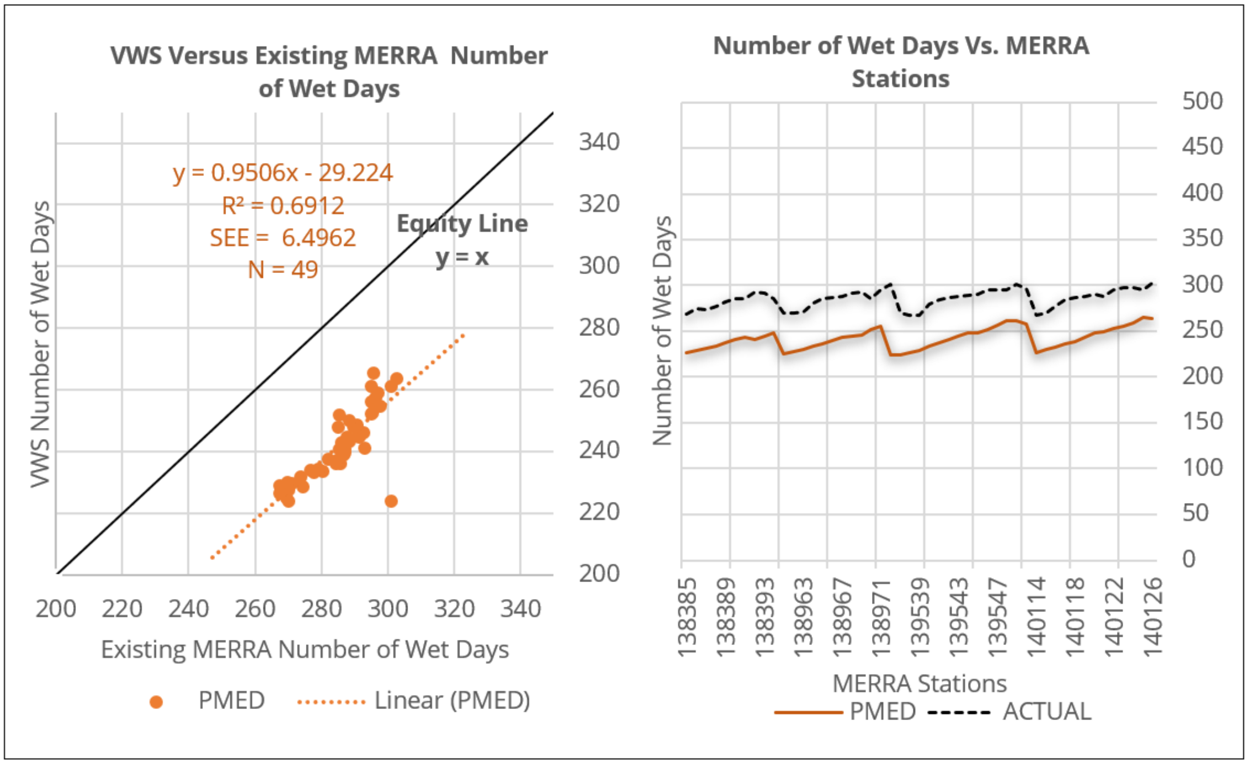


Figure 4-2 PMED VWS versus Existing MERRA Number of Wet Days

More information is given in the appendices as follows: Appendix G shows the climatic summary output values of PMED VWSs and MERRA stations. Appendix H presents the comparison of the climatic summaries using PMED VWSs and MERRA climatic data files. Appendix I shows the summary of PMED software predicted distress values for each climatic data file (PMED VWSs and MERRA) on the five LTPP sites.

4.2.2 Comparison of Predicted Distresses

Following the analysis of the climatic summaries, the forty-nine (49) climatic data files from both MERRA and PMED VWSs were used in pavement distress predictions and their results were compared. Five LTPP pavement sections were used in this analysis, four flexible pavements, and one rigid pavement. Correlation analysis (SEE and R^2) and hypothesis tests (T-test and Wilcoxon rank sum test) were used in the analysis of the predicted pavement distress outputs. For each LTPP pavement section, a total of ninety-eight (98) distress prediction runs were made with forty-nine (49) runs from each MERRA and PMED VWS stations at identical locations (Refer to Appendix I for pavement distress output and Appendix K for Q-Q plots). To understand the normality of data, Q-Q plots were used as a tool on all predicted distress data sets. The general information of the rigid pavement section used in the VWS performance analysis can be observed in Table 4.5. The information includes location, elevation, pavement cross section layers with their types and thicknesses, traffic volume, and depth of water table information which are all part of the inputs used in the PMED software for pavement distress predictions.

Table 4-5 Rigid Pavement General Information

LTPP Section ID	*47-0602*
Latitude, Longitude (decimals degree)	35.71, -88.64
Elevation (ft.)	571.05
LTPP Lane AADTT	3149
Direction of Travel	Westbound
Number of Lanes on LTPP Direction	2
Functional Class	Interstate
PCC Surface Layer Thickness (in.)	8.9
Chemical Stabilized Base Layer (in.)	6
Subgrade Layer	A-2-4
Water Table Depth (ft.)	18.5

For the rigid pavement section (LTPP site 47-602), normality testing using Q-Q plots showed varying results on the predicted distresses. Terminal IRI followed a normal distribution while mean joint faulting, and JPCP transverse cracking were does not follow a normal distribution. T-test was performed for the parametric terminal IRI pair, and Wilcoxon Rank Sum test was performed for both non-parametric mean joint faulting, and JPCP transverse cracking pairs. From the correlation analysis on distresses predicted using the MERRA and PMED VWSs climatic data files, all the three predicted distresses on a rigid pavement section showed a very weak correlation (Table 4.6). A very weak correlation refers to the correlation with R^2 values less than 0.5, which signifies a variation of values from the two compared groups.

Table 4-6 Rigid Pavement Correlation Analysis

Climatic Summary	*R^2*	*SEE*
Terminal IRI	0.0791 (Very weak)	12.6702
Mean joint faulting	0.0933 (Very weak)	0.0198
JPCP transverse cracking	0.3781 (Very weak)	4.3480

Hypothesis testing showed a significant difference when comparing MERRA, and PMED VWSs JPCP transverse cracking outputs (Table 4.7). From these results it can be concluded by accepting the alternative hypothesis that states, "there is a difference between MERRA, and PMED VWSs predicted JPCP transverse cracking outputs." Terminal IRI and mean joint faulting had no significant difference between MERRA and PMED VWSs climate file inputs, at a 95% confidence level.

Table 4-7 Rigid Pavement Hypothesis Testing

Climatic Summary	*P-value*
Terminal IRI	0.0915
Mean joint faulting	0.1935
JPCP transverse cracking	0.0009**

*NOTE: ** refers to a 0.05 level of significance*

The observation on the rigid pavement section indicated that the correlation analysis, and hypothesis testing showed a very weak correlation when comparing the pavement distresses predicted on the same location using MERRA and PMED VWSs climatic data files. Apart from the weak correlation, only JPCP transverse cracking showed a significant difference in their values implying a disagreement of the null hypothesis and thus indicating a difference in the two climatic data sources. This concludes that, the use of PMED VWSs on rigid pavements in distress prediction has potential of producing results that are different from actual or expected results, it is therefore advised to avoid the use of the VWS tool in the PMED software until it is updated.

For flexible pavements, four LTPP sites were used for distress prediction and their respective information are shown on Table 4.8. The information included location, elevation, flexible pavement cross section layers with their types and thicknesses, traffic volume, and depth of water table information, which are all part of the inputs used in the PMED software for pavement distress predictions.

For each of the four LTPP sites, six (6) distresses predicted using PMED VWSs, and MERRA climatic data files were used for the comparison. The six distresses included terminal IRI, total pavement permanent deformation, bottom-up cracking, thermal cracking, top-down cracking, and AC only permanent deformation.

Correlation analysis was used to understand the relationship (correlation) between the pavement distresses predicted using the MERRA and PMED VWSs climatic files. From the correlation analysis, a preliminary understanding of the compared data can be established.

Table 4-8 Flexible Pavements General Information

LTPP Section ID	*47-3075*	*47-3104*	*47-B330*	*47-C330*
Latitude, Longitude (decimals degree)	36.06, -85.73	36.24. -83.75	36.06, -85.73	36.18, -84.1
Elevation (ft.)	1018.98	1259.08	1019.01	1112.53
LTPP Lane AADTT	38	6	38	2673
Direction of Travel	Southbound	Southbound	Southbound	Northbound
Number of Lanes on LTPP Direction	1	1	1	2
Functional Class	Rural Principal Arterial	Rural Major Collector	Rural Principal Arterial	Rural Principal Arterial
AC Surface Layer Thickness (in.)	5	1.3	1.8	5.3
AC Base Layer Thickness (in.)	-	-	3.2	5.7
Crushed Stone Subbase Layer (in.)	9.2	8.7	9.2	6
Subgrade Layer	A-4	A-4	A-5	A-6
Water Table Depth (ft.)	45.77	1.45	45.77	23.14

Since the MERRA and PMED VWS climatic data were derived from the exact same location, it was expected that the results will have a very strong to perfect correlation and be statistically significant. However, the correlation coefficient (R^2) results (Tables 4.9 and Table 4.10) varied widely from perfect to very weak correlation for the six distresses. LTPP 47-3075 had very weak correlation for all six predicted distresses except one (top-down cracking). LTPP 47-3104 had three distresses with perfect correlation, however, thermal cracking and terminal IRI had very weak correlation and total pavement permanent deformation had weak correlation (Table 4.9). LTPP sites 47-B330 and 47-C3104 distresses had moderate to very weak correlation except for site 47-B330 which had one distress (top-down cracking) with perfect correlation (Table 4.10).

Analyzing each predicted distress for the four LTPP sites, terminal IRI values ranged from moderate to very weak, leaning towards weak correlation on average for the four sites. Total pavement permanent deformation ranged from weak to very weak correlation, leaning towards very weak. Bottom-up cracking predicted distresses had three sites with very weak and one with perfect correlation. On average it is leaning towards weak or very weak correlation. Thermal cracking had moderate to very weak correlation with large SEE values. On average it is leaning towards weak correlation. The top-down cracking had perfect correlation for three sites except one, which had very weak correlation. On average this can be moderate to perfect correlation. AC only permanent deformation had three sites with very weak correlation and one distress with perfect correlation. On average this is a weak to very weak correlation.

Table 4-9 Flexible Pavement Correlation Analysis for LTPP Sites 47-3075 and 47-3104

	LTPP 47-3075		*LTPP 47-3104*	
Climatic Summary	R^2	SEE	R^2	SEE
Terminal IRI	0.4347 (Very weak)	4.4922	0.2651 (Very weak)	3.6465
Permanent deformation – total pavement	0.2564 (Very weak)	0.0075	0.5146 (Weak)	0.0043
Bottom-up cracking	0.2270 (Very weak)	0.0107	1 (Perfect)	0
Thermal cracking	0.4878 (Very weak)	590.758	0.3411 (Very weak)	470.55
Top-down cracking	1(Perfect)	0	1 (Perfect)	0
Permanent deformation – AC only	0.2950 (Very weak)	0.0052	1 (Perfect)	0

Table 4-10 Flexible Pavement Correlation Analysis LTPP Sites 47-B330 and 47-C330

	LTPP 47-B330		*LTPP 47-C330*	
Climatic Summary	R^2	SEE	R^2	SEE
Terminal IRI	0.5961 (Weak)	4.4367	0.7145 (Moderate)	3.9435
Permanent deformation – total pavement	0.3023 (Very weak)	0.0076	0.2884 (Very weak)	0.0124
Bottom-up cracking	1.0e-10 (Very weak)	1.1e-15	0.1858 (Very weak)	2.0924
Thermal cracking	0.6228 (Moderate)	588.26	0.7068 (Moderate)	584.4
Top-down cracking	1 (Perfect)	1	0.1066 (Very weak)	0.0058
Permanent deformation – AC only	0.2782 (Very weak)	0.4717	0.3210 (Very weak)	0.0107

From the correlation analysis the preliminary understanding of the predicted output groups has been established where a very weak correlation hinted the probability of existence of a large difference on predicted distresses, and on the other end, perfect correlation hinted identical predicted outputs. To confirm the extent of the differences, hypothesis testing was conducted.

Table 4.11 show the results of hypothesis testing on the four flexible pavements when comparing predicted distresses using MERRA and PMED VWS climatic data files. Type of hypothesis testing used depended on the normality of the respective pavement distresses dataset. T-test was used for the data sets that followed a normal distribution, and Wilcoxson rank sum test was used for the non-parametric (not normally distributed) dataset.

As shown in Table 4.11 the predicted distresses on LTPP site 47-3104 showed no significant difference between MERRA and PMED VWS distress outputs since all the p-values are greater than the level of significance 0.05. A significant difference was observed on AC permanent deformation prediction on three of the four LTPP sites (47-3075, 47-B330, and C330). Further significant differences were observed on LTPP 47-3075 bottom-up cracking, and LTPP 47-C330 total pavement permanent deformation values.

Table 4-11 Flexible Pavement Hypothesis Test P-Value Results for all Sites

Pavement Distresses	*LTPP 47-3075*	*LTPP 47-3104*	*LTPP 47-B330*	*LTPP 47-C330*
Terminal IRI	0.6544	0.6089	0.7304	0.4139
Permanent deformation – total pavement	0.0619	0.4038	0.0851	0.0234**
Bottom-up cracking	0.0329**	1	1	0.1404
Thermal cracking	0.2192	0.2698	0.2983	0.6162
Top-down cracking	1	1	1	0.4969
Permanent deformation – AC only	0.0306**	1	0.0235**	0.0445**

*NOTE: ** refers to a 0.05 level of significance.*

Observing Tables 4.9 to 4.11, not all very weak correlated distresses had a significant difference on comparing MERRA and PMED VWSs predicted distresses (a low R^2 value may not necessarily lead to a small p-value) however, all distresses determined to have a significant difference, had very weak correlation. Significantly different distresses explains that PMED VWSs and MERRA don't produce the same output on the respective distresses.

Virtual Weather Station Results Discussion

As previously discussed from the climatic summary comparison of MERRA, and PMED VWSs, a significant difference was observed in the climatic summaries of mean annual number of freeze/thaw cycles, and number of wet days. The climatic summary output data from MERRA and PMED VWS were used in correlation analysis and hypothesis testing.

From these results, distress predictions were compared to evaluate the effects of the observed climatic summary differences. On the distress analysis of the forty-nine (49) climatic stations from each MERRA and PMED VWSs, the following significant observations were made:

- Rigid pavement JPCP transverse cracking predicted distresses were significantly different.
- Rigid pavement terminal IRI and mean joint faulting predictions showed no significant difference.
- For the four flexible pavements, bottom-up cracking (47-3075), AC permanent deformation (on sites 47-3075, 47-B330 & 47-C330), and total pavement permanent deformation (on site 47-C330) showed a significant difference. The rest of the distresses were not significantly different (Table 4-11).

In summary, the comparison of the climatic output summaries developed by PMED VWSs and MERRA at identical locations showed moderate (R^2 = 0.6912) to very weak (R^2 = 0.0055) correlations between the two climatic datasets (Table 4-4). Since the PMED VWSs were created using eight MERRA station at the location where there is an existing MERRA station, the expectation was a very strong to perfect correlation and statistically significant results, assuming the PMED VWS model was accurate. Moreover, two out of five climatic outputs (mean annual number of freeze/thaw cycles, and number of wet days) showed significant difference between the two climatic datasets. The distresses predicted using the two climatic datasets had a range of results, with some distresses being significantly different and others not. Some correlations were perfect and others very weak. Significance in difference on both climatic summaries and predicted pavement distress values confirmed that creating VWSs using the PMED software may result in incorrect predicted pavement distresses, hence faulty designs. From these observations, this research did not use PMED VWS generation tool to create virtual weather stations for comparative analysis of NARR and MERRA climate data. Instead, data from a single NARR station and a nearby MERRA station were used per analyzed pavement section. It is recommended that TDOT may use the VWS function on PMED software with caution, knowing that the created station may contain errors, until the PMED VWS creation model is modified or updated. Instead, a single nearby NARR or MERRA weather station may be used.

4.3 Distress Prediction – NARR versus MERRA

After understanding the performance of the PMED EICM module through its sensitivity analysis to climatic inputs and PMED VWS performance evaluation, PMED climatic data source selection was performed. The selection process considered findings from this study on PMED EICM performance and PMED VWS creation. When this project started in 2019, only NARR climatic data source was available on PMED software as the climatic data input, MERRA could be used by importing climatic files to PMED software. The latest PMED software version has both NARR and MERRA climatic data sources as default climatic files within the PMED software. In this research, both climatic files were formatted, analyzed, and compared for use in the comparative analysis of distress prediction and layer optimization. One of the major modifications made was trimming of both climatic files to fit the same timeline (have the same length of hourly climatic data).

