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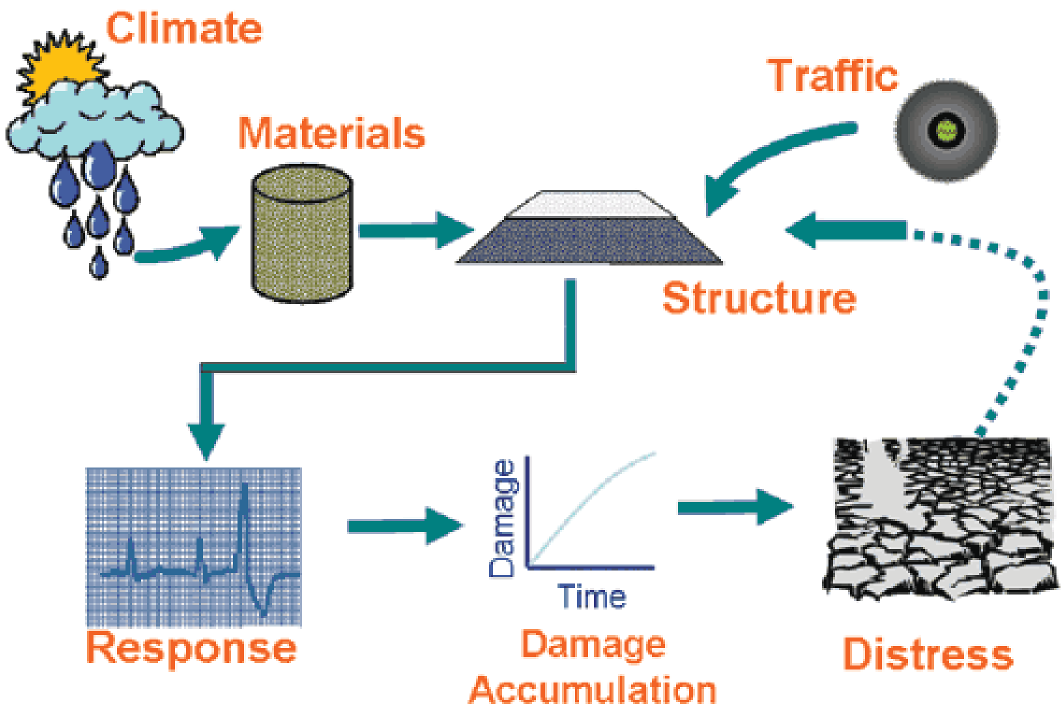

Climate and Groundwater Data to Support Mechanistic-Empirical Design in South Dakota

Study SD2013-05

Final Report

Prepared by:
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DISCLAIMER

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16. Abstract
The analysis methodology in the AASHTO mechanistic pavement design guide (MEPDG) places a strong emphasis on the influence of climate conditions and groundwater on the prediction of pavement performance. The accuracy and reliability of these data are crucial for accurate and reliable pavement structure design. This report summarizes the quality of climate and groundwater data collected from different sources that are available in South Dakota, and compares pavement performance predictions for asphalt concrete and jointed plain concrete pavements calculated using three different climate data sources. These sources include weather stations embedded in the AASHTOWare® Pavement ME Design™ software, ground-based weather stations (GBWS) and NASA`s Modern-Era Retrospective Research Analysis (MERRA). The results of this study indicate that MEPDG predictions calculated with MERRA, GBWS and MEPDG weather station data were similar. Results also indicate that use of MERRA data has many advantages over GBWS and MEPDG weather data, such as (1) greater and more uniform spatial coverage area; (2) longer periods of continuous climate data; and (3) higher quality data.

The results of this study show that the groundwater table depth does not have a significant impact on pavement performance predictions inb the current version of the AASHTOWare® Pavement ME Design™ software. However, determination of the stiffness and strength of highway base/subgrade layers materials under different moisture content conditions is recommended.

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Climate data, Modern-Era Retrospective Research Analysis, pavement design, pavement distress

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Acronym	Definition
AADTT	Annual Average Daily Truck Traffic
AASHTO	American Association of State Highway and Transportation Officials
AC	Asphalt Concrete
EICM	Enhanced Integrated Climate Model
ESS	Environmental Sensor Station
FHWA	Federal Highway Administration
GBWS	Ground Based Weather Station
GEOS-5	Nasa Goddard Earth Observing System Model Version 5
GIS	Geographic Information System
GSI	Grid-Point Statistical Interpolation
IAU	Incremental Analysis Update
IRI	International Roughness Index
JPCP	Jointed Plain Concrete Pavement
LTPP	Long Term Pavement Performance
ME (M-E)	Mechanistic-Empirical
MEPDG	Mechanistic-Empirical Pavement Design Guide
MERRA	Modern-Era Retrospective Analysis for Research and Applications
NASA	National Aeronautics and Space Administration
NSI	Normalized Sensitivity Index
OAT	One at a time
QCLCD	Quality Controlled Local Climatological Data
SDDENR	South Dakota Department of Environment and Natural Resources
SDDOT	South Dakota Department of Transportation
SDSM&T	South Dakota School of Mines and Technology
ULCD	Unedited Local Climatological Data
USGS	United States Geological Survey
w/c	Water/Cement (Ratio)

1 EXECUTIVE SUMMARY

1.1 INTRODUCTION

The Mechanistic-Empirical Pavement Design Guide (MEPDG) represents a major improvement over its predecessors, particularly in its comprehensive coverage of environmental impacts such as climate and groundwater on pavement performance. However, accurate and reliable data first must be collected to take advantage of such improvements in the pavement design. Hourly climate data are the principal environmental inputs to the MEPDG (Li et al. 2013). The MEPDG software itself contains hourly time series for only 12 ground-based weather station locations in South Dakota. There are some other sources of ground-based weather station data available for South Dakota, but as will be described later most are deficient in important ways. Instead, the project team used a new source for high quality weather data, the Modern-Era Retrospective Analysis for Research and Applications (MERRA) product from the National Aeronautics and Space Administration (NASA). MERRA provides continuous hourly weather observations from 1979 onward at a uniform 0.5 degrees (latitude) by 0.67 degrees (longitude) horizontal resolution (approximately 50 by 66 kilometers at mid-latitudes), which corresponds to nearly 70 locations across South Dakota. MERRA data is also subjected to rigorous and sophisticated quality checks by NASA for its own internal purposes.

Groundwater level is another major environmental input to the MEPDG. However, the MEPDG software does not include detailed groundwater data for specific locations. This project developed a database of groundwater levels across South Dakota using groundwater monitoring well data from the United States Geological Survey (USGS) and the South Dakota Department of Environment and Natural Resources (SDDENR).

An extensive comparison of MEPDG predictions using climatic information provided by ground-based weather stations (GBWS), GBWS embedded in MEPDG, and MERRA was conducted. These comparison analyses were conducted on 2 different pavement types: (1) asphalt concrete (AC) and jointed plain concrete pavement (JPCP). The results of this study show that overall the pavement performance predicted by conventional ground-based weather stations and the ones predicted via MERRA are very similar. This indicates that MERRA is an acceptable and advantageous source for climate data to be used in MEPDG pavement designs. In addition, MERRA has overall the best quality data and spatial continuity.

This study involved a sensitivity analyses to determine which environmental inputs have the most impact on pavement performance. It was observed that the groundwater level did not impact the pavement performance unless it is very near the ground surface. This suggests that the current version of MEPDG may not incorporate the effects of groundwater impact properly.

As a result of this study, the following recommendations were provided: (1) South Dakota Department of Transportation should adopt MERRA as a primary climate data source for pavement designs, (2) South Dakota Department of Transportation could use the groundwater data from the online sources provided in this report; however, South Dakota Department of Transportation should initiate a new project to determine the stiffness and the strength of pavement subgrade and base layers under different moisture content condition for use as input in the MEPDG software because the current version of the MEPDG software does not fully incorporate the impact of groundwater table level into pavement distress predictions.

1.2 OBJECTIVES

The objectives of this research were the following:

1) Assess the availability and quality of climate and groundwater data within the MEPDG software and from other existing sources.

   Climate data were collected from four different sources and the quality of the data collected from these sources were compared with each other. These sources are listed below:

   a. Weather stations embedded in the MEPDG software
   b. Ground-based weather stations (GBWS) throughout South Dakota
   c. Environmental sensing stations (ESS) throughout South Dakota
   d. NASA`s Modern-Era Retrospective Analysis for Research and Applications (MERRA)

   Groundwater data was collected from United States Geological Survey (USGS) and South Dakota Department of Environment and Natural Resources archives and online websites.

2) Develop procedures enabling the South Dakota Department of Transportation (SDDOT) to acquire, maintain, and use climate and water table data in MEPDG design.

   The ground-based weather stations (GBWS) were reformatted into hourly data in the input format required for the MEPDG weather data files. As for the MERRA data, a research-grade code was developed for extracting and downloading the data from the NASA servers. The extracted MERRA data were reformatted in the format required by the Pavement ME Design™ software. The extraction code was written in MATLAB®. The research team could provide this extraction code to the SDDOT. However, it requires the purchase of a MATLAB® license and trained personnel to run the programs. The Federal Highway Administration’s (FHWA) Long Term Pavement Performance (LTPP) program is working on the development of an online source for the extraction of MERRA data in a format required by the MEPDG software for the entire United States. It is expected to be available in beta test version sometime in the last half of 2015.

   Groundwater table data was collected from over 1000 groundwater wells throughout South Dakota. The summary of this data is provided in this report and all data are provided in Excel format.

3) Identify enhancements needed to supply and maintain climate and water table data adequate for M-E design.

   This objective was accomplished by comparing results of the M-E pavement performance predictions using MERRA weather data, ground-based weather station data, and weather data embedded in the MEPDG software. These results do not include the data collected from environmental sensing stations (ESS) since ESS data do not possess percent sunshine information, which is one of the climate data inputs required by the MEPDG software for pavement performance predictions.

1.3 RESEARCH APPROACH

This research was conducted in two phases. Phase 1 consisted of a detailed literature review related to the evaluation of the effect of climate and the groundwater depth in mechanistic-empirical pavement design guide (MEPDG) predictions and performing sensitivity analyses and assessment of the adequacy of climate and groundwater data embedded in the (MEPDG) software. The research team also identified the gaps present in the weather data included with the MEPDG software and identified alternative climate and groundwater table data sources and assessed their availability and quality for use in M-E pavement design in South Dakota.

Phase 2 focused on developing software (1) to extract MERRA data and (2) interpolate ground-based weather station (GBWS) data in order to provide weather data for a specific location. In the technical memorandum meeting held in Pierre, SD on October 15, 2014 it was decided that the SDDOT would use the MERRA data for pavement designs and the collection of GBWS data was not necessary due to the data quality issues and inadequate spatial coverage. At this meeting, the technical panel also decided that the groundwater level did not have any significant impact on the pavement performance predictions. Therefore, the development of GIS maps to extract and download climate and groundwater data was abandoned.

This research consisted of 13 tasks distributed across the two phases of the project.

Task 1 – Meet with the project`s technical panel to review the project scope and work plan

The research team and the technical panel personnel held a meeting in Pierre, South Dakota on January 28th 2014. An outline of the project was presented to the panel.

Task 2 – Review and summarize literature pertinent to climate and groundwater data

In this task, the research team conducted a comprehensive literature search of conference compendiums, technical journals, and research/project reports. This task was led by researchers from SDSM&T and Charles W. Schwartz and Associates, LLC. The literature review indicated that accuracy and reliability of the climate data play a very important role in the MEPDG design approach and the prediction of pavement performance. Climatic factors affect the behavior of all layers in the pavement system and have a direct influence on several deterioration processes including thermal cracking, frost heave and thaw weakening, rutting, infiltration potential, and decreasing drainability of pavement layers (Mills et al. 2007; Johanneck and Khazanovic, 2010). However, there have been concerns about the reliability and the accuracy of the climate data provided with the MEPDG software. Therefore, the transportation community is investigating more accurate, reliable and continuous climate data sources.

It is suspected that groundwater table level (i.e., depth of ground water below the surface) may have a significant impact on the overall performance of pavement structures. However, the literature did not contain many studies on this subject. The research team speculates that the recent version of the MEPDG software does not fully incorporate the impact of the groundwater table level into pavement performance predictions.

Task 3 – Perform a sensitivity analysis to evaluate the climate and groundwater data needed to support MEPDG design in South Dakota

The research team performed a sensitivity analysis to determine which changes in traffic levels, pavement types, subgrade types, climate zones, and climatic and groundwater conditions most affected the prediction of the pavement performance via use of M-E design in South Dakota. The one-at-a-time (OAT) methodology was followed during these analyses. The three pavement structures chosen for this sensitivity analysis were rural asphalt concrete, rural jointed plain concrete pavement, and a rehabilitation of asphalt concrete over rubblized concrete. The four locations in South Dakota chosen for this sensitivity analysis included Rapid City, Sioux Falls, Pierre, and Mobridge. A low, a medium, and a high level of traffic were analyzed. Three levels of subgrade were analyzed, including a poor quality subgrade (A-7-6), a medium quality subgrade (A-6), and a high quality subgrade (A-4). Several different climate parameters were analyzed to determine their effect on pavement performance. These climate data include air temperature, precipitation, wind speed, relative humidity, and percent sunshine. Three levels of the water table (2 feet, 5 feet, and 10 feet below the ground surface) were analyzed. Annual mean air temperature, precipitation, percent sunshine, and wind speed were individually varied by ±5% to determine the sensitivity of the resulting pavement performance. The results of the sensitivity analyses are summarized below.

Summary of the results for asphalt concrete (AC) pavements:

1. Air temperature had the greatest impact on asphalt pavement performance. Asphalt rutting increased with increasing air temperature. Alligator cracking and longitudinal cracking were also greatly impacted by temperature.
2. Thermal cracking increased with decreasing air temperature.
3. Percent sunshine impacted longitudinal cracking on asphalt pavement performance.
4. Increasing wind speed decreased thermal and longitudinal cracking.
5. The effect of precipitation on the asphalt pavement performance was negligible.
6. Decreasing subgrade modulus increased total rutting. Total rutting includes the combined deformation of the asphalt layer, the base layer, and the subgrade layer.
7. The groundwater table depth had negligible impact on asphalt pavement performance.
8. Increasing traffic increases all asphalt pavement distresses.

Summary of the sensitivity analysis results for asphalt concrete (AC) over rubberized jointed plain concrete pavement (JPCP):

1. Air temperature had the greatest impact on AC over JPCP pavement performance. These distresses include asphalt rutting and longitudinal cracking.
2. Thermal cracking was not sensitive to air temperature.
3. Precipitation and changes in water table depth had negligible impact on the composite pavement performance.
4. Increasing traffic increased distresses in the AC over JPCP pavement system.
5. Subgrade quality had the greatest impact on total rutting in composite pavements.

Summary of the sensitivity analysis results for rural jointed plain concrete pavement (JPCP):

1. Air temperature appeared to be the only climate parameter that influenced concrete pavement performance.
2. According to the result of this study, joint faulting and transverse cracking were not affected by meteorological conditions, traffic, or subgrade changes. This may be due to the traffic levels used in this study. Traffic levels may have been too low for large enough stresses to accumulate in the concrete pavement for the design period.

Task 4 – Assess the adequacy of climate and groundwater data currently embodied in the MEPDG Software:

Under this task, the research team assessed the reliability, accuracy and adequacy of climate and groundwater data currently embedded in the MEPDG software. Data quality in the MEPDG software is very important. Poor data quality leads to poor pavement performance predictions. The accuracy of predicted pavement performance depends strongly on the pavement structure (Wu et al. 2013). The reliability of a pavement design can be improved by using a larger time period for climate data (Mills et al. 2009). The research team considered three aspects to assess the adequacy and quality of the weather data embedded in the MEPDG software. These aspects include: spatial coverage, continuity of the data, and time duration. Overall, the research team suggested that the data embedded in the MEPDG software requires significant improvements: The issues regarding these data sources are summarized below:

1. The MEPDG software contains only 11 stations. The spatial coverage area is thus very small and does not adequately represent the variety of climate conditions throughout South Dakota.
2. The earliest year available from the MEPDG weather data for South Dakota is 1996. Even though there are no gaps in the data throughout the collection times, the average time period available in the MEPDG weather data is 8.2 years for South Dakota stations. This is important when considering climate events that only happen every 10 to 20 years. Therefore, the data embedded in MEPDG is not recommended for predicting pavement performance for 15 and 20 years or longer.

Task 5 – Identify other existing sources of climate and groundwater data and evaluate the availability and quality of data for use in MEPDG design

Under this task, the research team investigated three alternative climate data sources. These sources include the NASA`s Modern-Era Retrospective Analysis for Research and Applications (MERRA) product, ground-based weather stations (GBWS) throughout South Dakota, and environmental sensing stations (ESS). The pavement performance predictions from MEPDG analysis conducted with MERRA climate data were compared with those obtained from MEPDG analysis conducted with ground-based weather station data and climate data embedded in the MEPDG software. These comparison analyses were conducted for asphalt concrete (AC) and jointed plain concrete pavement (JPCP) designs. Total rutting, AC rutting, alligator cracking, International Roughness Index (IRI), and thermal cracking distresses were calculated for AC analyses while transverse cracking, joint faulting, and IRI were calculated for JPCP designs. The following conclusions were drawn from the results of this task:

1. Environmental sensing stations (ESS) cannot be used as an alternative climate source due to the lack of percent sunshine data. Therefore, pavement performance predictions could not be made using ESS data.