The PMED VWS tool analysis indicated that the climatic files and distresses predicted at the same location using the two climatic data sources (MERRA and PMED VWSs) varied widely and most of the statistical analysis results showed a weak or very weak correlations and the comparisons of some of the distresses were significantly different. This gave the research team an indication that erroneous data could be derived from the VWS creation tool. Keeping this in mind, the comparison of the predicted pavement distresses and layer optimization using the two climatic data sources (NARR and MERRA) considered the closest pair of both climatic stations to the analyzed pavement section. As a result, a total of 12 NARR and 10 MERRA stations were used in the comparative analysis of the predicted distresses and layer optimization (Figure 3-5) and the study avoided the use of PMED VWSs.

This climatic data source comparative study used a total of 59 pavement sections/sites, 37 were LTPP, and 59 TDOT sites. The 59 pavement sites included 43 flexible pavements, 9 rigid pavements, and 7 composite pavements (Rigid pavements rehabilitated with an asphalt layer) sites (Table 3-6).

Distress predictions of the pavement sections used available site material specifications, the two climatic data sources (MERRA and NARR), and traffic inputs at three hierarchical levels (Level 1, Level 2, and Level 3) (refer to Table 3-4). The traffic inputs consideration was a result of the availability of all three levels of traffic data from the LTPP and TDOT sites. TDOT pavements and some LTPP sites were analyzed using Level 2, and/or Level 3 due to unavailable Level 1 traffic data. On all analysis levels, material properties, pavement structure, traffic inputs, and water table depth were kept constant while changing the climatic data source. Level 1 and Level 2 analysis included the local/regional inputs for materials and traffic while Level 3 used default PMED values.

Analysis Using Traffic Input Level 1

For traffic input Level 1 analysis, 36 LTPP sites were used. To evaluate the correlation and the significance of the two data sources, correlation analysis and hypothesis testing were conducted. The correlation analysis of Level 1 inputs predicted distresses comparing the two climatic data sources showed a very high correlation when total pavement permanent deformation, and top-down cracking from the two climatic sources were compared, a moderate correlation when AC only permanent deformation was compared, a weak correlation with terminal IRI comparisons, and a very weak correlation on thermal cracking, and bottom-up cracking (Table 4.12).

To further understand the results, hypothesis tests were performed. From Table 4.12, both hypothesis tests showed a significant difference on NARR and MERRA thermal cracking predictions, and a significant difference in the median (using Wilcoxon rank sum test) on AC only permanent deformation prediction.

Table 4-12 Level 1 Statistical Analysis of Various Predicted Distresses using NARR and MERRA Climatic Data

Pavement Distresses	*n*	*R²*	*SEE*	*P-value* (T-test)	*P-value (Wilcoxon rank sum test)*
Terminal IRI	36	0.5724 (Weak)	8.3117	0.9144	0.8969
Permanent deformation – total pavement	26	0.9506 (Very Strong)	0.0440	0.5375	0.3136
Bottom-up cracking	34	0.0076 (Very weak)	0.8865	0.3202	0.7497
Thermal cracking	25	0.0704 (Very weak)	727.59	0.0006**	0.0001**
Top-down cracking	34	0.9664 (Very Strong)	1.0544	0.8408	0.5969
Permanent deformation – AC only	34	0.6697 (Moderate)	0.0146	0.1288	0.0051**

*NOTE: ** refers to a 0.05 level of significance. n = number of test sites*

Analysis Using Traffic Input Level 2

Fifty-nine (59) TDOT and LTPP sites were used for Level 2 traffic analysis. From the analysis, significant differences were observed similar to Level 1 predictions. Thermal cracking distress predictions showed significant differences in the mean and median when NARR and MERRA climate data were compared. The SEE value observed for thermal cracking indicated a large existing difference between NARR and MERRA predicted distress values and the R^2 values suggested a very weak correlation.

Both hypothesis tests showed significant differences in AC permanent deformation predictions in spite of the SEE value suggesting a small standard error, and R^2 suggesting a moderate correlation between NARR and MERRA predictions.

Terminal IRI, total pavement permanent deformation, and top-down cracking showed very strong correlation, small SEE and no significant difference between NARR and MERRA climatic files.

Table 4-13 Level 2 Statistical Analysis of Various Predicted Distresses using NARR and MERRA Climatic Data

Pavement Distresses	*n*	*R^2*	*SEE*	*P-value* (T-test)	*P-value (Wilcoxon rank sum test)*
Terminal IRI	59	0.9199 (Very strong)	9.3558	0.7477	0.9506
Permanent deformation – total pavement	43	0.9705 (Very strong)	0.0322	0.3952	0.1599
Bottom-up cracking	50	0.4092 (Very weak)	7.9692	0.184	0.4154
Thermal cracking	42	0.4033 (Very weak)	651.05	0.0184**	0.0065**
Top-down cracking	50	0.9729 (Very strong)	0.8774	0.7208	0.5136
Permanent deformation – AC only	50	0.6903 (Moderate)	0.0103	0.0002**	0.0004**

*NOTE: ** refers to a 0.05 level of significance.* *n = number of test sites*

Analysis Using Traffic Input Level 3

As previously mentioned, Level 3 analysis considered PMED default values including model calibrations and traffic inputs except traffic volume. The analysis of the pavement distress predictions reflects what would be the expected outputs when PMED default values are used.

On comparing the predicted distress results using the two climatic data sources, correlation and statistical analysis were performed. The correlation analysis as observed on Table 4-14 shows the Level 3 compared results to have a very strong correlation with total pavement permanent deformation, and top-down cracking predictions. A strong correlation with terminal IRI values, and very weak correlation with bottom-up cracking, thermal cracking, and AC permanent deformation outputs. Since the results showed very strong, strong, and very weak correlations, to fully understand the difference between the predicted distresses, hypothesis testing was conducted.

For hypothesis testing the predicted distresses considered both mean and median differences (T-test and Wilcoxon rank sum test). Both hypothesis tests showed no significant difference when comparing terminal IRI, total pavement permanent deformation, top-down cracking, and bottom-up cracking. The hypothesis tests suggests that the predicted distress results were comparably similar, however, opposite observations were reached on thermal cracking and AC permanent deformation predictions, which showed a significant difference between the two climatic data files (MERRA and NARR).

Table 4-14 Level 3 Statistical Analysis of Various Predicted Distresses using NARR and MERRA Climatic Data

Pavement Distresses	*n*	R^2	*SEE*	*P-value* (T-test)	*P-value (Wilcoxon rank sum test)*
Terminal IRI	59	0.8819 (Strong)	8.9763	0.6481	0.9742
Permanent deformation – total pavement	43	0.9691 (Very strong)	0.0331	0.3702	0.1549
Bottom-up cracking	50	0.464 (Very weak)	8.3767	0.2692	0.4327
Thermal cracking	42	0.415 (Very weak)	650.17	0.0180**	0.0059**
Top-down cracking	50	0.9729 (Very strong)	0.8773	0.7213	0.5113
Permanent deformation – AC only	50	0.0013 (Very weak)	0.0110	0.0002**	0.0003**

*NOTE: ** refers to a 0.05 level of significance. n = number of test sites*

Further Discussion on Distress Prediction.

From the statistical analysis conducted using the three traffic input levels (Level 1, Level 2, and Level 3) comparing the two climatic datasets (MERRA and NARR), it was determined that permanent deformation total pavement, and top-down cracking predictions had statistically significant similarities with very strong correlations. Bottom-up cracking and thermal cracking showed very weak correlation for all three levels and thermal cracking predictions were statistically different when comparing the two climatic datasets. Terminal IRI showed a weak correlation for Level 1, very strong for Level 2 and strong for level 3, however, for all three levels the results are not significantly different. AC Permanent deformation had moderate correlation for Level 1 and Level 2, but Level 3 had very weak correlation between the two climatic data sources and the values are statistically different.

Traffic Level 2 and 3 showed a significant difference with both hypothesis tests when analyzing AC permanent deformation while Level 1 showed a significant difference with the Wilcoxon rank sum test (median).

However, it should be noted that the PMED thermal cracking model has been changed to a fracture model, which is not locally calibrated to meet the local conditions. Calibration of the thermal cracking model is recommended prior to considering the distress predicted values for pavement design and analysis.

4.4 Layer Optimization – NARR, and MERRA

The PMED software allows the design of optimum pavement layers using its pavement optimization tool. Layer optimization is employed to the designed pavement sections with their respective inputs while considering the reliability level thresholds for distress predictions. The layer optimization is an iterative process, where PMED software assigns a thickness to predict distress based on the thresholds. If the predicted distresses are far from the assigned thresholds, the thickness will be changed until assigned thresholds are met. This will be the optimized layer thickness.

In this study, surface layer thickness optimization was performed for both flexible and rigid pavement sections. This analysis considered 49 flexible pavement sections and 9 rigid pavement sections obtained from TDOT and LTPP sites. To understand the extent of layer thickness changes, a comparative analysis of surface layer optimization using NARR or MERRA climatic data files was performed. The resulting optimized layer thicknesses were compared to the original layer thickness at the same site.

As previously mentioned, Level 1 analysis included LTPP sites only, while Levels 2 & 3 included LTPP and additional TDOT sites. For this analysis, the number of LTPP and TDOT sites considered are as shown in Table 4-15 and Table 4-17 for flexible and rigid pavements respectively.

NARR Optimized Layer Thicknesses Versus Original Layer Thicknesses for Flexible Pavements

Flexible pavements analysis considered 33 sites for Level 1, and 49 sites for Level 2 and Level 3. The comparison of NARR optimized surface layer thicknesses with original thicknesses showed a significant difference in the mean using traffic inputs Level 2 and Level 3 (Table 4.15). This indicates that the layer thickness may significantly increase or decrease when using NARR as climatic data source in surface layer optimization. Level 1 surface layer optimization showed no significant difference, meaning, using traffic inputs level 1 and NARR climatic data source resulted in optimized layer thicknesses that are close to the original layer thicknesses. Likewise, traffic levels 2 and 3 may give results that are different from the original layer thicknesses. This makes sense since Level 1 inputs are actual traffic inputs at that particular site, Level 2 is state average traffic inputs, and level 3 is national average traffic inputs. For all three traffic input levels, the correlation between optimized and original surface layers is very weak.

Table 4-15 Statical Analysis Results of Flexible Pavement Layer Optimization – NARR

Analysis Levels	*n*	*R^2*	*SEE*	*P-value* (T-test)	*P-value (Wilcoxon rank sum test)*
Level 1	33	0.4207 (Very weak)	1.7518	0.1922	0.7184
Level 2	49	0.2927 (Very weak)	2.1565	0.0106**	0.2943
Level 3	49	0.2509 (Very weak)	2.2193	0.0322**	0.4138

*NOTE: ** refers to a 0.05 level of significance. n = number of test sites*

MERRA Optimized Layer Thicknesses Versus Original Layer Thicknesses for Flexible Pavements

Table 4.16 shows no significant difference for all traffic level inputs (Level 1, 2 and 3) when comparing MERRA optimized layer thicknesses, and the original layer thicknesses using both hypothesis testing methods for mean, and median. However, the correlation is very weak. This indicates that the optimized layers using MERRA accepts the null hypothesis, therefore the thickness change after optimization is not significant.

Table 4-16 Statical Analysis Results of Flexible Pavement Layer Optimization – MERRA

Analysis Levels	*N*	*R²*	*SEE*	*P-value* (T-test)	*P-value (Wilcoxon rank sum test)*
Level 1	33	0.3692 (Very weak)	1.8280	0.645	0.2510
Level 2	49	0.2031 (Very weak)	2.2890	0.0897	0.8341
Level 3	49	0.1510 (Very weak)	2.3627	0.2701	0.7818

*NOTE: ** refers to a 0.05 level of significance.* *n = number of test sites*

NARR Optimized Layer Thicknesses Versus Original Layer Thicknesses for Rigid Pavements

Surface layer optimization on rigid pavements was performed on twelve sites, three sites for Level 1 traffic inputs and nine sites for Level 2 and Level 3. The optimization was performed using the available material properties, traffic data and climatic files (MERRA or NARR) on each site. The results indicated that only level 1 traffic data mean hypothesis testing showed no significant difference (Table 4-17). The rest of the results for level 1 median testing and levels 2 and 3 mean and median hypothesis tests showed significant differences of optimized layer thicknesses compared to original thicknesses. The rigid pavements sections analyzed were too few for a meaningful conclusion.

Table 4-17 Statical Analysis Results of Rigid Pavement Layer Optimization – NARR

Analysis Levels	*n*	*R²*	*SEE*	*P-value* (T-test)	*P-value (Wilcoxon rank sum test)*
Level 1	3	0.206 (Very weak)	0.0728	0.0955	0.0084**
Level 2	9	0.1607 (Very weak)	0.7801	0.0088**	4.4e-05**
Level 3	9	0.1895 (Very weak)	0.7666	0.0091**	4.4e-05**

*NOTE: ** refers to a 0.05 level of significance* *n = number of test sites*

MERRA Optimized Layer Thicknesses Versus Original Layer Thicknesses for Rigid Pavements

The rigid pavement surface layer optimization results using MERRA climatic data source were similar to that of NARR climatic data source. Only Level 1 hypothesis t-test showed no significant difference between optimized and original layer thicknesses, and the rest indicated a significant difference (Table 4-18). All the three levels of analysis showed very weak correlation between the optimized and original surface layer thicknesses. Likewise, the small number of tested sites may contribute to poor results.

Table 4-18 Statical Analysis Results of Rigid Pavement Layer Optimization – MERRA

Analysis Levels	*n*	*R²*	*SEE*	*P-value* (T-test)	*P-value (Wilcoxon rank sum test)*
Level 1	3	0.206 (Very weak)	0.0728	0.0955	0.0084**
Level 2	9	0.0268 (Very weak)	0.8400	0.0118**	4.4e-05**
Level 3	9	0.0494 (Very weak)	0.8302	0.0106**	4.4e-05**

*NOTE: ** refers to a 0.05 level of significance.* *n = number of test sites*

Layer Optimization Discussion – NARR and MERRA.

The surface layer optimization analysis on flexible pavement sections, MERRA optimized thicknesses were observed to have no significant difference from the original layer thicknesses at all three input levels, while NARR showed a significant difference with Levels 2 and 3. Both climatic sources showed a very weak correlation with the original thicknesses. As much as the MERRA climatic data source showed a very weak correlation, the thicknesses were not significantly different, meaning it is a better choice for use at any traffic level as opposed to the NARR climatic data source.

Rigid pavement sections used on this analysis showed significant difference at all Levels, for both NARR and MERRA climatic data sources. However, the number of sites considered in the statistical analysis is not sufficient to make a sound conclusion.

Chapter Discussion

Chapter 4 considered the sensitivity analysis of PMED EICM (section 4.1), the performance of PMED VWSs (section 4.2), and the evaluation of climatic data sources MERRA and NARR, which was evaluated in twofold. Distress prediction using MERRA and NARR climatic data sources (Section 4.3), and layer optimization using MERRA and NARR climatic data sources (Section 4.4).

The sensitivity analysis was performed to evaluate what predicted pavement distresses were sensitive to climatic inputs (temperature, wind speed, percent sunshine, relative humidity, and water table depth). It was found that temperature was the most influential climatic input that affected all distresses, followed by wind speed, then percent sunshine. The variation of water table affected total pavement rutting especially for pavements with unbound base layer (LTPP site 47-3104). It is therefore imperative for TDOT to pay attention to the climatic data inputs as much as possible because they play a big role on pavement performance.

The performance of PMED VWSs was used to assess the VWS creation tool on the PMED software. 49 VWSs were created on PMED software using eight existing MERRA stations on a location with a MERRA station (Figure 3-3). The PMED created VWS climatic inputs were compared to the existing MERRA climatic inputs at the same location. It was determined that the correlation (R^2) between the climatic inputs ranged from moderate to very weak (Table 4-4), and the hypothesis testing showed no difference on the medians of PMED VWSs and MERRA climatic inputs except for the median of mean annual number of freeze/ thaw cycles, and number of wet days, which were significantly different.

The climatic inputs were then used to predict distresses on the five LTPP sites. The observations indicated that the results had a wide range from perfect correlation to very weak correlation, and on hypothesis testing some sites showed statistically significant difference and others did not. These results are contrary to expectations. Since the PMED VWS was developed from eight MERRA stations to form a station at the same location with another MERRA station. The expectation was to have very similar or very close climatic files and distresses prediction. The data indicated that the VWS tool on PMED software was not creating climatic files that are similar to the existing files at the same location, and hence using the tool may results to erroneous outcomes. Therefore, this research decided to compare MERRA and NARR climatic data sources without using the VWS tool on the PMED software.