2. Performance predictions using MERRA vs. MEPDG weather data are similar in nearly all cases.
3. Predicted distresses using GBWS were slightly lower than predictions using weather data embedded in the MEPDG software for both pavement designs.

The research team also investigated available groundwater table data sources. A total of 1572 ground water monitoring wells was found in South Dakota. These data were extracted from the South Dakota United States Geological Survey (SD USGS) and South Dakota Department of Environment and Natural Resources (SD DENR). However, the spatial coverage of these wells was not uniformly distributed throughout South Dakota. The majority of these wells were located in the eastern and southern parts of the state. Therefore, they do not represent the groundwater table levels in the entire state. In addition, the research team found that there were large gaps in the majority of the monitoring data, so it was impossible to obtain definitive information regarding the actual history of water levels in the state in a particular area. Moreover, the sensitivity analyses and the literature review indicated that the current version of the MPEDG software is not sensitive to groundwater table level unless it is very near the ground surface (less than 2 feet below the ground surface). Instead of relying on the groundwater table data, SDDOT should instead focus on determining the stiffness and strength of the materials used in pavement design under extreme wet-dry conditions.

Task 6 – Identify remaining gaps in climate and groundwater data needed to support MEPDG design in South Dakota

Under this task, the research team accomplished the first objective of this study. Based on the results obtained from the previous task (Task 5), the research team identified the gaps and quality issues that exist in the MEPDG weather data, GBWS, ESS and MERRA. The research team provided the following suggestions regarding ground-based weather stations (GBWS), environmental sensing stations (ESS), Modern-Era Retrospective Research and Applications (MERRA) data and monitoring wells for ground water levels.

Identified Gaps in the Climate Sources Investigated in the Current Study

1. Environmental sensing stations cannot be used as a climate input data since they do not collect percent sunshine data.
2. The climate data stations (11 stations) embedded in the MEPDG software cover only a very small spatial area of South Dakota, which requires creation of virtual weather stations. The results indicated there were discrepancies in the pavement performance predicted by the ground-based weather stations (GBWS) and virtual weather stations in the same locations. This suggests that pavements designed using virtual weather stations may lead to over or under designs.
3. Ground-based weather stations (GBWS) had better spatial coverage than the weather data embedded in the MEPDG software. However, the majority of these stations are located in the eastern part of South Dakota while there are very few on the western and northern sides of the state. Furthermore, GBWS data has significant data quality issues. For example, 11 of the 46 stations located in or nearby South Dakota do not possess any relative humidity or/and percent sunshine data. A majority of the GBWS data are missing more than 24 hours in a single gap in the climate data, which decreases the usable time period in the analyses. The average time period available with GBWS weather data is 12.9 years.

Identified Gaps in the Groundwater Data Sources Investigated in the Current Study

This study reveals the following conclusions regarding the groundwater data sources in South Dakota:

1. Even though there are 1572 ground water monitoring wells in the state, the majority of these are located in the eastern and southern part of the state. Data obtained from these wells are thus not representative of the entire state.
2. Sensitivity analysis indicated that pavement performance predictions from the MEPDG software are not influenced by groundwater depth unless the groundwater table level is very near the ground surface (i.e., less than 2 feet below ground surface). The majority of the data collected from 1572 wells in South Dakota showed groundwater table depths greater than 2 feet below the ground surface.
3. The research team suggests that SDDOT should conduct research to determine the stiffness and strength of materials used in pavement designs under wet and dry conditions rather than collect groundwater data.

Task 7 – Submit to the project`s technical panel a technical memorandum summarizing the results of tasks 1-6 and recommending the number of climatic stations, climatic record length, and water table data that should be used in the MEPDG

The research team prepared a technical memorandum based on the findings from Tasks 1 through 6. The summary interim report presented the findings of the literature review, summary of the sensitivity analysis, assessment the adequacy of climate and groundwater data embedded in the MEPDG software, identification of other existing climate and groundwater data sources and determination of the remaining gaps that need to be filled. The research team also gave a presentation to the technical panel. This meeting was held on October 15, 2014 in Pierre, SD.

The following conclusions were reached at this meeting:

1. GBWS, ESS, and the weather data embedded in the MEPDG software are not of sufficient quality for use as climate data for the MEPDG. MERRA data should be implemented as the primary climate data source.
2. GBWSs possess many data quality issues. Therefore, it was decided that it was not necessary to develop GIS maps for the climate data.
3. It is not necessary to develop GIS maps for groundwater data since the MEPDG software does not take the impact of groundwater into account unless the water level is less than 2 feet below the ground surface.

Task 8 – Update MEPDG climatic files for appropriate weather stations based on panel recommendations

The research team updated the M-E Design climatic files both for GBWS and MERRA climate data. These files are provided in a format required by the Pavement ME Design™ software. MERRA data is available on NASA servers. Programs for extracting and downloading the data from the NASA servers, extracting the subset of MERRA data elements required by the MEPDG, and reformatting the MERRA data into MEPDG climate input files were developed in MATLAB®. The research team will provide this program to the SDDOT technical panel upon request. However, it requires the purchase of a MATLAB® license and the requisite personnel to run this code. This task accomplished the second objective of this project.

Tasks 9 and 11 – Develop a procedure and map and software tools for dividing the state into climate zones and selecting one or more weather stations for interpolation to a specific location to assist with the selection of water table depth at a specific location

Under this task, the research team originally planned to develop a tool to accomplish the second objective of the project. The research team planned to create a GIS map of South Dakota using ArcGIS software and to make publicly available the relevant geospatial data for South Dakota in order to extract and download climate data from these online sources. However, it was decided that MERRA data should be implemented as the primary climate data source at the technical memorandum meeting which was held on October 15, 2014 in Pierre, SD. The FHWA Long Term Pavement Performance (LTPP) program is working on the development of online tools for the extraction of MERRA data in a format required by the MEPDG software for the entire United States. These tools are expected to be available in the second half of 2015.

The results of this study showed that groundwater table did not impact pavement performance in the current version of the MEPDG software. Therefore, it was decided that GIS maps to update groundwater data were not necessary.

Task 10– Provide a methodology and automated means to automatically update climatic files in the format required by MEPDG Design

Programs for downloading and extracting the MERRA data from NASA servers was developed in MATLAB®. Climate data from both GBWS and MERRA were extracted, formatted to meet .hcd file format requirements, and written in ASCII format for eventual use by the MEPDG model. This code will be provided to the SDDOT technical panel upon request. However, it requires the purchase of a MATLAB® license and the requisite personnel to run this code. The technical panel decided to continue with the implementation of MERRA data as the primary source in the pavement performance predictions. The FHWA Long Term Pavement Performance (LTPP) program is working on the development of online tools for the extraction of MERRA data in a format required by the MEPDG software for the entire United States. These tools are expected to be available in the second half of 2015 (FHWA, 2015).

Task 12– Prepare a final report summarizing the research methodology, findings, conclusions and recommendations

The research team prepared a draft final report that included a comprehensive summary of the project and documented the project results, findings, and conclusions related to the improvement of the climate and groundwater data to support mechanistic-empirical pavement design in South Dakota. The final report will be submitted after this draft final report has been reviewed by the Project Technical Panel and the responses to all comments have been incorporated.

Task 13– Make an executive presentation to the SDDOT research review board at the conclusion of the project

The research team will make an executive presentation to the SDDOT Research Review Board and Project Technical Panel that will summarize all research activities and present any conclusions and recommendations that resulted from this research.

1.4 CONCLUSIONS

A research study was conducted to identify alternative climate data sources to be used as inputs to the MEPDG software. The research team used three different climate data sources (1) Ground-based weather stations (GBWS) embedded in MEPDG software, (2) ground-based weather stations (GBWS) throughout South Dakota, and (3) NASA's Modern-Era Retrospective Analysis for Research and Applications (MERRA) product. Extensive comparisons of MEPDG pavement predictions were made with the data collected from these three sources. The results of these analyses are summarized below:

1. MERRA provides 70 uniformly distributed grid points throughout South Dakota whereas there are only 11 MEPDG and 36 GBWS weather stations in South Dakota and nearby states. In addition, these GBWS are not spread out uniformly and do not possess the same spatial coverage as MERRA does.
2. MERRA has continuous hourly climate data from 1979 to the present and does not have gaps in the data in space or time. Moreover, extensive data quality checks are applied to MERRA data by NASA, which limits the amount of MERRA processing prior to use in MEPDG. The results show that the comparisons of the pavement distresses calculated via MEPDG weather stations data and GBWS data are slightly different from each other although they were collected from the same source. This indicates that there are quality issues with the GBWS data.
3. MERRA provides direct use of surface solar radiation instead of using percent cloud cover in GBWS in order to estimate the percent sunshine. That is, MERRA provides a more robust, physically-based approach for estimating the amount of energy incident at the land surface.
4. NASA has plans to move to ~10 km horizontal spatial resolution in the future, which will greatly increase the MERRA grid cell density.
5. Sensitivity analyses indicate that the groundwater table does not have any impact on the pavement performance unless it is very close (i.e., less than 2 feet) to the ground surface. This suggests that there is no need to quantify the groundwater table data accurately for the existing version of MEPDG software in regions where the depth to groundwater is greater than 2 feet. Furthermore, there are large gaps in the groundwater data in space and time..

1.5 RECOMMENDATIONS

The purpose of this research project was to identify the best climate sources to use in MEPDG pavement performance predictions. The results of this study showed that MERRA is as reliable as ground-based weather stations for critical weather data. In addition, MERRA has several advantages over currently available ground-based weather sources: denser, more uniform, and broader spatial coverage; better temporal frequency and continuity; excellent data consistency and quality. The results of this study also confirmed that the MEPDG software is not sensitive to groundwater table unless it is within 2 feet of the ground surface. The following recommendations are made based on the results of this study:

1.5.1. South Dakota Department of Transportation should adopt MERRA as a primary climate data source for pavement designs.

As mentioned in the previous sections of the report, MERRA possesses many advantages over other available climate data sources including ground-based weather stations (GBWS) and environmental sensing stations (ESS). GBWS data have significant discontinuities in the collected data. It requires significant amounts of effort to fill these gaps if SDDOT decides to use them for pavement performance predictions. Moreover, GBWSs do not cover the entire state uniformly.

On the other hand, MERRA provides uniform and more representable climate data with a spatial coverage of the entire state. In addition, there are no gaps in the data, which are continuous since 1979 and subjected to rigorous quality checks by NASA.

Even though the research team strongly recommends the adoption of MERRA as a primary climate data source for pavement performance predictions, it should be emphasized that in mountainous regions none of the climate data sources may provide accurate and reliable pavement performance predictions due to spatial scale issues in complex terrain as well as installation bias of instrumental networks (e.g., preferential installation in lower elevation valleys rather than higher elevation mountain tops).

1.5.2. South Dakota Department of Transportation should initiate a new project to determine the stiffness and the strength of pavement subgrade and base layers under different moisture content conditions (dry, optimum, and wet) and to use these values as input values in the MEPDG pavement performance predictions.

This study showed that the groundwater table depth does not have a significant impact on pavement performance unless it is within 2 ft of the ground surface. The current version of the MEPDG software does not simulate all aspects of water in the field such as frost heave and lateral drainage.

2 PROBLEM DESCRIPTION

In the Mechanistic-Empirical Pavement Design (MEPDG) approach (AASHTO, 2008), pavement performance is evaluated based on mechanistically determined critical stresses, strains, temperatures, and moisture levels that are in turn the inputs to empirical prediction models for specific pavement distresses such as rutting, fatigue cracking, thermal cracking, and roughness for flexible pavements and cracking, faulting, and roughness for rigid pavements. Accurate characterization of the traffic, climate, and material input parameters is therefore important to ensure that the theoretical computation of pavement stresses, strains, temperatures, and moisture levels are accurate at the critical locations within the system. Local calibration is desirable to improve the accuracy of the empirical distress model predictions for a particular state or region.

Proper implementation of the MEPDG requires realistic values for the input parameters. The main inputs include: general site and project information, allowable distress limits and associated reliability levels, traffic volumes and axle load distributions, pavement structure, material properties, groundwater depth, and climate conditions. Groundwater depth and climate affect the overall pavement performance because material properties change with temperature and moisture. Temperature and moisture distributions over the pavement design life are determined via the Enhanced Integrated Climate Model (EICM). Climate inputs required by the EICM include hourly air temperature, precipitation, wind speed, percent sunshine and relative humidity. This weather-related input data is generally obtained from a ground-based weather station located near the project site. The MEPDG software includes a weather database of over 1000 ground-based weather stations in the United States. However, these weather stations are mostly located near highly populated areas, and thus large portions of the United States are underrepresented.

Groundwater depth is another factor that can affect pavement performance in the M-E design approach. However, these data are less commonly available than the weather-related input data in the MEPDG software. Groundwater depth needs to be determined from groundwater monitoring wells or geotechnical subsurface investigation.

The SDDOT has been working on material characterization and collection of reliable traffic data for the MEPDG pavement designs in South Dakota. However, no work has been initiated to compile the climate and groundwater inputs. Consequently, the objectives of this project are to evaluate the reliability and adequacy of the climate and groundwater data already included in the MEPDG software and additional data collected from ground-based weather stations and existing groundwater monitoring wells in South Dakota. A particular emphasis is on alternative sources of climate and groundwater data that are more reliable and easier to collect and update.

To address these needs, our research team used a new and spatially comprehensive weather data source for MEPDG software in addition to data available from ground-based weather stations. NASA's Modern-Era Retrospective Analysis for Research and Applications (MERRA) product can be used to provide hourly climatic data for MEPDG analysis. MERRA is a global climate reanalysis product that combines computed model fields with ground-, ocean-, atmospheric-, and satellite-based observations. The FHWA Long Term Pavement Performance (LTPP) program has recently adopted MERRA as the source for hourly climate data in the next update of the climate module in the LTPP database.

The work summarized in this report includes an extensive comparison of MEPDG predictions using climatic information included with the MEPDG software, data from other South Dakota ground-based weather stations (GBWS), and from MERRA. In addition, groundwater depth data was collected from monitoring wells measured by the United States Geological Survey (USGS) and the South Dakota Department of Environment and Natural Resources (SDDENR).

3 OBJECTIVES

The objectives of this research were the following:

1) Assess the availability and quality of climate and groundwater data within ME design and from other existing sources. This objective was accomplished through the following steps.

   a. Evaluate the quality of the climate data embedded in the MEPDG software and determine the adequacy of the spatial coverage area of the 11 weather stations in South Dakota.

   b. Identify other climate data sources. The following data sources were identified: ground-based weather station (GBWS) data, environmental sensing station (ESS) data and MERRA data. The quality of the data collected from these three different climate sources was evaluated.

   c. Compare predicted pavement performance using the weather data in the MEPDG software weather database, weather data from GBWSs throughout South Dakota and nearby states, and weather data from MERRA. At first, comparisons of MEPDG pavement performance predictions were made between the MEPDG weather database (11 stations) and their collocated GBWS and MERRA data. Then, comparison analyses were conducted between the GBWS (36 stations) and MERRA data.

   d. Quality control checks were performed on GBWS and ESS data. Quality checks were not performed on MERRA data since this is already rigorously performed by the NASA. ESS data were found to be unsuitable for use in the MEPDG because they do not include percent sunshine or solar radiation data and the time duration of the data is less than 2 years, which is the minimum required by the MEPDG.

      The following method was followed to fill the gaps in GBWS: (1) The stations missing 100% of any climate data (air temperature, percent sunshine, relative humidity, precipitation, etc.) were excluded; (2) any stations missing any data for more than 2 days were excluded; (3) hourly gaps in data were filled via linear interpolation.

   e. Identify the locations of the ground water monitoring wells in South Dakota via coordinating with United States Geological Survey (USGS) and South Dakota Department of Environment and Natural Resources (SD DENR). Groundwater data were collected from over 1,000 monitoring wells and are being delivered in Excel format along with the final report.

2) Develop procedures enabling SDDOT to acquire, maintain, and use climate and water table data in M-E design.

   The ground-based weather stations were reformatted into hourly data in an input format required for the MEPDG weather data files. As for the MERRA data, research-grade programs were developed in MATLAB® for downloading and extracting the data from the NASA servers. The extracted MERRA data were reformatted as required by the MEPDG software. The research team will provide this extraction code to the SDDOT. However, it requires a MATLAB® license and skilled personnel to operate MATLAB®. The FHWA Long Term Pavement Performance (LTPP) program is working on the development of an online source for the extraction of MERRA data in a format required by the MEPDG software for the entire United States. It is expected to be available in the second half of 2015.