The comparative analysis of the two climatic data sources used the existing MERRA and NARR stations near the site to be analyzed. The state of Tennessee has twelve NARR stations; therefore, twelve NARR stations and ten nearby MERRA stations were used to analyze 59 LTPP and TDOT sites. The analysis included predicted distresses and surface layer optimization. The correlation of the compared distresses varied from perfect to very weak for the three traffic levels. The layer optimization of rigid pavements indicated that both NARR and MERRA climatic data sources showed significant difference from the original thicknesses. For flexible pavements NARR climatic data source showed significant difference on input Levels 2 and 3, while Level 1 was not significantly different. MERRA climatic data source showed no significant difference from the original thicknesses for all three traffic levels. From this analysis we recommend using a nearby climatic station for pavement design and analysis. MERRA has a wide geographical coverage therefore it is recommended. Furthermore, the optimized layer thicknesses using MERRA as climate input were close to the original thicknesses than NARR.

Chapter 5 Conclusion and Recommendations

The purpose of this research was to determine the climatic data source that can be used by TDOT to implement PMED for its pavement design and analysis. For this research two climatic data sources were evaluated for their suitability for PMED implementation. The first data source was the North American Regional Reanalysis (NARR), which consisted of actual stations located in the state of Tennessee. Currently, Tennessee has twelve NARR stations throughout the state of which five are located in TDOT Region 1, Knoxville area. The second climatic data source used in the study is the Modern Era Retrospective-analysis for Research and Application (MERRA). Unlike the NARR stations, MERRA stations are equally spatially distributed throughout the state of Tennessee with 49 stations. Other than the broader geographic coverage, the second advantage of MERRA climatic data is its richness of data. MERRA climatic data is updated with data of the previous year, unlike NARR data that has climatic data currently up to 2015.

Along with the focus of comparing these two climatic data sources for their implementation in PMED, other studies were conducted to determine the general performance of the PMED EICM climatic model. This study sought to understand the sensitivity of the climate model and the performance in creating virtual weather stations. This played a significant role in understanding the final generated outputs when comparing NARR and MERRA climatic data sources, and it helped avoid some operations that could have led to unrealistic results, such as, the use of the current PMED VWS tool. In addition, it helped the consideration of trimming the two climatic data sources into equal sizes in terms of hourly climatic data length. From the study, it was determined that, the PMED VWS did not create climatic data files that were similar to MERRA data files at the same locations. It was expected that since eight MERRA stations were used to create the VWS at a location with a MERRA station, the VWS results should ascertain the null hypothesis in all cases. But this was not the case, in some cases the Null hypothesis, which states that “there is no difference between MERRA and PMED VWS climatic data sources” was rejected. Therefore, it was determined that using the PMED VWS may lead to erroneous results and faulty pavement design.

Findings

On analyzing EICM performance and comparing NARR and MERRA climatic data sources using the PMED software, the findings can be summarized as follows:

1. Sensitivity analysis showed PMED distresses to be mostly sensitive to the air temperature climatic input values than most other climatic inputs.
2. The depth of water table is most sensitive in shallow pavement structures with a granular or unbound base course.
3. Virtual weather stations currently generated with the PMED software showed a significant difference when compared to existing MERRA stations at the same location. Significant differences in the climatic summary observed included number of wet days, and mean annual number of freeze/thaw cycles. The significant difference observed in predicted distresses included AC permanent deformation, total pavement permanent deformation, bottom-up cracking, and JPCP transverse cracking.
4. Comparing NARR and MERRA predicted distresses, all three traffic input levels showed a significant difference when comparing thermal cracking, and AC permanent deformation (AC rutting) distresses.

5. AC surface layer optimization showed a significant difference with traffic input Level 2 and Level 3 having a relatively thicker optimized layer when using NARR climatic files, while Level 1 showed no significant difference when compared to the original layer thickness.
6. AC Surface layer optimization using MERRA data showed no significant difference with all three traffic input levels of analysis.
7. Surface layer optimization of rigid pavements showed a significant difference with both climatic data sources. This can be attributed to the low/few number of rigid pavements available for analysis.

Conclusions

This study was conducted to provide recommendations on PMED climatic data source input. The climatic data chosen will enable TDOT to use more proactive design inputs for efficient pavement design. PMED method is cost effective and provides a designer with predicted distresses and expected pavement performance.

From the research findings it can be concluded that temperature, and wind speed are the climatic inputs that mostly affect pavement performance. On the other hand, depth of water table affects mostly pavements with unbound base layer. Therefore, TDOT should be careful when considering climatic inputs by obtaining climatic files that represents the design site as close as possible, to minimize pavement failures and improve their performance.

The PMED virtual weather station generation tool was used to replicate a MERRA station using eight MERRA stations. The results did not replicate the actual MERRA stations on many accounts. This indicated that the VWS tool on the PMED software may need improvements to be able to create virtual weather stations that have climatic files that are close to the existing situation. The analysis indicated that if PMED VWS is used there is a possibility of creating erroneous climatic files and producing undesirable pavement structures. On this account, this research did not use VWSs for the comparative analysis of MERRA and NARR to eliminate any possibility of introducing errors on the predicted results, hence only one actual climatic station (MERRA or NARR) was used for the analysis. It is advised that TDOT should use the VWS tool on PMED software with caution, otherwise one of the closest actual weather station should be used for design and analysis.

In conclusion, comparing the two climatic data sources, it is advised to use MERRA climatic data source closest to the design site as its layer optimization indicated no significant difference from the original layers at all three traffic levels. Furthermore, MERRA has a better geographical representation, 49 stations in Tennessee as opposed to the NARR, which has 12 stations in the state. In addition, MERRA climatic data is updated yearly, unlike NARR data that has climatic data currently up to 2015.

Benefits to TDOT

The benefits of this research to TDOT include:

1. Recommended climate data source input for PMED Method. The climatic data recommended will enable TDOT to use more proactive design inputs for efficient pavement design.
2. PMED is a new pavement design method that is cost effective and provides pavement performance as design output.

Research Project Challenges & Limitations

- This research consisted of 59 pavement sections including LTPP and TDOT sections. Among the challenges faced with these sections included missing data such as site recorded material data and traffic data. The solution used for these scenarios was using either Level 2 data or the default values found in the PMED software (Level 3). This issue mostly affected the Level 1 group analysis as there is a low availability of Level 1 data for each site.
- The distress predicted using NARR and MERRA climatic data sources were not compared to measured distresses on those sites due to unavailability of measured distresses on the respective sites. The correlation and hypothesis testing of predicted distresses using NARR and MERRA climatic data sources was used.
- The state of Tennessee has only 12 NARR stations available for pavement design and analysis in the PMED software. Therefore, the comparison of NARR and MERRA climatic data sources considered 12 NARR stations and 10 MERRA stations in the same vicinity, trimmed to have the same length of hourly climatic data.
- The latest PMED version 2.6.1, used during the research had an updated thermal cracking model (fracture model), which is not calibrated to suit Tennessee local design conditions. The thermal cracking model on the previous version was locally calibrated but not available on the current version. Therefore, thermal cracking predictions used default model calibration values available on the PMED software.

Recommendations

Based on this research, the followings are the recommendations to TDOT on implementation of climatic data in the PMED design and pavement analysis.

- TDOT should consider the calibration of the recent thermal cracking model, otherwise consider with caution the predicted thermal cracking values.
- Based on spatial coverage and up-to-date climatic data, MERRA is recommended for use in the pavement design and analysis for Tennessee pavements.
- For selecting weather stations, TDOT should consider the use of the nearest available weather station (NARR or MERRA) and should avoid creating virtual weather stations unless the current VWS model is updated.
- As noted in the literature, selection of weather stations should take into consideration the difference in elevation between the weather station and the pavement site.
- Water table depth values are to be carefully considered when designing and analyzing pavements using PMED software, as they have shown to be a sensitive input to predicted distresses, especially on pavements with unbound bases. Therefore, it is recommended to TDOT to use water table values from geological exploration or those available from USGS (United States Geological Survey) that best represent the design site.

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Appendices

Appendix A: Climatic Input Level Combinations for HCD Stations.

Appendix A shows the climatic input level for hourly climatic data (HCD) stations as used in the 2^k factorial analysis explained in Section 3.1. A combination matrix of total 32 (2^5) stations that were tested on three pavement sections. On Table A-1, negative sign implies low values and positive sign implies high input values (refer to Table 3-1).

Table A-1 The 2^k Factorial Stations

STATIONS	A	B	C	D	E
1	-	-	-	-	-
2	+	-	-	-	-
3	-	+	-	-	-
4	+	+	-	-	-
5	-	-	+	-	-
6	+	-	+	-	-
7	-	+	+	-	-
8	+	+	+	-	-
9	-	-	-	+	-
10	+	-	-	+	-
11	-	+	-	+	-
12	+	+	-	+	-
13	-	-	+	+	-
14	+	-	+	+	-
15	-	+	+	+	-
16	+	+	+	+	-
17	-	-	-	-	+
18	+	-	-	-	+
19	-	+	-	-	+
20	+	+	-	-	+
21	-	-	+	-	+
22	+	-	+	-	+
23	-	+	+	-	+
24	+	+	+	-	+
25	-	-	-	+	+
26	+	-	-	+	+
27	-	+	-	+	+
28	+	+	-	+	+
29	-	-	+	+	+
30	+	-	+	+	+
31	-	+	+	+	+
32	+	+	+	+	+

Appendix B: VWS Climatic Summary Comparison Flow Chart

The flow chart on Figure B-1 shows the steps/process followed in the comparative analysis of PMED VWSs and MERRA climatic summaries. More information is given in Section 3.2.

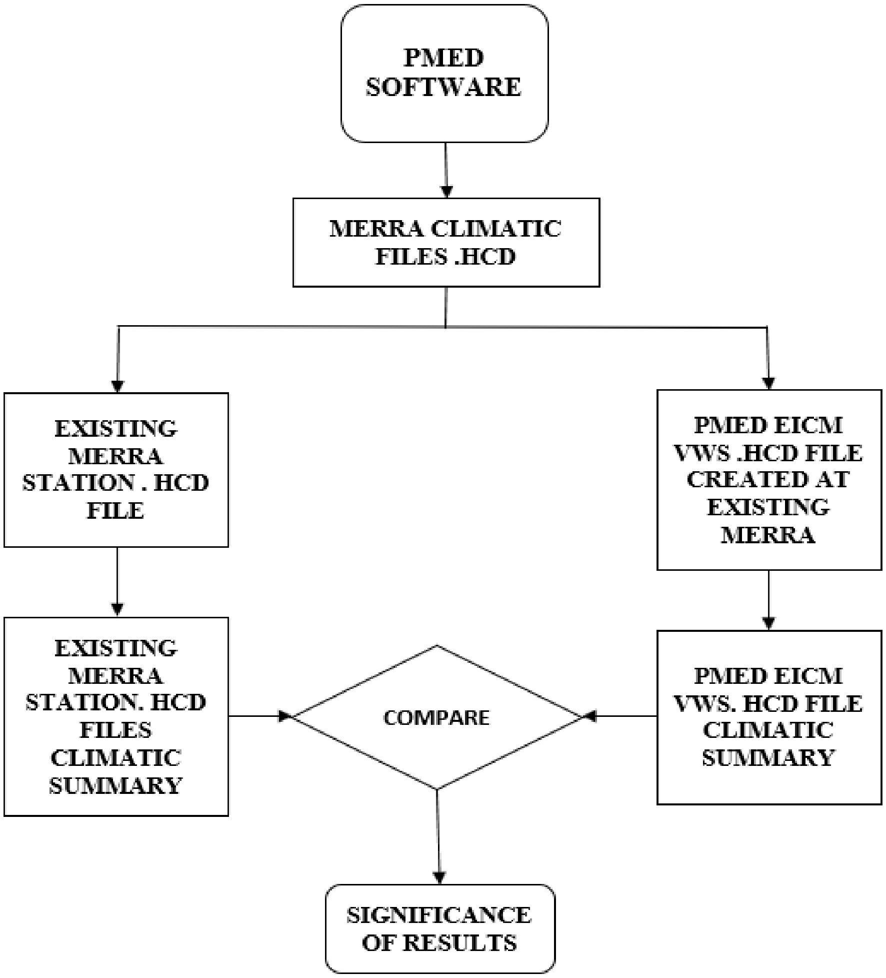

Figure B-1 Flow Chart of the VWSs Climatic Summary Comparisons

Appendix C: VWS Distress Prediction and Comparison Flow Chart

The flow chart on Figure C-1 shows the steps/process followed in the comparative analysis of PMED VWSs and MERRA predicted distresses. More information is given in Section 3.2.

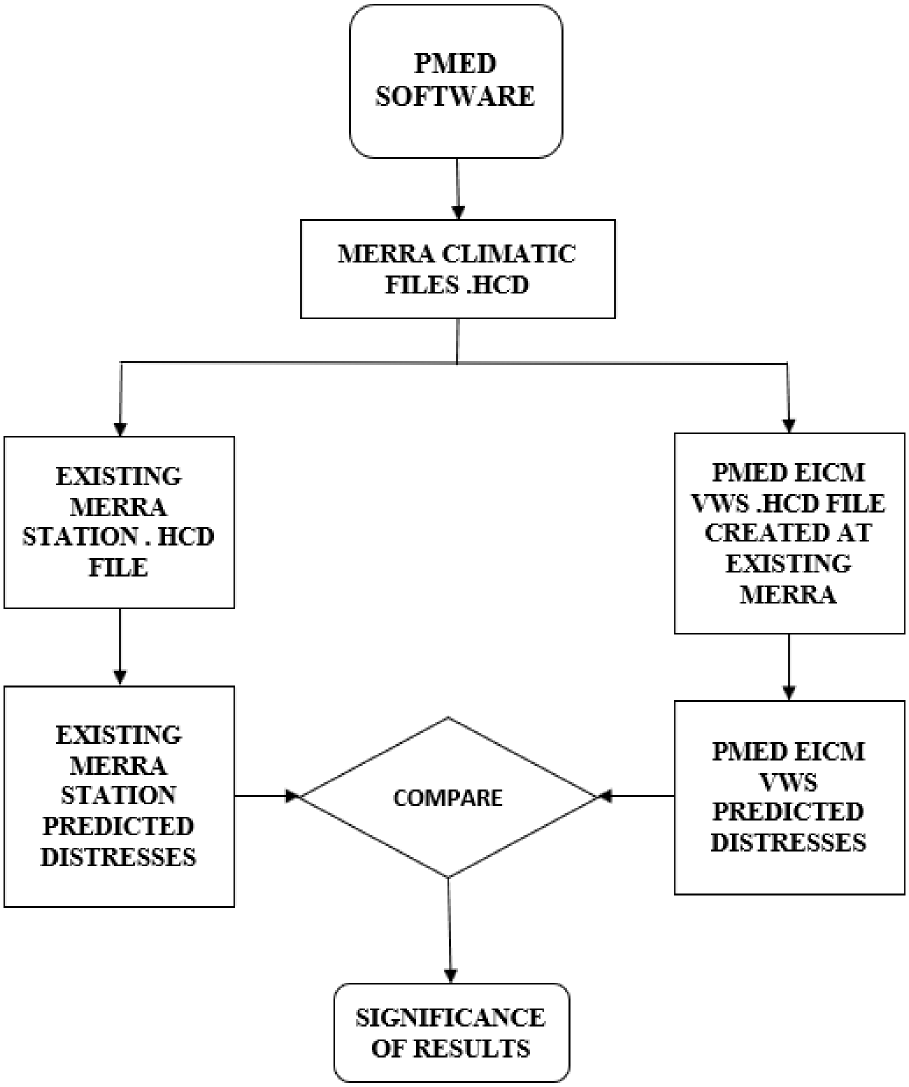

Figure C-1 Flow Chart with the Comparison of Predicted Distresses using VWS and MERRA data

Appendix D: NARR and MERRA Distress Comparison Flow Chart

The flow chart on Figure D-1 shows the steps/process followed in the comparative analysis of NARR and MERRA predicted distresses. More information is given in Sections 3.3 and 4.3.