3) Identify enhancements needed to supply and maintain climate and water table data adequate for M-E design.

   This objective was accomplished with comparisons of results of the M-E design analyzed using MERRA weather data, GBWS data, and data supplied with the MEPDG software. These results do not include the data collected from environmental sensing stations (ESS) since these were determined to be not suitable for use in M-E pavement performance predictions. It is recommended that SDDOT adopt the MERRA data as the primary climate data source.

4 TASK DESCRIPTION

4.1 Task 1 – Meet with the project`s technical panel to review the project scope and work plan

The research team and technical panel met on January 28, 2014 in Pierre, SD.

4.2 Task 2 – Literature review

In this task, the research team conducted a comprehensive literature search of conference proceedings, technical journals, and research/project reports. This task was led by researchers from SDSM&T and Charles W. Schwartz and Associates, LLC. The summary of the literature review is provided below.

The principal objective of the development of the MEPDG was to provide the highway community with a state-of-practice methodology for the design of new and rehabilitated pavement structures based on mechanical-empirical principles. The design process consists of three steps. The first step is the collection of the project site inputs such as traffic, climate, material properties and existing pavement conditions (if the design is rehabilitation). In the second step the MEPDG software predicts individual pavement distresses as functions of time/traffic. Based on the results obtained from the second step, the pavement design is adjusted until all key distresses remain within their design limits. Key distresses include International Roughness Index (IRI), longitudinal cracking, transverse cracking, alligator cracking, and rutting for flexible pavements and IRI, slab cracking, and faulting for rigid jointed plain concrete pavements (JPCP).

Accuracy and reliability of the input data play a very important role in the M-E design approach for the prediction of pavement performance. Climatic factors affect the behavior of all layers in the pavement system and have a direct influence on several deterioration processes including thermal cracking, frost heave and thaw weakening, rutting, infiltration potential, and decreasing drainability of pavement layers (Mills et al. 2007; Johanneck and Khazanovic, 2010).

The properties of asphalt are significantly dependent on temperature. At low temperatures, asphalt becomes hard and brittle while it becomes soft and more viscous at high temperatures. Rutting is directly related to pavement temperature, with the greatest rutting occurring during heavy long-duration loading at high temperatures. On the other extreme, thermal cracking occurs at very low pavement temperatures. Climatic factors also control the selection of asphalt binder grade in the M-E design (Breakah et al. 2011).

Pavement structures generally contain 3 layers: asphalt (often consisting of several sublayers or lifts), or Portland cement concrete (PCC), base/subbase, and subgrade. The layers beneath the asphalt/PCC usually consist of unbound materials, and their physical and engineering properties are very sensitive to moisture content (Cetin et al. 2012). Excessive moisture lowers the stiffness and strength of the unbound materials (Cetin et al. 2010). It also can lead to frost action, which can quickly deteriorate a pavement.

Past literature concluded that climate is a crucial parameter that must be taken into account during the design of pavements. However, there have been concerns about the reliability and the accuracy of the climate data provided with the MEPDG software. Zaghloul et al. (2006) predicted the performance of flexible pavements in New Jersey by using the MEPDG-provided climate data from eight weather stations located between 12 to 60 miles from the project site. They found significant discrepancies in the predicted performances depending on which weather stations were used in the analyses. These discrepancies are troubling given the uniform topography and weather patterns over the small state of New Jersey.

In addition, climate data used in the Mechanistic-Empirical Pavement Design Guide (MEPDG) often needs to be interpolated since there are a finite number of weather stations. This is typically done by interpolating weather data from several nearby weather stations to create a virtual weather station for the project site. The accuracy of using these virtual weather stations was checked in a study that set up automated weather stations at several project sites. The weather data from the virtual weather stations was compared with the automated weather stations. The average difference between these stations was as follows: the daily mean temperature deviation varied from -1.0°C to 0.6°C, the daily maximum temperature deviation varied from -0.6°C to 1.4°C, and the daily minimum temperature deviation varied from -1.7°C to 1.5°C. The majority of the virtual weather data fit within the 95% confidence limits. There was one site that differed greatly in weather data for this study. However, the closest actual weather station to this site was 18.6 miles away and had an elevation difference of 1,575 feet. When comparing the automated weather stations with the virtual weather stations, there was less variation for monthly data than for daily data. This study confirmed that virtual weather station data is adequate for MEPDG as long as attention is given to proximity and elevation difference of weather stations. (Wu et al. 2013).

Another study examined how using the interpolated data affects the pavement performance predictions by the MEPDG software. The interpolated data predicted higher rutting, lower thermal cracking, and lower IRI values. This study recommended using more comprehensive data and recommended using forecasted climate data for future pavement designs (Breakah et al. 2011).

Studies have been done to compare the pavement performance of asphalt when using a baseline climate scenario and a future climate scenario. Climate change led to many changes in the asphalt pavement performance parameters. Asphalt rutting increased between 14% and 36%. Alligator cracking increased between 2% and 14%. Longitudinal cracking showed only a small increase with climate change (Mills et al. 2009). Total rutting of the pavement system varied from a decrease of 3% to an increase of 10%. The IRI value changed by up to 3% in either direction. Transverse cracking was the least impacted by climate change (Tighe et al. 2008). One study examined the impact of temperature change and physical location on asphalt pavement performance. This study showed alligator cracking to increase for coastal locations. Rutting deviation varied from 4% to 16% in this study. Inland locations showed the highest increase in rutting. Temperature change only had a moderate impact on rutting and a negligible impact on alligator cracking (Meagher et al. 2012). Another study showed rutting to also increase with percent sunshine. (Li et al. (2013).found that average annual temperature and average annual temperature range had the greatest impact on pavement performance.

One study (Li et al. 2013). compared asphalt pavement performance between different climate zones and traffic conditions. The cold-wet climate zone with low traffic had the highest longitudinal cracking and the highest alligator cracking. The hot-dry climate with low traffic had the highest rutting. The cold-wet climate with high traffic had the highest IRI value. A similar study showed that longitudinal cracking and alligator cracking are much less sensitive to climate change than to traffic change or changes in pavement structure (Mills et al. 2009). Longitudinal cracking was most sensitive to the thickness of the asphalt, nominal maximum aggregate size, and asphalt-binder grade (Tashman et al. 2013). Rutting was more sensitive to climate change than traffic change (Mills et al. 2009). One study recommended using Level 1 accuracy for predicting rutting and longitudinal cracking in asphalt pavements (Tashman et al. 2013). The effects of climate change on asphalt pavement performance means that maintenance, reconstruction, or rehabilitation will be required sooner (Mills et al. 2009).

The material properties of Superpave asphalt mixes were slightly modified to determine if there was a significant impact on pavement performance. Slight modifications to the aggregate gradation had no significant effect on dynamic modulus or rut depth. Lowering the dynamic modulus resulted in a greater rut depth (Tashman et al. 2013).

Concrete pavements are also vulnerable to climate and climate change. Curling of concrete pavement occurs when there is a large temperature change. Warping occurs when there is a large moisture change. Curling and warping lead to an increase in stresses in the concrete pavement and ultimately leads to failure of the concrete (Johanneck et al. 2010).

Pavement performance parameters for concrete pavements have different sensitivities to different inputs. Transverse cracking was most affected by the effective temperature difference, thermal conductivity, coefficient of thermal expansion, thickness, strength properties, and joint spacing. Faulting was most sensitive to the curl/warp effective temperature difference and the coefficient of thermal expansion. Roughness of concrete pavements was most sensitive to the curl/warp effective temperature difference (Guclu et al. 2009). Faulting and roughness increased with increased average annual and daily temperature ranges and percent sunshine. Li et al. (2013) found that slab cracking was the pavement performance parameter that was most sensitive to climate.

One study examined the impact of climate and traffic on concrete pavement performance. Climate zones were created to compare pavement performance. The cold-wet climate with high traffic had the highest faulting and IRI values. The cold-wet climate with low traffic had the highest slab cracking (Li et al. 2013).

A composite pavement is typically when an asphalt overlay is placed on a concrete pavement. The asphalt layer has an insulating effect on the concrete pavement layer, which reduces the temperature difference in the concrete. This insulating effect leads to lower curling stresses in the concrete and improved performance and longevity (Johanneck et al. 2011). One study showed that for composite pavements the MEPDG software overpredicted rutting (Zhou et al. 2013).

The soil below the pavement can also have a significant impact on the pavement performance. Soil properties are sensitive to moisture. The soil resilient modulus is reduced when excessive moisture is present (Qiao et al. 2013). Low temperatures also impact soil stiffness. When moisture in the soil freezes the soil strength artificially increases. However, the added strength is lost when that moisture thaws (Johanneck et al. 2010).

The depth of the groundwater table is another factor to consider in pavement design. The groundwater table has the greatest impact on the unbound soil layers. When the groundwater table is raised the rate of both asphalt rutting and total rutting in the pavement is increased and permanent deformation is accelerated. The saturated unbound layers lose stiffness. One study showed that when the groundwater table was raised, the subgrade had the largest increase in permanent deformation. This study also showed that the strength of unbound materials was partly regained after groundwater was subsequently lowered. This may be due to additional compaction (Erlingsson 2010). As the groundwater table was lowered the required thickness of the subbase also decreased. One study examined how groundwater table and environmental conditions affected pavement design. This study showed that when the groundwater table was near the surface, the environmental location has less impact on pavement thickness. When the groundwater table dropped below 5 to 8 feet, external environmental conditions controlled the design of the pavement structure (Zapata et al. 2012).

The literature review suggests that the climate data used in MEPDG software are very crucial and important for proper pavement designs. The quality of the climate data must be carefully evaluated since it may cause significant reliability and accuracy issues in the prediction of pavement distresses. Therefore, it is very important to determine climate data sources that provides continuous, quality weather data along with uniform spatial coverage.

4.3 Task 3: Perform a sensitivity analysis to evaluate the climate and groundwater data needed to support M-E design in South Dakota

Under this task, the project team performed sensitivity analyses to determine the effects of traffic levels, pavement types, subgrade types, climate zones, climatic and groundwater conditions on pavement performance as predicted via the MEPDG design in South Dakota. It also evaluated the sensitivity of pavement performance to the individual climate inputs of air temperature, precipitation, wind speed, percentage sunshine or relative humidity.

The three pavement structures chosen for this sensitivity analysis were rural asphalt concrete (AC), rural jointed plain concrete pavement (JPCP), and a rehabilitation of asphalt concrete over rubblized concrete. The four locations in South Dakota chosen for this sensitivity analysis included Rapid City, Sioux Falls, Pierre, and Mobridge. These locations were chosen to represent the variety of climate throughout South Dakota. A low, medium, and a high level of traffic were analyzed. These values were 50, 250, and 450 AADTT (Annual Average Daily Truck Traffic) respectively. Three levels of subgrade were analyzed, which included a low quality subgrade (A-7-6), a medium quality subgrade (A-6), and a high quality subgrade (A-4). Three levels of the water table were analyzed. The three levels are two, five, and ten feet below the surface. A full list of inputs is in table form in Appendix A. Several different climate parameters were analyzed to determine their effect on pavement performance. Annual air temperature, precipitation, percent sunshine, relative humidity, and wind speed were individually changed by ±5% to determine their influence on pavement performance. Daily air temperature was changed by ±10%. The MEPDG software was run 300 times in total to determine the individual contribution of each parameter on the performance of the pavement.

Input data used in the base cases are summarized in Table 4.1 through 4.3 for asphalt concrete (AC), jointed plain concrete pavement (JPCP), and asphalt concrete overlay over rubberized rural joint plain concrete pavement.

Table 4.1. Traffic and pavement layer thickness for base cases

Traffic Level	Low	Medium	High
Nominal AADTT	50	250	450
AC Thickness (in.)	3	4	5
Base Thickness (in.)	10	12	14
JPCP Thickness (in.)	8	9	10
Base Thickness (in.)	3	5	7

Table 4.2. Pavement design properties for base cases

Input Parameter	Value
Design Life	20 years for flexible pavements 40 years for rigid pavements
Construction Month	June 2014
Reliability	90%
AADTT Category	Rural
Number of Lanes in Design Direction	1
Truck Direction Factor	55%
Truck Lane Factor	100%
Default Growth Rate	None
First Layer Material Type	Jointed Plain Concrete Pavement / Asphalt Concrete
Second Layer Material Type	Crushed Gravel
*Subgrade Material Type	A-4
Base Resilient Modulus	25000 psi
Base Poisson's Ratio	0.35
*Subgrade Resilient Modulus	15000 psi
*Subgrade Poisson's Ratio	0.35
Note:*Subgrade modulus and types was kept constant while conducting sensitivity analysis on change in air temperature, relative humidity, wind speed, precipitation, percent sunshine, groundwater table, and traffic level.	

Table 4.3. Surface layer properties for base cases

		Base Value
Asphalt Properties	Surface Shortwave Absorption	0.85
	Unit Weight	149 pcf
	Poisson's Ratio	0.35
	Thermal Conductivity	0.67 BTU/hr-ft-˚F
	Heat Capacity	0.23 BTU/lb-˚F
	Effective Binder Content by volume	5%
	Air Void	7%
	Binder Type	64-34
Concrete Properties	Design Lane Width	14 feet
	Joint Spacing	15 feet
	Dowel Diameter	1.25 in.
	Erodibility Index	5
	Surface Shortwave Absorption	0.85
	Unit Weight	145 pcf
	Poisson's Ratio	0.2
	Coefficient of Thermal Expansion	5.5 in./in./˚F x 10^{-6}
	Thermal Conductivity	1.25 BTU/hr-ft-˚F
	Cement Content	600 lb/yd^3
	W/C ratio	0.42

The values obtained during the sensitivity analysis were normalized by comparing the change in pavement performance with the change in inputs. The normalized sensitivity index (NSI) allows easy comparison as to the magnitude of effect an input has on the pavement performance according to the MEDPG software. A large positive NSI value indicates that increasing the input will greatly increase the output value. A negative NSI value indicates that increasing the input will decrease the output. The equation for this method is displayed below (Li et al. 2013).

$$NSI = \frac{\frac{\Delta Y}{DL}}{\frac{\Delta X}{X}}$$

- ΔY = the change in pavement performance due to change in design input
- DL = the design limit for the pavement performance parameter
- ΔX = the change in the design input from the baseline X
- X = the baseline design input value

Under this task, quantitative evaluation of the sensitivity of MEPDG pavement performance predictions to key design parameters were completed. These design parameters include, subgrade quality, climate data, traffic level and water table level. The sensitivity analyses were conducted on three different pavement types: (1) asphalt concrete (AC), (2) jointed plain concrete pavement (JPCP), and a rehabilitation of asphalt concrete over rubblized concrete (AC over JPCP).

Figure 4.1 summarizes the results of the sensitivity analyses for AC. The following conclusions are drawn from the AC sensitivity analyses:

1. The results show that asphalt pavement is the pavement type that is most sensitive to changes in air temperature, which is most probably due to the nature of the asphalt material. Asphalt rutting was the distress most significantly influenced by the change in annual average temperature and daily average temperature. Longitudinal cracking, alligator cracking and total rutting are also sensitive to changes in temperature. The NSI values are all positive. This means that an increase in annual average temperature and daily average temperature increases pavement distresses.

2. Traffic has a significant impact on asphalt pavement performance, particularly for asphalt rutting, longitudinal and alligator cracking.

3. Alligator cracking and longitudinal cracking are sensitive to percent sunshine while asphalt rutting and total rutting are not significantly affected by percent sunshine.

4. Wind speed generally has negative NSI values for many of the distresses, indicating that pavement distresses decrease with an increase in wind speed. Wind speed only has significant impact on longitudinal cracking and alligator cracking. This is similar to the findings of Li et al. (2013).

5. Figure 4.1 shows that effects of precipitation on pavement distresses are negligible. The reason for this is that precipitation is ignored in the mechanistic design in MEPDG analyses since EICM does not include the effects of surface infiltration in its modeling of temperature and moisture within the pavement.

The sensitivity analyses for AC over JPCP rigid pavements are shown in Figure 4.2. Summary of the results are below:

1. As observed in the AC sensitivity analyses, pavement distresses in AC over JPCP designs are the most sensitive to the average daily and annual temperature. These pavement distresses include asphalt rutting, total rutting and longitudinal cracking.
2. Figure 4.2 also shows that an increase in traffic level increases asphalt rutting, total rutting and longitudinal cracking pavement distresses.
3. Percent sunshine and wind speed were the second most sensitive parameters after air temperature for asphalt rutting at high traffic conditions. NSI values for percent sunshine and wind speed sensitivity analyses were positive and negative, respectively. This indicates that an increase in percent sunshine increases asphalt rutting while an increase in wind speed decreases the asphalt rutting.
4. Results also show that precipitation did not have any impact on the pavement distress predictions.

Figure 4.3 shows the sensitivity analyses results for JPCP. Results of these analyses are summarized below:

1. JPCP was shown to be less sensitive to climate than AC and AC over JPCP pavements.
2. Average annual and daily temperature exhibited the highest NSI values at any traffic conditions. The NIS values of air temperature for IRI were negative indicating that an increase in temperature would produce less IRI pavement distress.
3. Percent sunshine and wind speed had a slight impact on IRI pavement distress.
4. IRI distresses did not seem to be affected significantly by traffic levels that were used in these analyses.
5. The sensitivity of JPCP to precipitation was negligible at any traffic level.