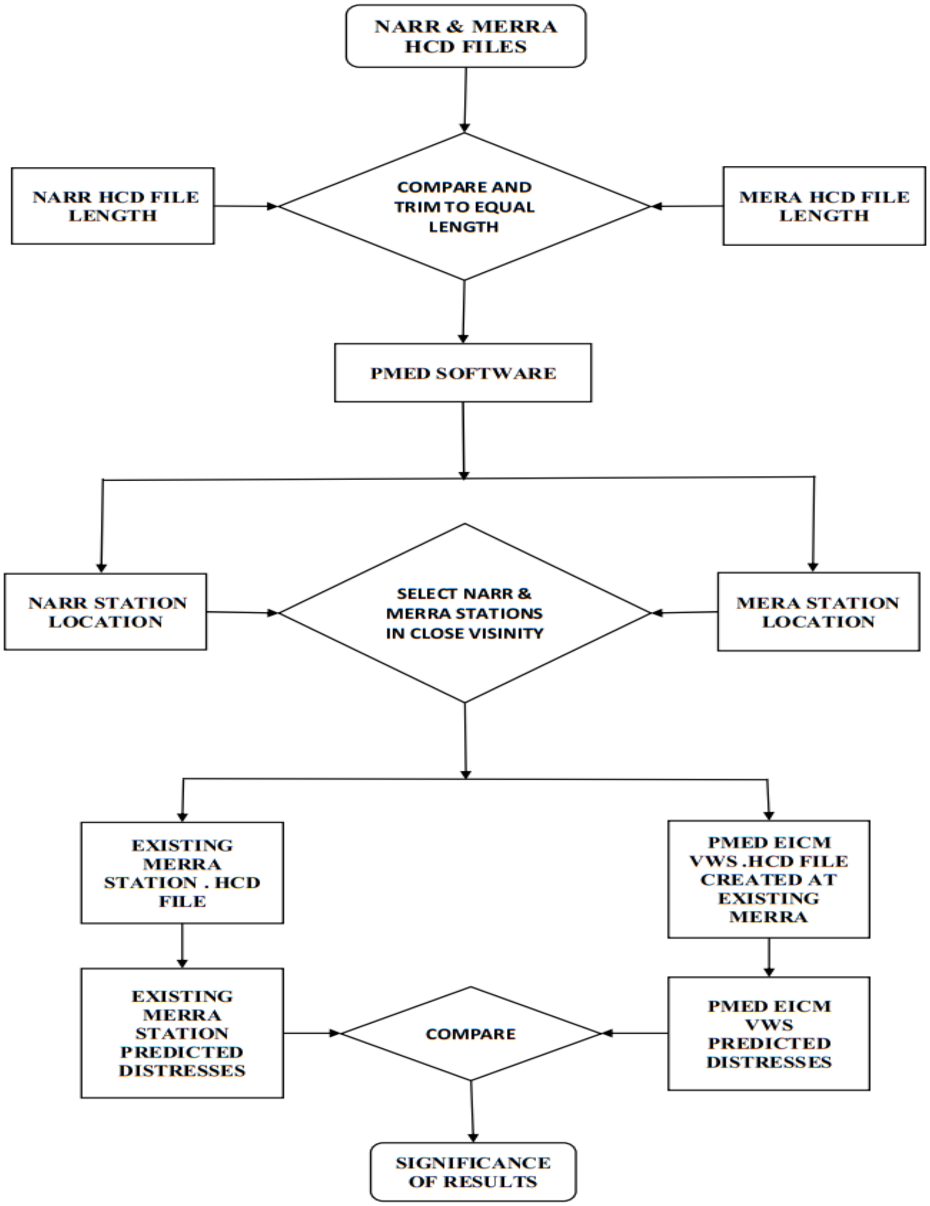

Figure D-1 Flow Chart showing MERRA and NARR Predicted Distress Comparisons

Appendix E: NARR and MERRA Optimized Layer Thickness Comparison.

The flow chart on Figure E-1 shows the steps/process followed in the comparative analysis of NARR and MERRA layer optimization. More information is given in Sections 3.3 and 4.4.

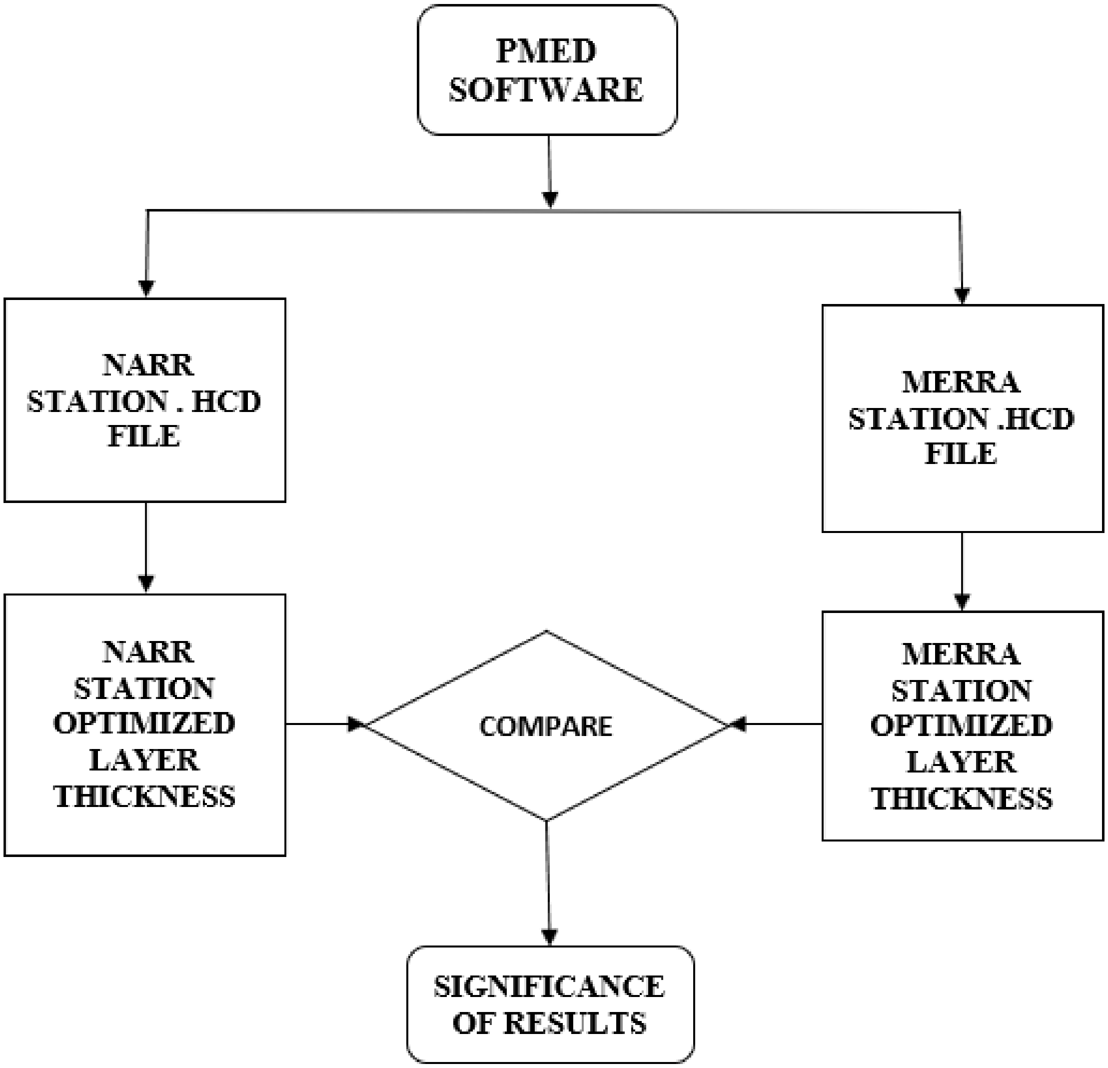

Figure E-1 Flow Chart of the Comparison Between MERRA and NARR Optimized Layer Thickness

Appendix F: MERRA Stations for the State of Tennessee

MERRA stations are spatial, equally spaced in the state of Tennessee. Table F-1 shows the locations, coordinates, and elevations of MERRA climatic stations used in this study for PMED VWSs creation, and comparative analysis of MERRA and PMED VWSs climatic data files.

Table F-1 MERRA Stations for the State of Tennessee

MERRA ID	State	Location	Coordinates	Station Elevation
138385	Tennessee	Memphis	35,-90	337.84
138386	Tennessee	Moscow	35,-89.375	390.32
138387	Tennessee	Pocahontas	35,-88.75	518.24
138388	Alabama	Waterloo	35,-88.125	718.32
138389	Alabama	Killen	35,-87.5	698.64
138390	Tennessee	Ardmore	35,-86.875	656
138391	Tennessee	Huntland	35,-86.25	951.2
138392	Tennessee	Jasper	35,-85.625	783.92
138393	Tennessee	Apison	35,-85	954.48
138394	Tennessee	Copperhill	35,-84.375	1610.48
138961	Tennessee	Drummonds	35.5,-90	232.88
138962	Tennessee	Stanton	35.5,-89.375	288.64
138963	Tennessee	Pinson	35.5,-88.75	537.92
138964	Tennessee	Decaturville	35.5,-88.125	593.68
138965	Tennessee	Hohenwald	35.5,-87.5	793.76
138966	Tennessee	Lewisburg	35.5,-86.875	715.04
138967	Tennessee	Normandy	35.5,-86.25	947.92
138968	Tennessee	McMinnville	35.5,-85.625	1679.36
138969	Tennessee	Dayton	35.5,-85	803.6
138970	Tennessee	Madisonville	35.5,-84.375	970.88
138971	North Carolina	Robbinsville	35.5,-83.7 5	2292.72
138972	North Carolina	Maggie Valley	35.5,-83.125	4569.04
139538	Tennessee	Dyersburg	36,-89.375	272.24
139539	Tennessee	Milan	36,-88.75	492
139540	Tennessee	Camden	36,-88.125	429.68
139541	Tennessee	Dickson	36,-87.5	741.28
139542	Tennessee	Franklin	36,-86.875	738
139543	Tennessee	Milton	36,-86.25	760.96
139544	Tennessee	Sparta	36,-85.625	931.52
139545	Tennessee	Crossville	36,-85	1777.76
139546	Tennessee	Oliver Springs	36,-84.375	957.76
139547	Tennessee	Knoxville	36,-83.75	1111.92
139548	Tennessee	Parrottsville	36,-83.125	1197.2
139549	Tennessee	Erwin	36,-82.5	4155.76

Table F-1 MERRA Stations for the State of Tennessee Continues . . .

MERRA ID	State	Location	Coordinates	Station Elevation
139550	North Carolina	Newland	36,-81.875	3686.72
140114	Kentucky	Hickman	36.5,-89.375	288.64
140115	Tennessee	Martin	36.5,-88.75	498.56
140116	Kentucky	Buchanan	36.5,-88.125	406.72
140117	Tennessee	Woodlawn	36.5,-87.5	439.52
140118	Tennessee	Springfield	36.5,-86.875	662.56
140119	Tennessee	Bethpage	36.5,-86.25	790.48
140120	Tennessee	Moss	36.5,-85.625	915.12
140121	Tennessee	Jamestown	36.5,-85	1708.88
140122	Tennessee	Oneida	36.5,-84.375	2220.56
140123	Tennessee	Speedwell	36.5,-83.75	1551.44
140124	Tennessee	Sneedville	36.5,-83.125	1672.8
140125	Tennessee	Kingsport	36.5,-82.5	1443.2
140126	Tennessee	Mountain City	36.5,-81.875	3516.16

Appendix G: Climatic Summary Output

Appendix G presents the climatic summaries outputs for PMED VWSs and MERRA climatic files at the same location. In Table G-1, the acronyms used are as explained here: Prec. = Precipitation, Temp. = Temperature, EXT = Existing MERRA, VWS = PMED VWS station, freeze thaw = Mean Annual Number of Freeze/Thaw Cycles, Wet days = number of wet days

Table G-1 Comparison of Climatic Outputs for MERRA And PMED Stations

Location ID	Mean Annual Air Temp. VWS	Mean Annual Air Temp. EXT	Mean Annual Prec. VWS	Mean Annual Prec. EXT	Freezing Index VWS	Freezing Index EXT	Freeze /Thaw Cycles VWS	Freeze /Thaw Cycles EXT	Wet Days VWS	Wet Days EXT
138385	61.1	61.5	54.1	54.4	87.4	87.9	52.3	52.5	226.3	268.6
138386	61	60.6	55.3	55.6	86.5	94.9	52.4	56.1	228.6	274.4
138387	60.6	60.6	56.1	56.4	86	87.8	53.3	58.3	231.9	273.9
138388	59.8	60.5	57.2	56.7	94.9	82.3	56.1	55.6	234	276.8
138389	59.8	59.7	57.1	57.2	91	92.5	55.5	59.4	237.7	282.2
138390	60.1	59.6	57.4	57.3	84.3	97	52.9	58.5	240.9	285.3
138391	59.4	59.1	57.5	57.6	91.5	104.3	55.3	59.3	242.9	286.1
138392	60.1	58.2	56.3	59.7	71.3	104	50.1	64.1	241.2	292.9
138393	59.4	59.5	57.7	52.8	72.5	72.1	52.8	58.6	244.8	291.3
138394	57	57	57.7	60.3	105.8	114.1	62.8	67.8	247.8	285.2
138961	60.7	60.7	52.6	52.8	101.1	106.3	54.7	57	224.9	269.6
138962	60.5	60.2	54.1	53.3	104.4	114.4	54.6	58.5	227.5	270
138963	60	59.6	55.1	56.5	109.7	119.7	56.5	61.2	229.8	271.2
138964	59.6	59.8	56.4	55.8	109.8	108.8	57.5	61.8	233.6	280.4
138965	58.8	58.8	56	59	123	120.6	60.1	64.8	236.2	285.6
138966	59.1	58.7	56.5	56.2	113.9	126.7	57.7	61.9	239.7	287.2
138967	58.3	58.4	56.8	57.1	126	132.7	60.4	61.6	243.6	287.7
138968	55.7	57.2	57.4	58.1	186.1	143.1	69.2	64.5	245.1	291.2
138969	59	58.1	56.8	59.6	91	106.9	54.7	66.3	246.2	292.6
138970	58.5	58.5	58.3	52.3	90.6	97.6	55.4	65.2	251.9	285.5
138971	55	54.7	57.2	62.2	164	180.1	72.1	74.6	256	295.3
138972	59.8	53.3	51.6	59.3	125.7	204.5	58.2	81.3	224	301.1
139537	59.8	59.7	51.6	50.9	125.7	130.3	58.2	60.8	224	270.1
139538	59.7	59.5	53	52.6	131.3	137.8	57.8	60.2	226.9	267.8
139539	59	59	54.4	55.2	145.7	148.7	59.3	63.2	229	267.6
139540	59.3	59.3	55.7	56.4	132.3	137.5	58.8	62.1	234.2	279.2
139541	58.1	58.5	56	55	155.5	143.4	63.3	66.5	237.3	284.8
139542	58.2	58.5	56.5	54.6	147.7	144.9	62.8	63.6	240.9	286.9
139543	58.3	58.4	56.5	55.8	137.2	141.9	60.2	63	244.7	287.6
139544	58.2	57.3	57.4	56.1	130.4	155.7	58.9	66.5	247.9	289.6
139545	55.5	55.7	56.1	61.7	193.6	184.8	69.7	75.4	248.7	290.7

Table G-1 Comparison of Climatic Outputs for MERRA And PMED Stations Continues . . .

Location ID	Mean Annual Air Temp. VWS	Mean Annual Air Temp. EXT	Mean Annual Prec. VWS	Mean Annual Prec. EXT	Freezing Index VWS	Freezing Index EXT	Freeze /Thaw Cycles VWS	Freeze /Thaw Cycles EXT	Wet Days VWS	Wet Days EXT
139546	58.4	57.4	56.4	55.2	106.1	126	56.6	72	252.2	294.9
139547	58.9	57.5	56	49.4	90.2	127.3	53.6	66	256.3	294.9
139548	59.2	55.7	55.7	51.6	81.3	165.7	49.5	71.9	261.2	295
139549	48.5	53.6	55.7	59.5	470.4	224.8	96.9	80.2	261	300.9
139550	49.7	53.3	54.7	60.6	390.1	216.1	97.3	87.1	257.7	296.4
140114	58.7	58.8	52.4	51.7	165.6	171.8	63	62.7	226.6	267.3
140115	58.1	58.2	53.7	54.6	185.5	184.4	63	66.3	230.2	269.7
140116	58.5	58.6	54.7	55.5	168.2	175.4	62.2	61.8	233.1	277.6
140117	58.6	57.8	55	55.6	162.2	181.2	60.9	68.9	236.1	284.5
140118	57.7	57.7	55.4	56.1	175.9	180	65	67.4	239	286.7
140119	57.4	57.4	55.7	58.3	178.4	180.2	65.2	68	243.4	288.3
140120	57.4	57.3	56.7	56.6	166.8	171.4	63.7	67.9	247.9	289.9
140121	55	56.3	56.6	53.7	230.8	190.8	72.1	72.3	249.9	288.5
140122	53.3	55.5	54.8	58.3	288.7	194.5	79.2	78.5	252.7	295.2
140123	55.7	56.2	54	55.2	182.7	170.7	71.5	75.6	254.9	297.8
140124	56	55.5	54.3	54.9	167.7	181.9	69.5	77	259	297
140125	58.3	55.1	56.7	47.8	105.4	198.3	51.8	78.3	265.3	295.6
140126	50.7	51.7	55	60.1	359	316.8	91.4	88.5	263.7	302.7

Appendix H: PMED VWS Climatic Summary Comparison

Plots in Figures H-1 to H3 show the comparison between MERRA and PMED VWS outputs, Mean annual air temperature Figure H-1, Mean annual precipitation Figure H-2 and Freezing Index Figure H-3.

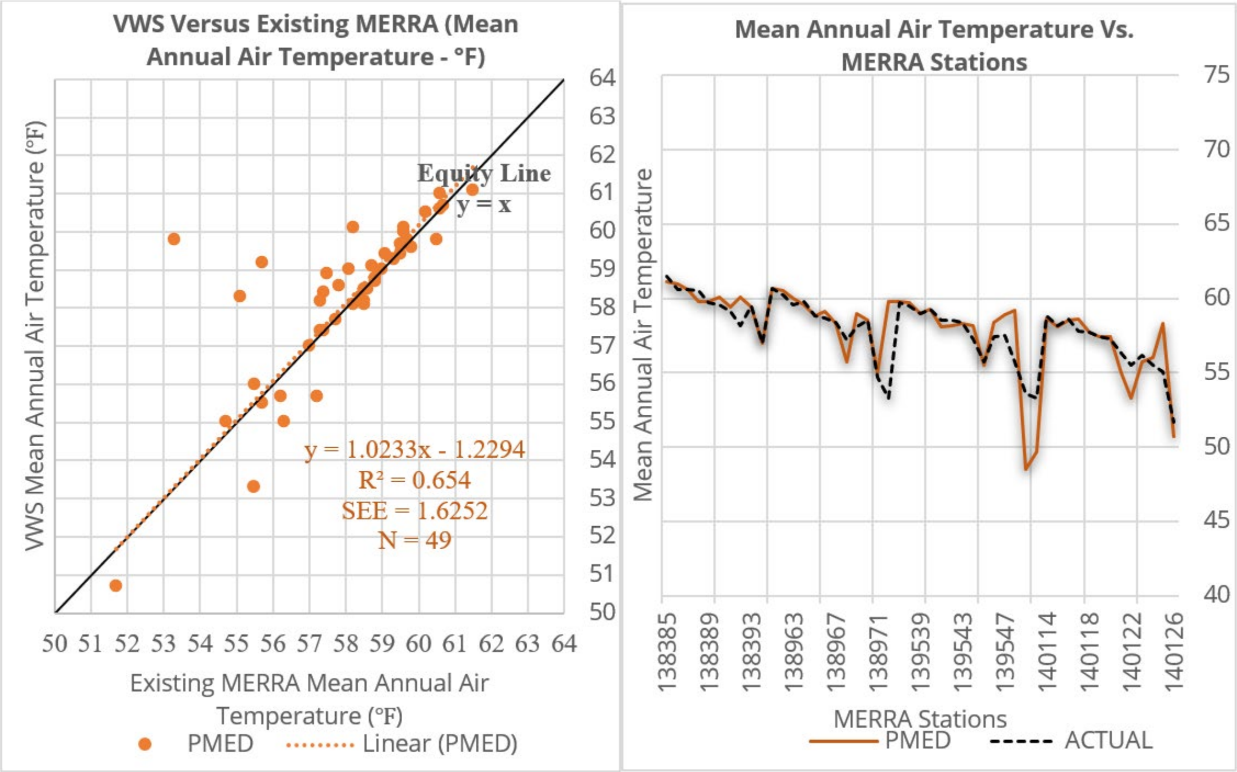

Figure H-1 PMED VWS versus MERRA Mean Annual Air Temperature

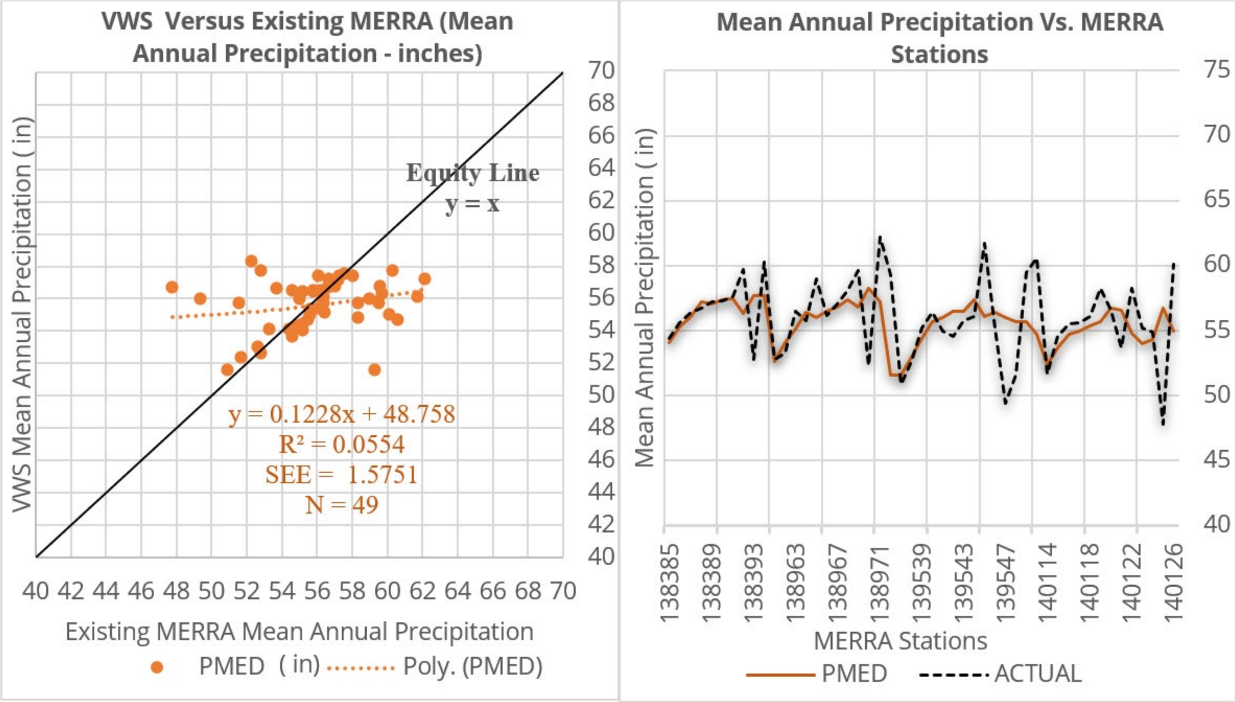

Figure H-2 PMED VWS versus Existing MERRA Mean Annual Precipitation

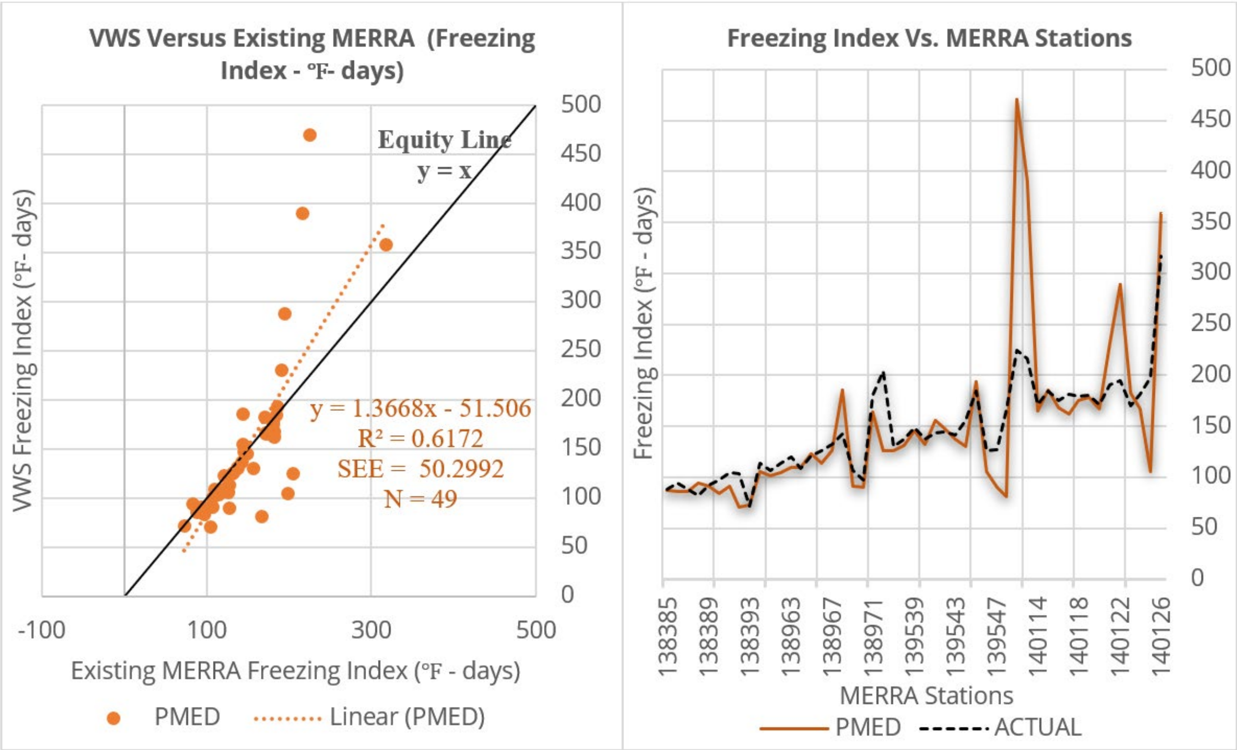

Figure H-3 PMED VWS versus Existing MERRA Freezing Index

Appendix I: VWS Pavement Distress Prediction Output

Appendix I presents predicted pavement distress outputs for PMED VWSs and MERRA climatic files at the same location. In Tables I-1 to I-5 the acronyms used are as explained here: EXT = Existing MERRA, VWS = PMED VWS station, JPCP = Jointed Plain Concrete Pavement, and IRI = International Roughness Index.

Table I-1 Predicted distresses on Rigid pavement using MERRA and PMED VWS on SITE 47-602

Location ID		**Terminal IRI - VWS**	**Terminal IRI - EXT**	**Mean Joint Faulting VWS**	**Mean Joint Faulting EXT**	**JPCP Transverse Cracking VWS**	**JPCP Transverse Cracking EXT**
138385		180.51	182.19	0.15	0.16	8.87	9.16
138386		179.64	183.91	0.15	0.15	9.62	12.62
138387		179.5	184.59	0.15	0.13	12.56	32.69
138388		180.19	193.93	0.15	0.14	13.85	39.01
138389		180.31	184.04	0.15	0.15	15.67	12.56
138390		179.58	186.11	0.15	0.16	12.28	14.43
138391		180.73	187.98	0.15	0.16	14.38	16.49
138392		175.18	184.02	0.14	0.13	16.74	34.68
138393		170.33	182.05	0.12	0.13	26.09	30.52
138394		174.24	160.57	0.12	0.09	27.51	32.29
138961		184.07	187	0.16	0.16	8.54	9.29
138962		183.58	187.7	0.16	0.16	9.21	9.77
138963		184.5	188.03	0.16	0.16	12.22	11.93
138964		183.58	183.91	0.15	0.12	14.25	37.28
138965		186.68	189.2	0.16	0.14	14.58	32.9
138966		184.73	189.55	0.16	0.16	12.34	13.2
138967		186.86	190.21	0.16	0.16	13.45	12.16
138968		195.08	188.32	0.17	0.14	16.19	28.06
138969		174.52	183.41	0.12	0.13	25.77	33.97
138970		172.68	164.68	0.13	0.09	21.48	34.92
138971		179.27	189.35	0.13	0.13	21.18	33.5
138972		190.67	174.36	0.17	0.11	8.65	31.06
139537		190.67	193.47	0.17	0.17	8.65	9.57
139538		189.31	191.78	0.17	0.17	8.17	9.52
139539		191.37	192.86	0.17	0.17	10.15	9.21
139540		187.54	197.16	0.16	0.15	12.3	30.16
139541		192.31	193.6	0.16	0.14	13.7	32.24
139542		190.3	193.37	0.16	0.17	11.85	12.18
139543		187.7	192.47	0.16	0.17	12.14	11.93
139544		185.41	193.31	0.15	0.14	14.49	34.13
139545		188.31	174.77	0.14	0.11	24.4	34.42
139546		175.46	183.8	0.13	0.13	22.62	33.88
139547		171.98	188.83	0.12	0.16	23.87	17.27
139548		172.48	192.95	0.13	0.15	18.44	25.27
139549		232.41	180.16	0.21	0.12	21.64	31.84
139550		232.54	191.06	0.21	0.13	17.7	35.34
140114		197.18	199.8	0.18	0.18	8.46	8.73

Table I-1 Predicted distresses on Rigid pavement using MERRA and PMED VWS on SITE 47-602 Continues . . .

Location ID	Terminal IRI - VWS	Terminal IRI - EXT	Mean Joint Faulting VWS	Mean Joint Faulting EXT	JPCP Transverse Cracking VWS	JPCP Transverse Cracking EXT
140115	200.04	200.88	0.18	0.18	9.16	9.21
140116	195.02	201.94	0.17	0.18	10.39	17.37
140117	193.77	201.02	0.17	0.17	11.47	16.68
140118	195.92	200.49	0.17	0.18	10.99	11.66
140119	195.84	199.67	0.17	0.18	11.3	11.13
140120	192.33	199.89	0.17	0.16	12.44	26.19
140121	198.89	194.29	0.17	0.14	17.09	37.78
140122	204.81	174.27	0.17	0.11	18.74	31.79
140123	185.91	187.87	0.14	0.13	20.85	33.12
140124	185.61	194.04	0.15	0.14	18.28	32.23
140125	171.98	207.27	0.12	0.18	23.02	16.34
140126	213.91	215.07	0.18	0.18	21.01	27.66

Table I-2 Predicted distresses on Flexible pavement using MERRA and PMED VWS on SITE 47-3075

Location ID	Terminal IRI - VWS	Terminal IRI - EXT	Total Pavement Permanent Deformation VWS	Total Pavement Permanent Deformation EXT	Bottom-Up Cracking VWS	Bottom-Up Cracking EXT
138386	160.9	161.13	0.26	0.26	1.46	1.47
138387	161.18	162.38	0.26	0.28	1.47	1.51
138388	161.51	162.12	0.26	0.28	1.47	1.5
138389	161.52	161.23	0.26	0.26	1.47	1.47
138390	161.2	161.39	0.26	0.26	1.47	1.47
138391	161.48	161.64	0.26	0.26	1.47	1.47
138392	161.24	150.95	0.27	0.28	1.48	1.51
138393	150.28	161.54	0.28	0.28	1.5	1.49
138394	144.51	140.64	0.28	0.28	1.5	1.52
138961	160.84	160.91	0.25	0.25	1.46	1.46
138962	161.04	161.08	0.25	0.25	1.46	1.46
138963	161.4	161.48	0.26	0.26	1.47	1.47
138964	161.64	162.78	0.26	0.29	1.47	1.52
138965	161.77	162.96	0.26	0.28	1.47	1.51
138966	161.56	161.63	0.26	0.26	1.47	1.47
138967	161.82	161.77	0.26	0.26	1.47	1.46
138968	156.83	140.55	0.26	0.28	1.47	1.49
138969	150.84	150.63	0.28	0.28	1.5	1.51
138970	149.88	146.26	0.27	0.28	1.49	1.51
138971	146.01	151.32	0.27	0.28	1.46	1.5
138972	161.11	141.73	0.25	0.28	1.46	1.51
139537	161.11	161.12	0.25	0.25	1.46	1.46
139538	161.24	161.28	0.25	0.25	1.46	1.46
139539	161.61	161.57	0.26	0.25	1.46	1.46
139540	161.69	162.43	0.26	0.27	1.47	1.49
139541	162.04	162.72	0.26	0.28	1.47	1.5
139542	161.88	161.6	0.26	0.25	1.47	1.46
139543	161.8	161.67	0.26	0.25	1.47	1.46
139544	156.17	141.01	0.26	0.28	1.47	1.5
139545	151.12	142.46	0.27	0.28	1.49	1.52
139546	150.14	140.46	0.27	0.28	1.49	1.51
139547	150.34	141.48	0.28	0.26	1.5	1.47
139548	150.51	151	0.27	0.27	1.48	1.48
139549	154.43	142.06	0.27	0.28	1.48	1.52
139550	158.84	146.23	0.26	0.28	1.47	1.52
140114	161.57	161.55	0.25	0.25	1.46	1.46
140115	161.87	161.84	0.25	0.25	1.46	1.46
140116	161.86	162.14	0.26	0.26	1.46	1.47
140117	161.87	158.43	0.26	0.26	1.47	1.47
140118	159.75	158.62	0.26	0.25	1.47	1.46
140119	147.06	152.7	0.26	0.25	1.47	1.46
140120	144.74	140.94	0.26	0.27	1.47	1.48
140121	155.85	148.79	0.26	0.28	1.48	1.51
140122	151.79	141.92	0.27	0.28	1.48	1.52
140123	150.52	151.16	0.27	0.28	1.49	1.51
140124	150.17	150.9	0.27	0.28	1.48	1.5
140125	144.66	155.89	0.28	0.26	1.49	1.46
140126	152.29	158.33	0.27	0.27	1.48	1.48

Table I-2 Predicted distresses on Flexible pavement using MERRA and PMED VWS on SITE 47-3075 Continues . . .