Figures 4.4, 4.5 and 4.6 show the groundwater table and subgrade type sensitivity analyses for AC, AC over JPCP and JPCP types of pavements, respectively.

1. Figure 4.4 and 4.5 indicate that the sensitivity of total rutting pavement distress to subgrade type is the highest in AC and AC overlay JPCP pavements.
2. IRI values were also sensitive to the quality of subgrades as shown in Figure 4.6. NSI values of subgrade in JPCP sensitivity analyses were negative. This indicates that quality subgrade will decrease the IRI pavement distress.
3. Figure 4.6 indicates that quality of subgrade does not have an impact on the joint faulting and transverse (slab) cracking.
4. AC was the most sensitive pavement type to subgrade quality.

Groundwater table sensitivity analyses were conducted on three different water table levels which were 2 feet, 5 feet and 10 feet. All results showed that groundwater did not pose a significant impact on the pavement distress unless the water table is at the ground surface. These results indicate that the current version of the MEPDG software does not properly quantify the impact of ground water table level on the pavement distress predictions. .

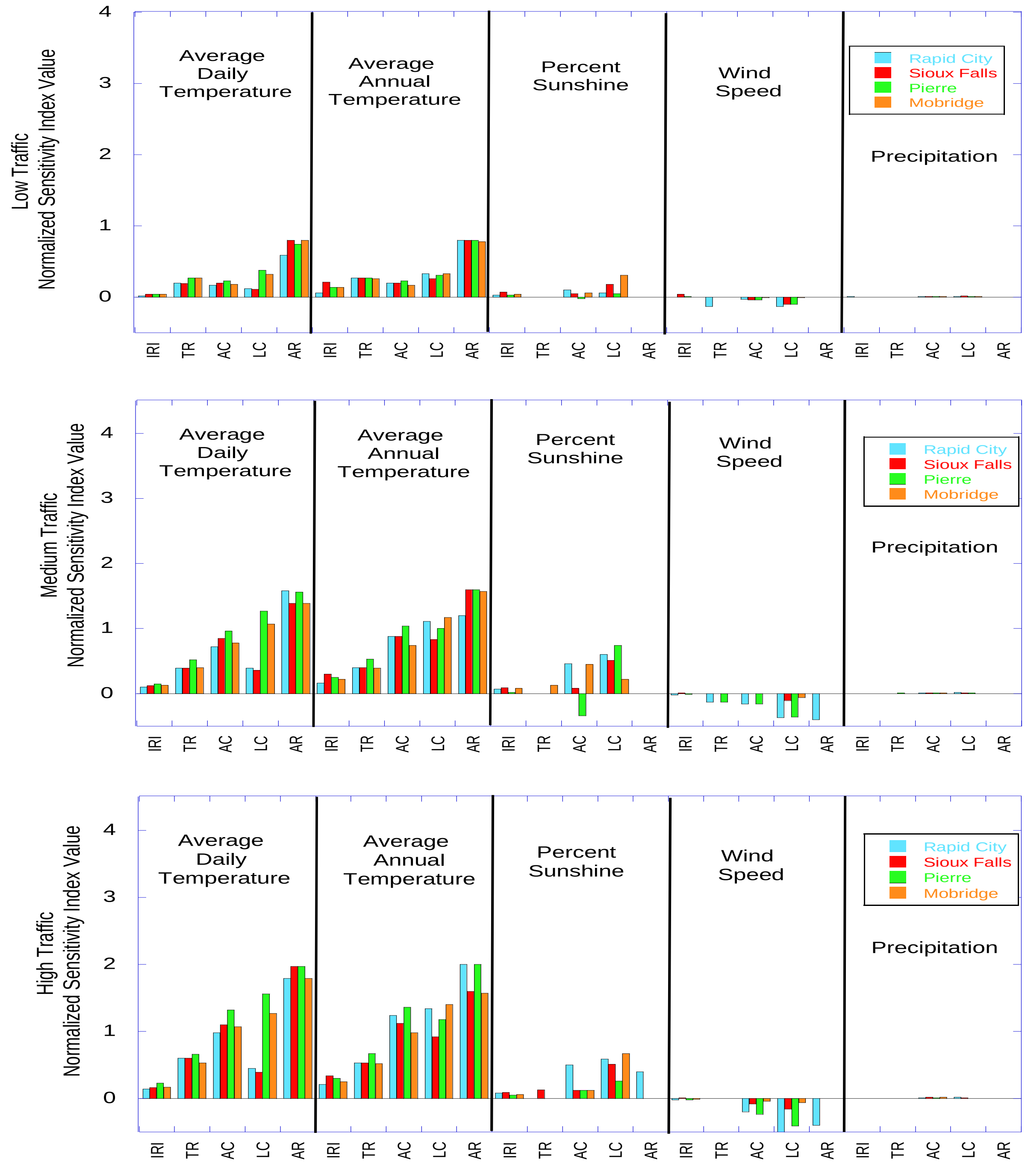

Figure 4. 1. Sensitivity analysis for asphalt.

IRI: International Roughness Index, TR: Total Rutting, AC: Alligator Cracking, LC: Longitudinal Cracking, AR: Asphalt Rutting

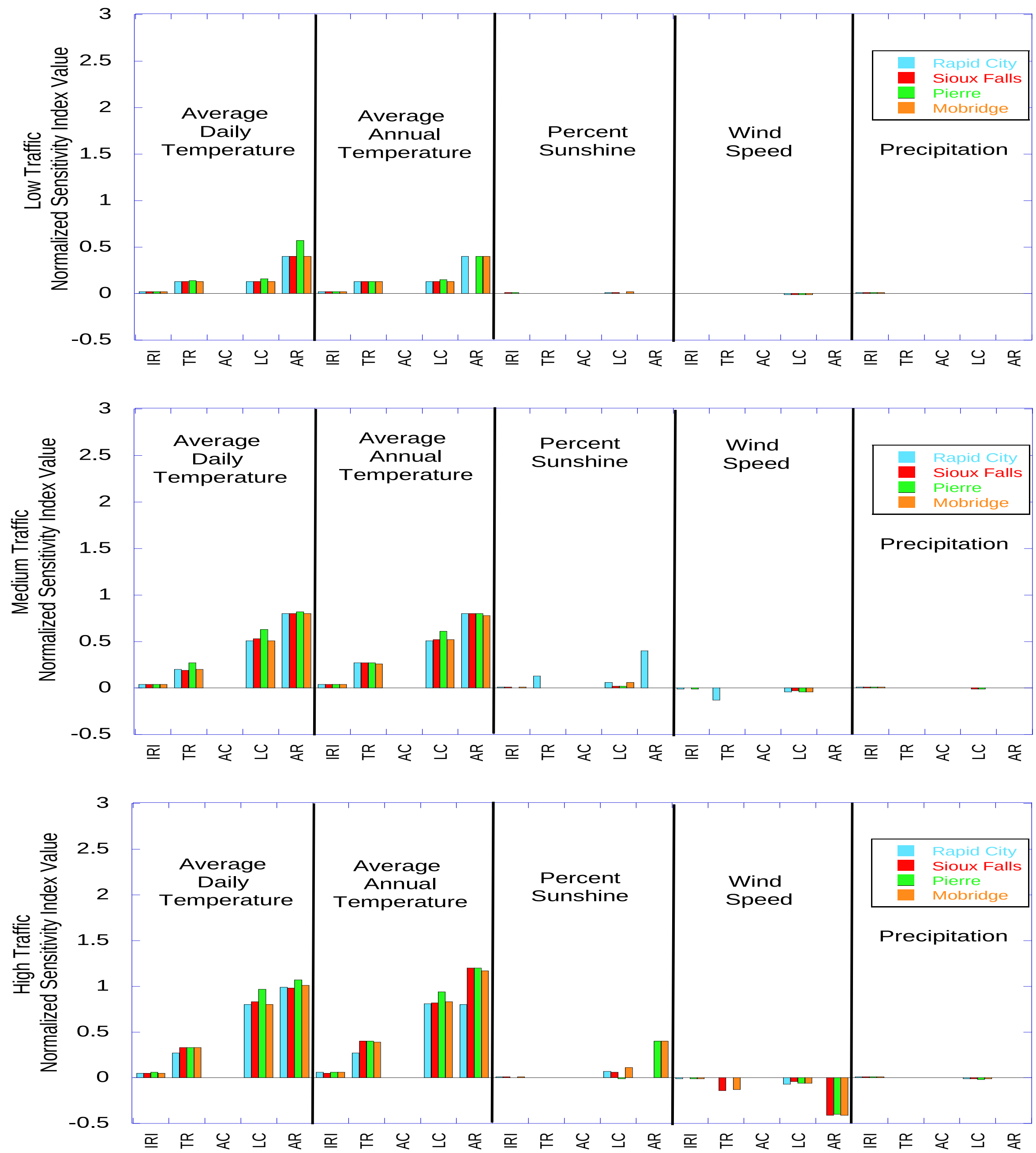

Figure 4.2. Sensitivity analysis for asphalt over JPCP.