Location ID	Thermal Cracking VWS	Thermal Cracking EXT	Top-Down Cracking VWS	Top-Down Cracking EXT	AC Only Permanent Deformation VWS	AC Only Permanent Deformation EXT
138386	3197.38	3197.38	4.69	4.69	0.01	0.02
138387	3197.38	3197.38	4.69	4.69	0.02	0.03
138388	3197.38	3197.38	4.69	4.69	0.02	0.03
138389	3197.38	3197.38	4.69	4.69	0.02	0.01
138390	3197.38	3197.38	4.69	4.69	0.02	0.02
138391	3197.38	3197.38	4.69	4.69	0.02	0.02
138392	3197.38	1719.2	4.69	4.69	0.02	0.03
138393	1749.53	3197.38	4.69	4.69	0.03	0.03
138394	799.93	440.57	4.69	4.69	0.03	0.03
138961	3197.38	3197.38	4.69	4.69	0.01	0.01
138962	3197.38	3197.38	4.69	4.69	0.01	0.01
138963	3197.38	3197.38	4.69	4.69	0.02	0.01
138964	3197.38	3197.38	4.69	4.69	0.02	0.03
138965	3197.38	3197.38	4.69	4.69	0.02	0.03
138966	3197.38	3197.38	4.69	4.69	0.02	0.01
138967	3197.38	3197.38	4.69	4.69	0.02	0.01
138968	2371.49	447.8	4.69	4.69	0.02	0.02
138969	1796.41	1677.83	4.69	4.69	0.03	0.03
138970	1699.88	1218.65	4.69	4.69	0.02	0.03
138971	962.01	1536.51	4.69	4.69	0.02	0.03
138972	3197.38	273.47	4.69	4.69	0.01	0.03
139537	3197.38	3197.38	4.69	4.69	0.01	0.01
139538	3197.38	3197.38	4.69	4.69	0.01	0.01
139539	3197.38	3197.38	4.69	4.69	0.01	0.01
139540	3197.38	3197.38	4.69	4.69	0.02	0.02
139541	3197.38	3197.38	4.69	4.69	0.02	0.03
139542	3197.38	3197.38	4.69	4.69	0.01	0.01
139543	3197.38	3197.38	4.69	4.69	0.01	0.01
139544	2480.35	483.56	4.69	4.69	0.02	0.03
139545	1575.58	356.68	4.69	4.69	0.02	0.03
139546	1709.55	446.53	4.69	4.69	0.02	0.03
139547	1756.42	755.34	4.69	4.69	0.03	0.02
139548	1846.05	1676.88	4.69	4.69	0.02	0.02
139549	1850.53	281.28	4.69	4.69	0.02	0.03
139550	2501.73	810.07	4.69	4.69	0.01	0.03
140114	3197.38	3197.38	4.69	4.69	0.01	0.01
140115	3197.38	3197.38	4.69	4.69	0.01	0.01
140116	3197.38	3197.38	4.69	4.69	0.01	0.02
140117	3197.38	2728.55	4.69	4.69	0.01	0.02
140118	2921.6	2783.71	4.69	4.69	0.01	0.01
140119	1352.4	2039.1	4.69	4.69	0.01	0.01
140120	1060.08	549.34	4.69	4.69	0.01	0.02
140121	2212.31	1242.75	4.69	4.69	0.02	0.03
140122	1634.92	306.18	4.69	4.69	0.02	0.03
140123	1553.88	1548.09	4.69	4.69	0.02	0.03
140124	1545.19	1540.86	4.69	4.69	0.02	0.03
140125	1029.74	2357.02	4.69	4.69	0.02	0.01
140126	1636.36	2385.96	4.69	4.69	0.02	0.02

Table I-3 Predicted distresses on Flexible pavement using MERRA and PMED VWS on SITE 47-3104

Location ID	Terminal IRI - VWS	Terminal IRI - EXT	Total Pavement Permanent Deformation VWS	Total Pavement Permanent Deformation EXT	Bottom-Up Cracking VWS	Bottom-Up Cracking EXT
138385	161.54	161.55	0.25	0.25	1.45	1.45
138387	161.9	162.09	0.26	0.26	1.45	1.45
138388	162.26	162.08	0.26	0.26	1.45	1.45
138389	162.19	162.24	0.26	0.26	1.45	1.45
138390	161.98	162.34	0.26	0.26	1.45	1.45
138391	162.19	162.56	0.26	0.26	1.45	1.45
138392	161.63	157.38	0.26	0.27	1.45	1.45
138393	159.06	161.43	0.26	0.26	1.45	1.45
138394	153.85	140.46	0.27	0.26	1.45	1.45
138961	161.7	161.79	0.25	0.25	1.45	1.45
138962	161.92	162.03	0.25	0.25	1.45	1.45
138963	162.21	162.45	0.26	0.26	1.45	1.45
138964	162.36	162.29	0.26	0.26	1.45	1.45
138965	162.6	162.91	0.26	0.26	1.45	1.45
138966	162.51	162.72	0.26	0.26	1.45	1.45
138967	162.82	162.93	0.26	0.26	1.45	1.45
138968	161.83	141.07	0.27	0.27	1.45	1.45
138969	158.88	157.05	0.26	0.27	1.45	1.45
138970	156.66	158.21	0.26	0.26	1.45	1.45
138971	156.51	158.38	0.27	0.27	1.45	1.45
138972	162	144.11	0.25	0.27	1.45	1.45
139537	162	162.04	0.25	0.25	1.45	1.45
139538	162.18	162.26	0.25	0.25	1.45	1.45
139539	162.56	162.64	0.26	0.26	1.45	1.45
139540	162.5	162.7	0.26	0.26	1.45	1.45
139541	162.95	162.72	0.26	0.26	1.45	1.45
139542	162.93	162.64	0.26	0.26	1.45	1.45
139543	162.81	162.78	0.26	0.26	1.45	1.45
139544	161.28	141.32	0.26	0.27	1.45	1.45
139545	156.33	146.47	0.27	0.27	1.45	1.45
139546	156.68	140.6	0.26	0.27	1.45	1.45
139547	157.96	141.88	0.26	0.26	1.45	1.45
139548	158.82	155.5	0.26	0.26	1.45	1.45
139549	160.57	146.55	0.27	0.27	1.45	1.45
139550	161.68	152.89	0.27	0.27	1.45	1.45
140114	162.57	162.52	0.26	0.25	1.45	1.45
140115	162.9	162.94	0.26	0.26	1.45	1.45
140116	162.79	162.93	0.26	0.26	1.45	1.45
140117	162.76	163.13	0.26	0.26	1.45	1.45
140118	161.02	160.86	0.26	0.26	1.45	1.45
140119	145.92	152.68	0.26	0.26	1.45	1.45
140120	142.49	141.31	0.26	0.26	1.45	1.45
140121	159.25	158.47	0.27	0.27	1.45	1.45
140122	158.32	143.99	0.27	0.27	1.45	1.45
140123	154.44	155.51	0.27	0.27	1.45	1.45
140124	155.07	154.33	0.27	0.27	1.45	1.45
140125	154.15	158.44	0.26	0.26	1.45	1.45
140126	158.52	163.4	0.27	0.27	1.45	1.45

Table I-3 Predicted distresses on Flexible pavement using MERRA and PMED VWS on SITE 47-3104 Continues . . .

Location ID	Thermal Cracking VWS	Thermal Cracking EXT	Top-Down Cracking VWS	Top-Down Cracking EXT	AC Only Permanent Deformation VWS	AC Only Permanent Deformation EXT
138386	3197.38	3197.38	4.69	4.69	0	0
138387	3197.38	3197.38	4.69	4.69	0	0
138388	3197.38	3197.38	4.69	4.69	0	0
138389	3197.38	3197.38	4.69	4.69	0	0
138390	3197.38	3197.38	4.69	4.69	0	0
138391	3197.38	3197.38	4.69	4.69	0	0
138392	3197.38	2521.71	4.69	4.69	0	0
138393	2852.65	3197.38	4.69	4.69	0	0
138394	1980.77	440.57	4.69	4.69	0	0
138961	3197.38	3197.38	4.69	4.69	0	0
138962	3197.38	3197.38	4.69	4.69	0	0
138963	3197.38	3197.38	4.69	4.69	0	0
138964	3197.38	3197.38	4.69	4.69	0	0
138965	3197.38	3197.38	4.69	4.69	0	0
138966	3197.38	3197.38	4.69	4.69	0	0
138967	3197.38	3197.38	4.69	4.69	0	0
138968	2877.98	457.23	4.69	4.69	0	0
138969	2783.71	2466.56	4.69	4.69	0	0
138970	2494.14	2742.34	4.69	4.69	0	0
138971	2212.31	2371.49	4.69	4.69	0	0
138972	3197.38	524.98	4.69	4.69	0	0
139537	3197.38	3197.38	4.69	4.69	0	0
139538	3197.38	3197.38	4.69	4.69	0	0
139539	3197.38	3197.38	4.69	4.69	0	0
139540	3197.38	3197.38	4.69	4.69	0	0
139541	3197.38	3197.38	4.69	4.69	0	0
139542	3197.38	3197.38	4.69	4.69	0	0
139543	3197.38	3197.38	4.69	4.69	0	0
139544	3004.33	498.59	4.69	4.69	0	0
139545	2168.9	873.74	4.69	4.69	0	0
139546	2480.35	462.74	4.69	4.69	0	0
139547	2687.18	698.81	4.69	4.69	0	0
139548	2825.07	2154.43	4.69	4.69	0	0
139549	2487.26	821.63	4.69	4.69	0	0
139550	2689.86	1623.34	4.69	4.69	0	0
140114	3197.38	3197.38	4.69	4.69	0	0
140115	3197.38	3197.38	4.69	4.69	0	0
140116	3197.38	3197.38	4.69	4.69	0	0
140117	3197.38	3197.38	4.69	4.69	0	0
140118	2949.17	2921.6	4.69	4.69	0	0
140119	1078.01	1887.42	4.69	4.69	0	0
140120	653.3	496.94	4.69	4.69	0	0
140121	2516.2	2487.26	4.69	4.69	0	0
140122	2342.55	566.95	4.69	4.69	0	0
140123	1966.3	2096.54	4.69	4.69	0	0
140124	2067.6	1937.36	4.69	4.69	0	0
140125	2176.99	2545.15	4.69	4.69	0	0
140126	2299.14	2906.92	4.69	4.69	0	0

Table I-4 Predicted distresses on Flexible pavement using MERRA and PMED VWS on SITE 47-B330

Location ID	Terminal IRI - VWS	Terminal IRI - EXT	Total Pavement Permanent Deformation VWS	Total Pavement Permanent Deformation EXT	Bottom-Up Cracking VWS	Bottom-Up Cracking EXT
138387	158.73	160.04	0.21	0.24	1.45	1.45
138388	159.07	159.77	0.21	0.23	1.45	1.45
138389	159.08	158.78	0.21	0.2	1.45	1.45
138390	158.74	158.95	0.21	0.2	1.45	1.45
138391	159.02	159.2	0.21	0.21	1.45	1.45
138392	158.78	148.9	0.21	0.23	1.45	1.45
138393	154.16	159.17	0.23	0.23	1.45	1.45
138394	137.68	138.19	0.23	0.23	1.45	1.46
138961	158.37	158.45	0.2	0.2	1.45	1.45
138962	158.59	158.62	0.2	0.2	1.45	1.45
138963	158.95	159.03	0.21	0.2	1.45	1.45
138964	159.2	160.47	0.21	0.24	1.45	1.46
138965	159.35	160.61	0.21	0.23	1.45	1.45
138966	159.12	159.19	0.21	0.2	1.45	1.45
138967	159.38	159.33	0.21	0.2	1.45	1.45
138968	148.27	138.03	0.21	0.22	1.45	1.45
138969	149.05	148.51	0.23	0.24	1.45	1.46
138970	147.77	150.12	0.22	0.23	1.45	1.45
138971	143.15	149.27	0.22	0.23	1.45	1.45
138972	158.65	140.03	0.2	0.23	1.45	1.46
139537	158.65	158.67	0.2	0.2	1.45	1.45
139538	158.79	158.84	0.2	0.2	1.45	1.45
139539	159.17	159.11	0.2	0.2	1.45	1.45
139540	159.26	160.03	0.21	0.22	1.45	1.45
139541	159.61	160.38	0.21	0.23	1.45	1.45
139542	159.45	159.17	0.2	0.2	1.45	1.45
139543	159.36	159.23	0.2	0.2	1.45	1.45
139544	153.82	138.35	0.21	0.23	1.45	1.45
139545	148.76	140.93	0.22	0.23	1.45	1.46
139546	147.91	138.05	0.22	0.23	1.45	1.45
139547	148.63	137.25	0.23	0.21	1.45	1.45
139548	148.84	142.79	0.22	0.21	1.45	1.45
139549	151.16	141.41	0.21	0.23	1.45	1.46
139550	150.19	144.67	0.21	0.23	1.45	1.46
140114	159.11	159.08	0.2	0.2	1.45	1.45
140115	159.41	159.37	0.2	0.2	1.45	1.45
140116	159.4	159.72	0.2	0.21	1.45	1.45
140117	159.43	155.65	0.2	0.21	1.45	1.45
140118	153.37	155.5	0.2	0.2	1.45	1.45
140119	139.97	143.05	0.2	0.2	1.45	1.45
140120	138.07	137.77	0.21	0.21	1.45	1.45
140121	146.91	145.62	0.21	0.23	1.45	1.46
140122	148.51	140.04	0.21	0.23	1.45	1.46
140123	143.16	148.27	0.22	0.24	1.45	1.46
140124	142.74	143.59	0.21	0.23	1.45	1.45
140125	142.41	148.24	0.22	0.2	1.45	1.45
140126	144.7	151.19	0.21	0.22	1.45	1.45

Table I-4 Predicted distresses on Flexible pavement using MERRA and PMED VWS on SITE 47-B330 Continues . . .

Location ID	Thermal Cracking VWS	Thermal Cracking EXT	Top-Down Cracking VWS	Top-Down Cracking EXT	AC Only Permanent Deformation VWS	AC Only Permanent Deformation EXT
138386	3197.38	3197.38	4.69	4.69	0.02	0.02
138387	3197.38	3197.38	4.69	4.69	0.02	0.05
138388	3197.38	3197.38	4.69	4.69	0.03	0.04
138389	3197.38	3197.38	4.69	4.69	0.03	0.02
138390	3197.38	3197.38	4.69	4.69	0.02	0.02
138391	3197.38	3197.38	4.69	4.69	0.03	0.02
138392	3197.38	1761.93	4.69	4.69	0.03	0.05
138393	2521.71	3197.38	4.69	4.69	0.04	0.04
138394	440.57	440.57	4.69	4.69	0.04	0.05
138961	3197.38	3197.38	4.69	4.69	0.02	0.02
138962	3197.38	3197.38	4.69	4.69	0.02	0.02
138963	3197.38	3197.38	4.69	4.69	0.02	0.02
138964	3197.38	3197.38	4.69	4.69	0.03	0.05
138965	3197.38	3197.38	4.69	4.69	0.03	0.05
138966	3197.38	3197.38	4.69	4.69	0.02	0.02
138967	3197.38	3197.38	4.69	4.69	0.02	0.02
138968	1588.6	443.15	4.69	4.69	0.02	0.04
138969	1873.63	1709.55	4.69	4.69	0.04	0.05
138970	1742.63	1983.94	4.69	4.69	0.04	0.05
138971	911.37	1579.93	4.69	4.69	0.03	0.04
138972	3197.38	368.7	4.69	4.69	0.02	0.04
139537	3197.38	3197.38	4.69	4.69	0.02	0.02
139538	3197.38	3197.38	4.69	4.69	0.02	0.02
139539	3197.38	3197.38	4.69	4.69	0.02	0.02
139540	3197.38	3197.38	4.69	4.69	0.02	0.04
139541	3197.38	3197.38	4.69	4.69	0.02	0.04
139542	3197.38	3197.38	4.69	4.69	0.02	0.02
139543	3197.38	3197.38	4.69	4.69	0.02	0.02
139544	2494.14	454.6	4.69	4.69	0.03	0.04
139545	1585.71	475.78	4.69	4.69	0.04	0.05
139546	1735.74	446.01	4.69	4.69	0.04	0.05
139547	1846.05	543.96	4.69	4.69	0.04	0.02
139548	1942.58	934.51	4.69	4.69	0.03	0.03
139549	1749.24	514.85	4.69	4.69	0.02	0.04
139550	1705.82	922.93	4.69	4.69	0.02	0.04
140114	3197.38	3197.38	4.69	4.69	0.02	0.02
140115	3197.38	3197.38	4.69	4.69	0.02	0.02
140116	3197.38	3197.38	4.69	4.69	0.02	0.02
140117	3197.38	2687.18	4.69	4.69	0.02	0.02
140118	2438.98	2700.97	4.69	4.69	0.02	0.02
140119	792.58	1162.11	4.69	4.69	0.02	0.02
140120	554.57	466.18	4.69	4.69	0.02	0.03
140121	1377.33	1144.34	4.69	4.69	0.03	0.05
140122	1530.72	377.37	4.69	4.69	0.03	0.05
140123	922.93	1484.41	4.69	4.69	0.03	0.05
140124	908.46	908.46	4.69	4.69	0.03	0.04
140125	1057.32	1691.35	4.69	4.69	0.04	0.02
140126	979.38	1778.18	4.69	4.69	0.03	0.03

Table I-5 Predicted distresses on Flexible pavement using MERRA and PMED VWS on SITE 47-C330

Location ID	Terminal IRI - VWS	Terminal IRI - EXT	Total Pavement Permanent Deformation VWS	Total Pavement Permanent Deformation EXT	Bottom-Up Cracking VWS	Bottom-Up Cracking EXT
138387	168.33	169.65	0.23	0.28	4.97	13.12
138388	170.25	169.00	0.23	0.27	5.36	10.57
138389	170.29	170.29	0.23	0.22	5.7	4.08
138390	170.42	171.66	0.22	0.22	4.61	4.28
138391	170.04	170.16	0.23	0.22	5.04	4.54
138392	162	158.08	0.24	0.27	6.47	13.08
138393	157.93	162.93	0.27	0.26	12.4	9.65
138394	155.54	157.92	0.26	0.27	11.1	14.47
138961	170.82	171.01	0.22	0.22	3.7	3.62
138962	170.69	171.77	0.22	0.22	3.87	3.61
138963	170.92	171.26	0.22	0.22	4.59	3.98
138964	170.4	166.98	0.23	0.28	5.27	16.62
138965	170.39	166.1	0.23	0.27	5	12.28
138966	170.19	170.2	0.22	0.22	4.4	3.95
138967	162.13	170.18	0.22	0.22	4.51	3.82
138968	155.97	154.87	0.23	0.25	4.85	8.55
138969	157.34	157.73	0.26	0.27	10.86	13.6
138970	154.23	157.77	0.25	0.27	8.78	14.96
138971	154.36	156.42	0.24	0.26	7.21	10.06
138972	172.01	157.47	0.21	0.26	3.58	12.51
139537	172.01	172.85	0.21	0.21	3.58	3.51
139538	173.31	174.91	0.21	0.21	3.52	3.46
139539	170.18	175.05	0.22	0.21	3.87	3.45
139540	170.37	171.56	0.22	0.25	4.56	8.03
139541	162.99	164.76	0.23	0.26	4.65	10.15
139542	163.19	170.06	0.22	0.22	4.22	3.79
139543	160.26	166.14	0.22	0.22	4.25	3.73
139544	157.21	156.16	0.23	0.26	5.04	10.78
139545	155.04	158.46	0.25	0.27	8.49	14.08
139546	154.77	156.95	0.25	0.27	9.33	12.74
139547	155.77	152.81	0.26	0.23	10.49	4.65
139548	155.32	153.92	0.24	0.23	7.42	5.89
139549	155.87	157.97	0.23	0.26	4.76	12.94
139550	155.77	158	0.22	0.27	3.7	12.79
140114	170.16	176.67	0.21	0.21	3.48	3.36
140115	164.51	170.4	0.21	0.21	3.56	3.34
140116	170.43	170.84	0.22	0.23	3.96	4.59
140117	170.38	156.74	0.22	0.23	4.23	4.61
140118	156.57	156.12	0.22	0.22	3.93	3.69
140119	153.42	153.58	0.22	0.22	3.89	3.55
140120	153.49	154.16	0.22	0.24	4.21	5.84
140121	154.77	157.58	0.23	0.27	5.16	13.02
140122	154.97	158.25	0.23	0.27	5.47	13.98
140123	154.36	157.76	0.24	0.27	7.24	13.6
140124	153.93	155.75	0.23	0.26	6.13	10.09
140125	154.71	153.42	0.25	0.22	9.77	3.66
140126	155.16	156.23	0.23	0.24	5.26	5.93

Table I-5 Predicted distresses on Flexible pavement using MERRA and PMED VWS on SITE 47-C330 Continues . . .

Location ID	Thermal Cracking VWS	Thermal Cracking EXT	Top-Down Cracking VWS	Top-Down Cracking EXT	AC Only Permanent Deformation VWS	AC Only Permanent Deformation EXT
138386	2755.14	2740.44	14.23	14.23	0.04	0.04
138387	2490.46	2152.26	14.23	14.23	0.05	0.09
138388	2681.62	2269.90	14.23	14.23	0.05	0.08
138389	2681.62	2740.44	14.22	14.22	0.05	0.04
138390	2755.14	2887.48	14.22	14.22	0.04	0.04
138391	2666.91	2666.91	14.22	14.22	0.05	0.04
138392	1687.6	673.3	14.22	14.22	0.06	0.09
138393	818.57	1665.54	14.22	14.23	0.08	0.08
138394	277.54	565.18	14.22	14.22	0.08	0.09
138961	2858.07	2872.78	14.23	14.23	0.04	0.04
138962	2813.96	2946.3	14.23	14.23	0.04	0.04
138963	2784.55	2828.66	14.23	14.23	0.04	0.04
138964	2681.62	1567.02	14.23	14.23	0.05	0.1
138965	2666.91	1702.3	14.23	14.23	0.05	0.09
138966	2681.62	2681.62	14.22	14.22	0.04	0.04
138967	1656.72	2666.91	14.22	14.22	0.04	0.04
138968	538.08	565.18	14.22	14.22	0.05	0.07
138969	820.04	598.3	14.22	14.22	0.08	0.09
138970	604.62	596.39	14.22	14.23	0.07	0.09
138971	280.41	320.74	14.22	14.22	0.06	0.07
138972	2975.71	277.34	14.23	14.22	0.04	0.08
139537	2975.71	3078.64	14.23	14.23	0.04	0.04
139538	3122.75	3313.91	14.23	14.22	0.03	0.03
139539	2681.62	3299.2	14.23	14.23	0.04	0.03
139540	2681.62	2681.62	14.23	14.23	0.04	0.07
139541	1728.77	1699.36	14.23	14.23	0.05	0.08
139542	1781.71	2666.91	14.23	14.23	0.04	0.04
139543	1433.22	2181.67	14.22	14.22	0.04	0.04
139544	1024.44	565.2	14.22	14.22	0.05	0.08
139545	296.28	277.39	14.22	14.23	0.07	0.09
139546	615.94	565.18	14.22	14.23	0.07	0.09
139547	682.4	565.24	14.22	14.22	0.07	0.04
139548	824.45	306.4	14.22	14.22	0.06	0.05
139549	316.07	277.35	14.25	14.22	0.05	0.08
139550	404.4	277.39	14.23	14.23	0.04	0.08
140114	2696.32	3505.06	14.23	14.22	0.03	0.03
140115	1961.1	2696.32	14.23	14.23	0.04	0.03
140116	2681.62	2681.62	14.23	14.23	0.04	0.05
140117	2666.91	936.21	14.23	14.23	0.04	0.05
140118	959.73	909.74	14.23	14.23	0.04	0.04
140119	569.96	589.47	14.23	14.23	0.04	0.04
140120	565.47	565.21	14.22	14.23	0.04	0.06
140121	341.46	297.52	14.23	14.23	0.05	0.09
140122	313.26	277.38	14.23	14.23	0.05	0.09
140123	281.84	282.44	14.22	14.23	0.06	0.09
140124	282.25	281.85	14.22	14.23	0.05	0.08
140125	571.23	335.69	14.22	14.23	0.07	0.04
140126	281.37	366.23	14.23	14.23	0.05	0.05

Appendix J: Q-Q Plots for Climatic Summary Data

Appendix J shows the Q-Q plots in Figure J-1 for climatic summary data used for the normality check. Correlating information is given in section 4.2. On these plots PMED = PMED VWSs and ACTUAL = MERRA stations.

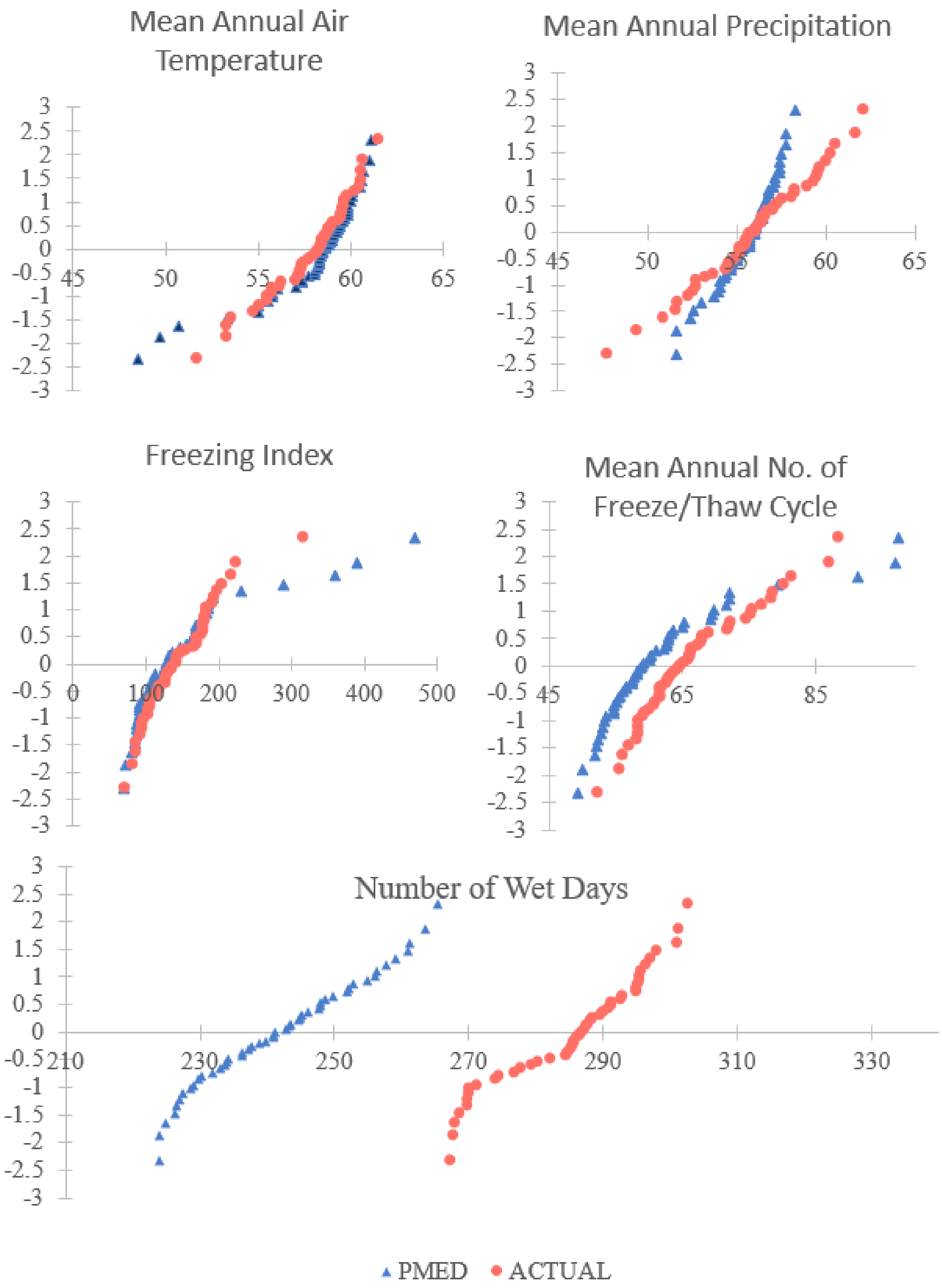

Figure J-1 Q-Q Plots for Climatic Summary Data

Appendix K: Q-Q Plots for Pavement Distresses

Appendix K shows the Q-Q plots in Figures K-1 – K-5 for pavement predicted distresses used for the normality check. Correlating information is given in section 4.2. On these plots PMED = PMED VWSs and ACTUAL = MERRA stations.

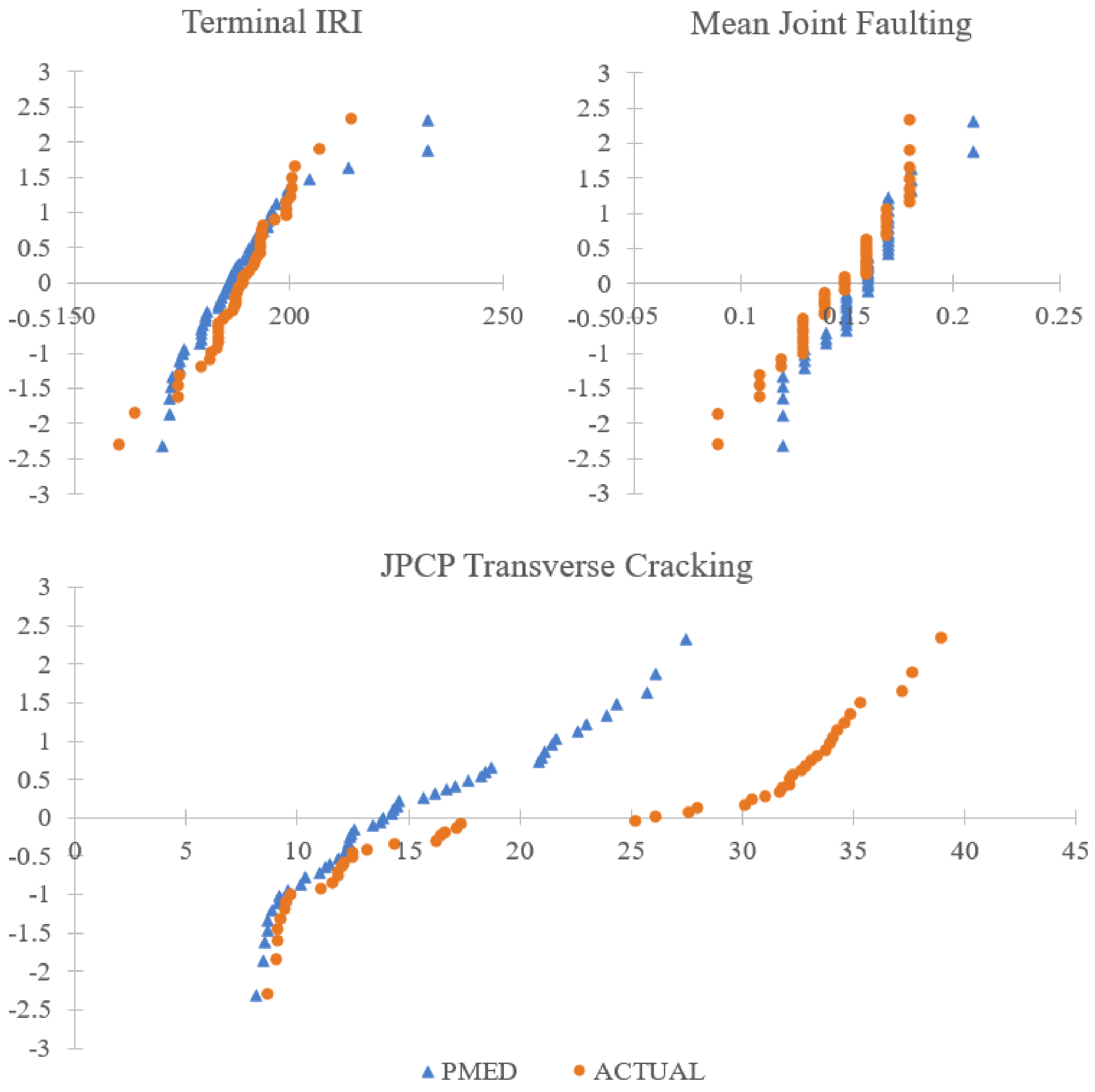

Figure K-1 Q-Q Plots for Distresses on LTPP Site 47-0602

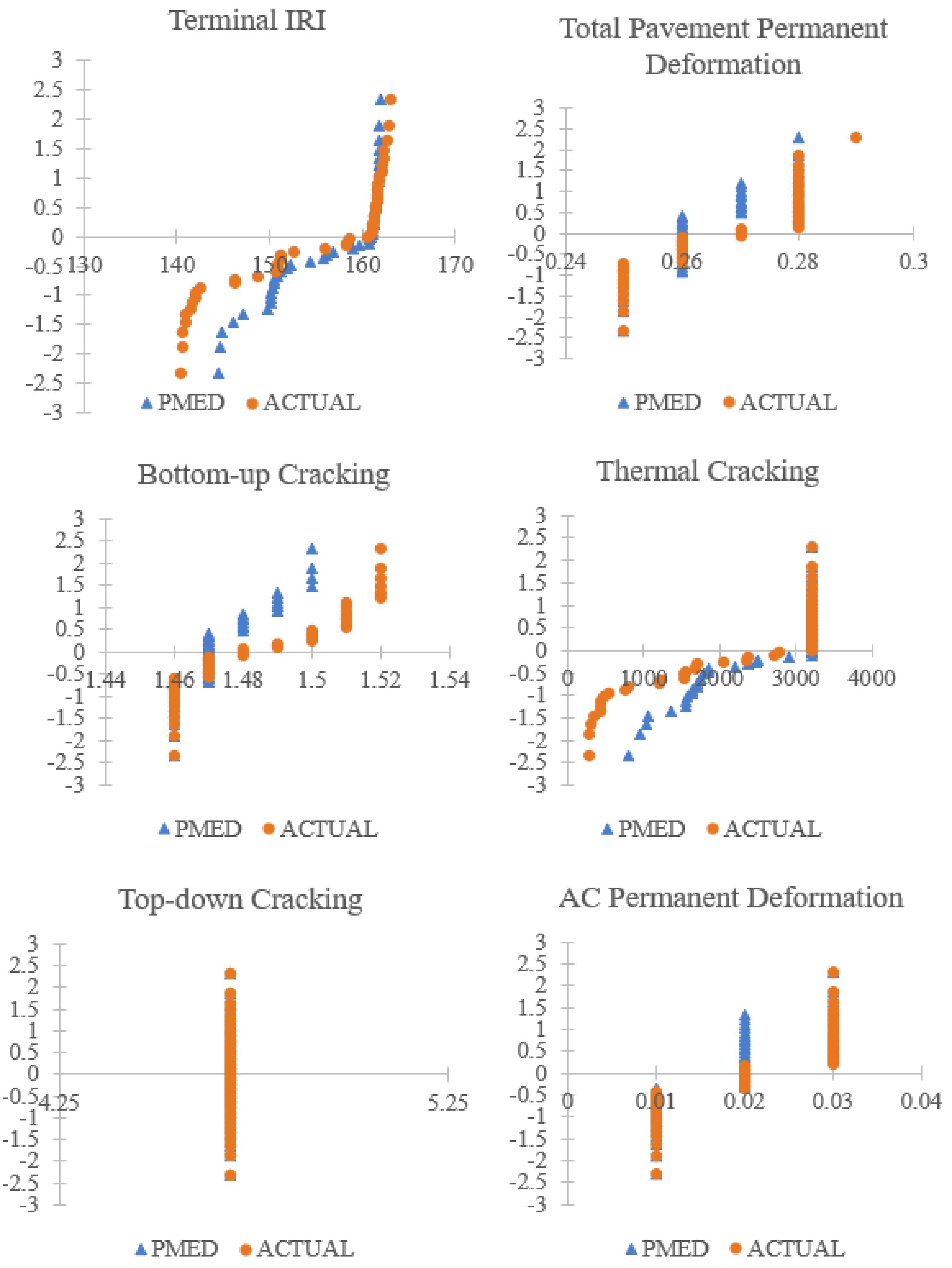

Figure K-2 Q-Q Plots for Distresses on LTPP Site 47-3075

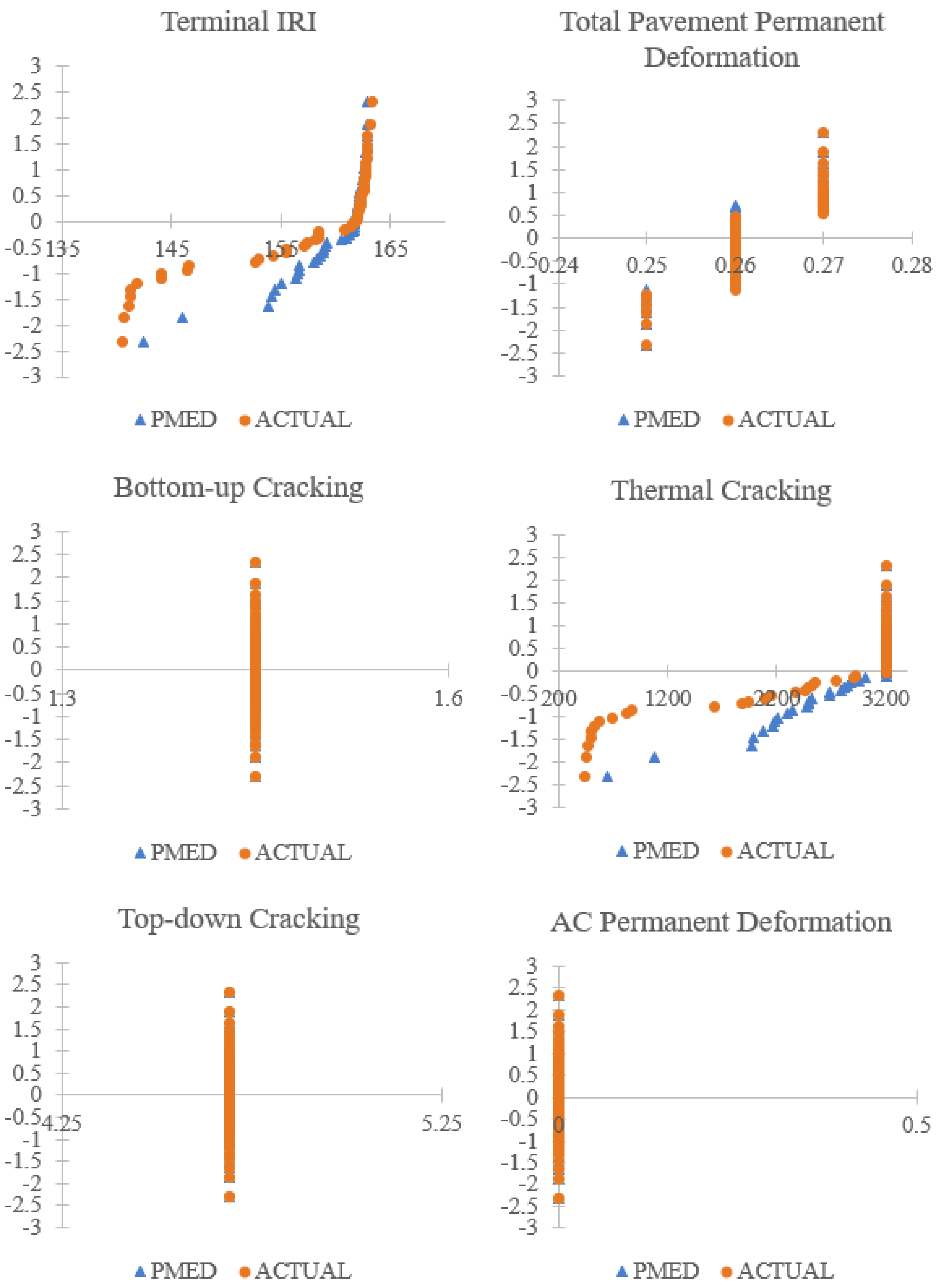

Figure K-3 Q-Q Plots for Distresses on LTPP Site 47-3104

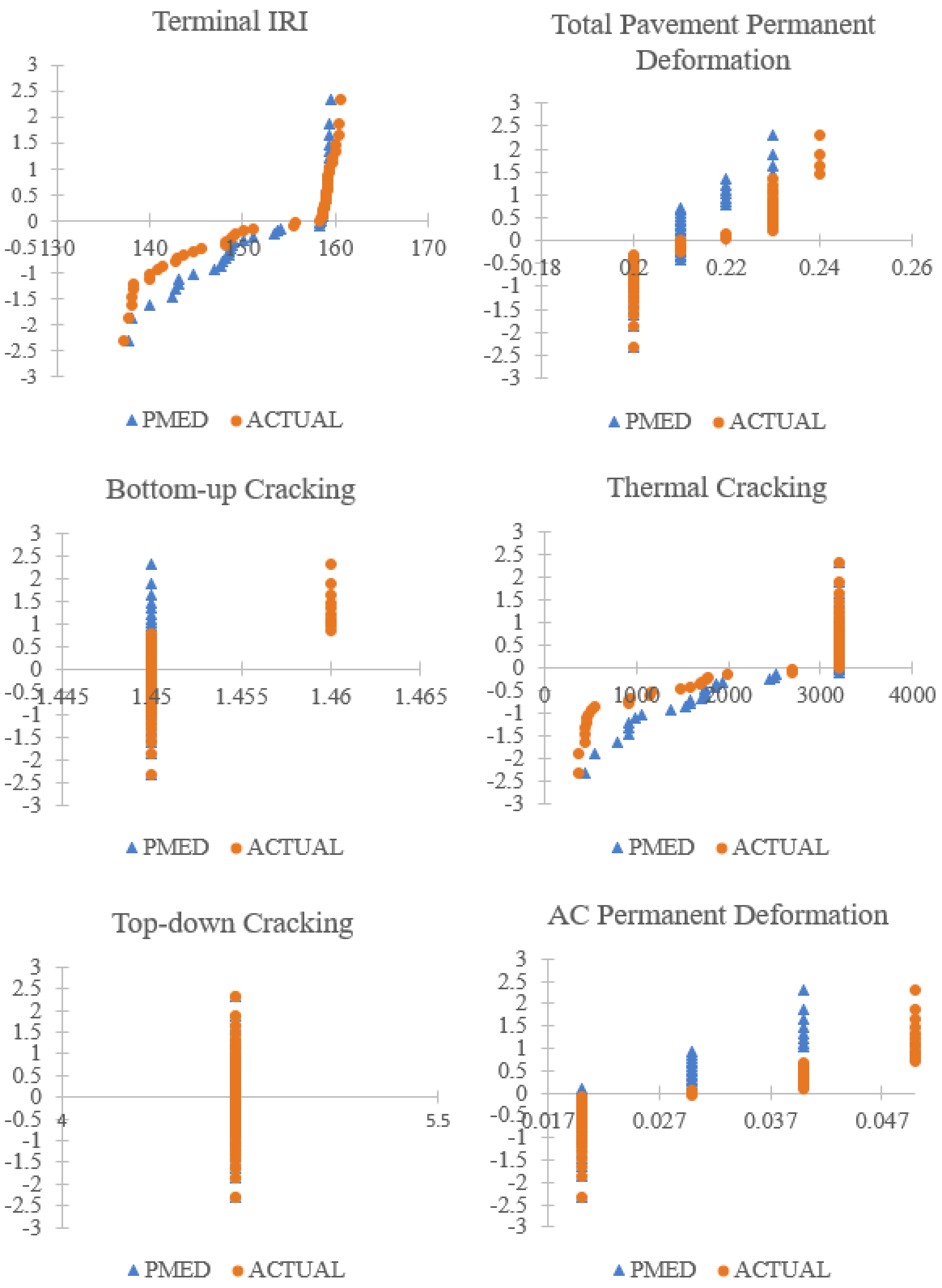

Figure K-4 Q-Q Plots for Distresses on LTPP Site 47-B330

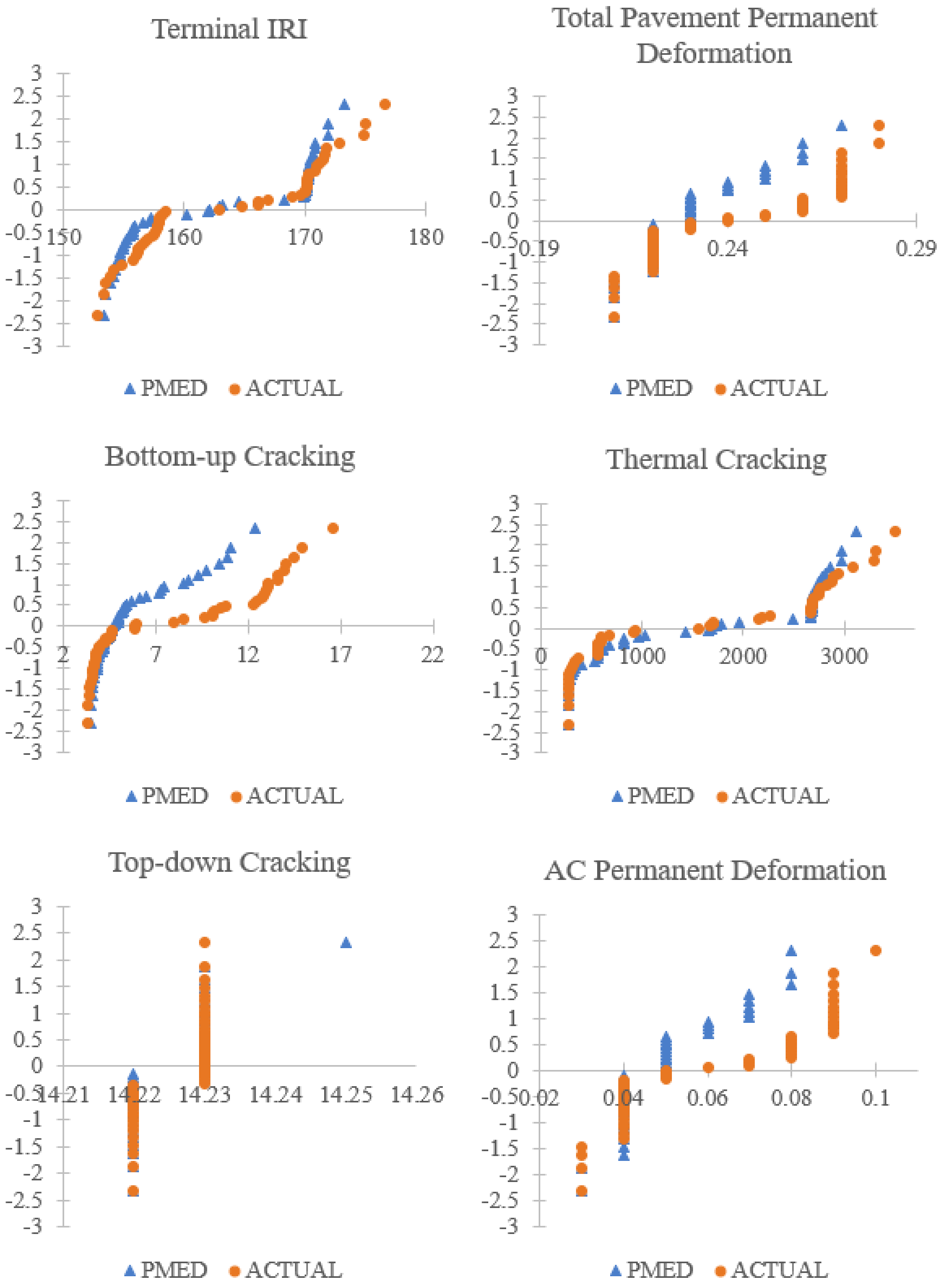

Figure K-5 Q-Q Plots for Distresses on LTPP Site 47-C330