IRI: International Roughness Index, TR: Total Rutting, AC: Alligator Cracking, LC: Longitudinal Cracking, AR: Asphalt Rutting.

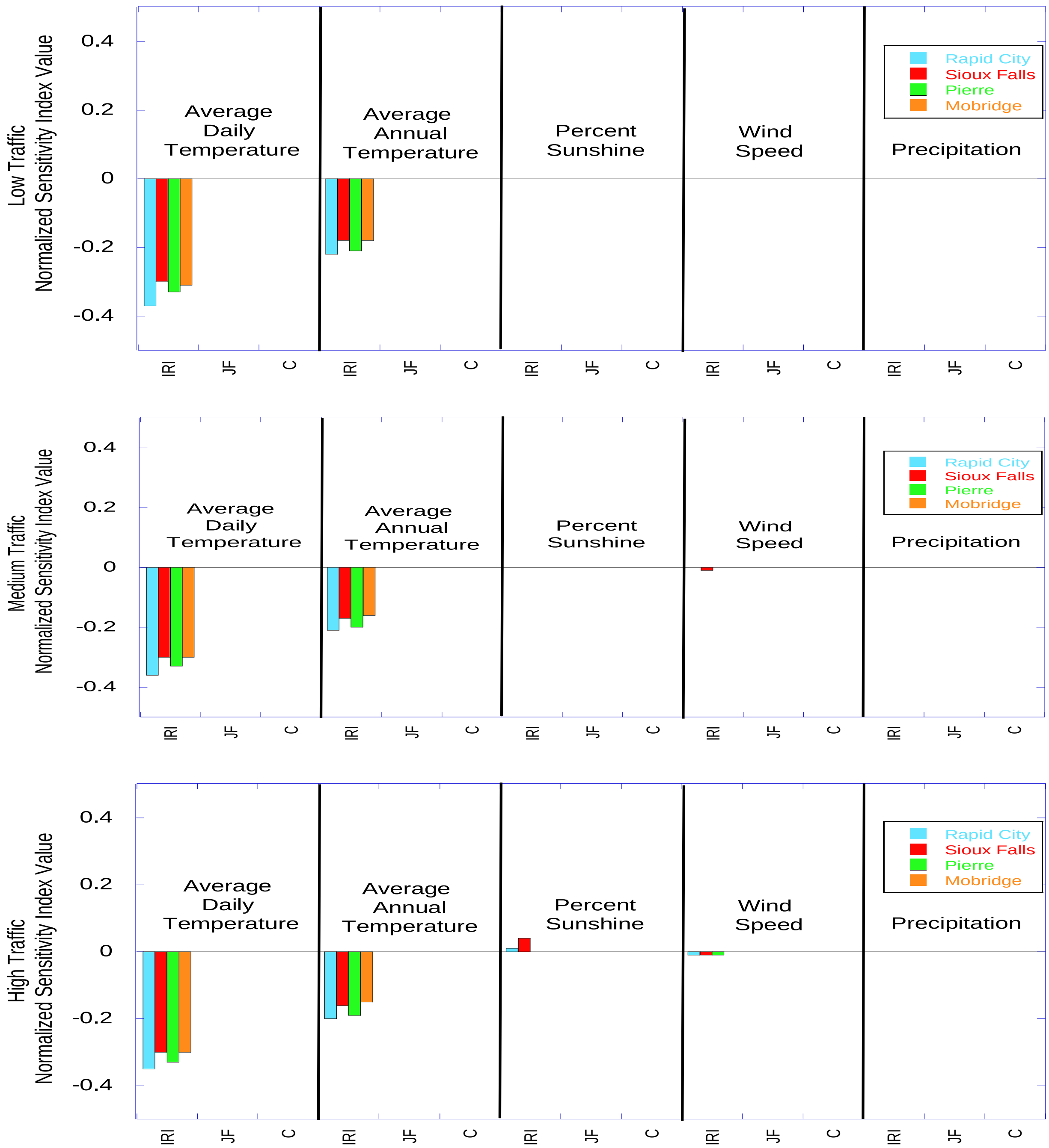

Figure 4.3. Sensitivity analysis for JPCP.
IRI: International Roughness Index, JF: Joint Faulting, C: Transverse Cracking

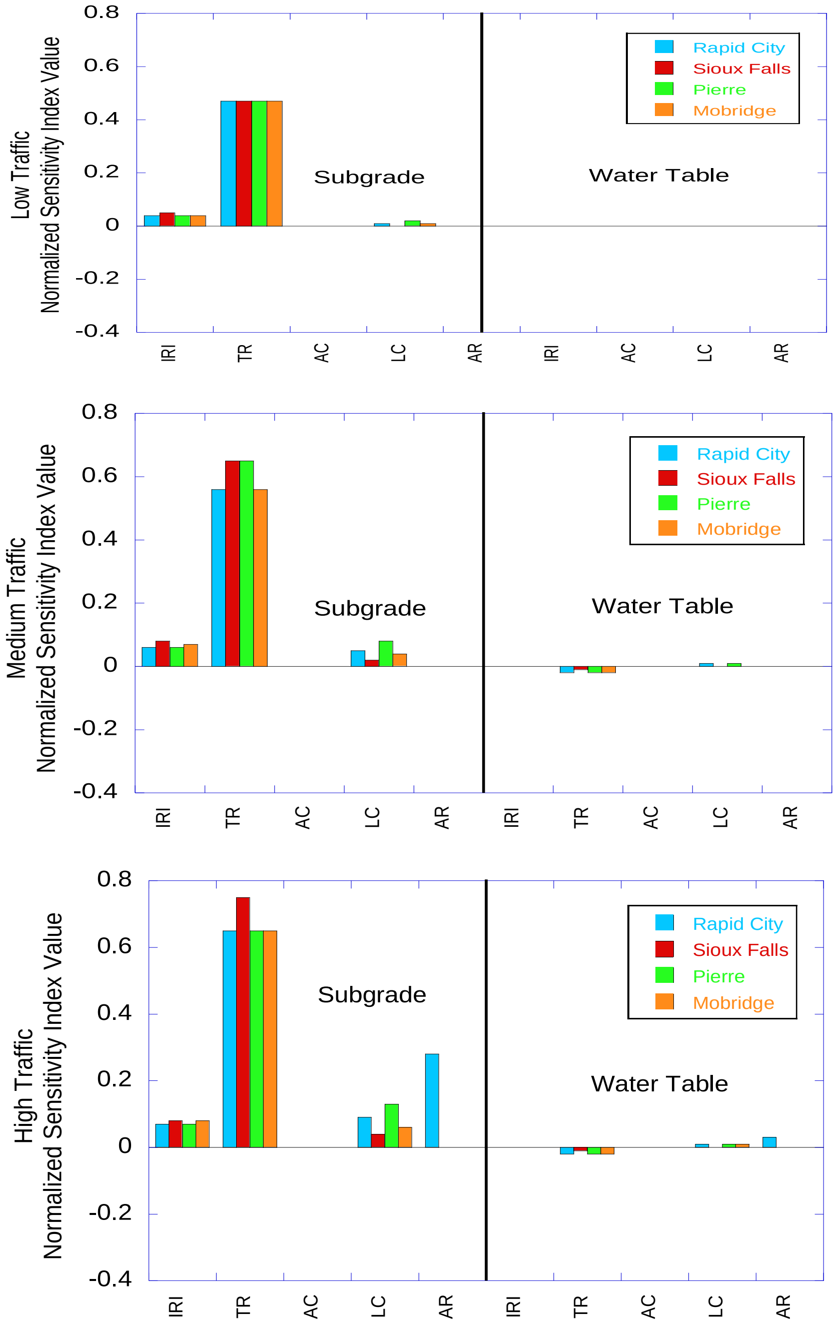

Figure 4.4. Sensitivity analysis for asphalt (subgrade and groundater table level). IRI: International Roughness Index, TR: Total Rutting, AC: Alligator Cracking, LC: Longitudinal Cracking, AR: Asphalt Rutting

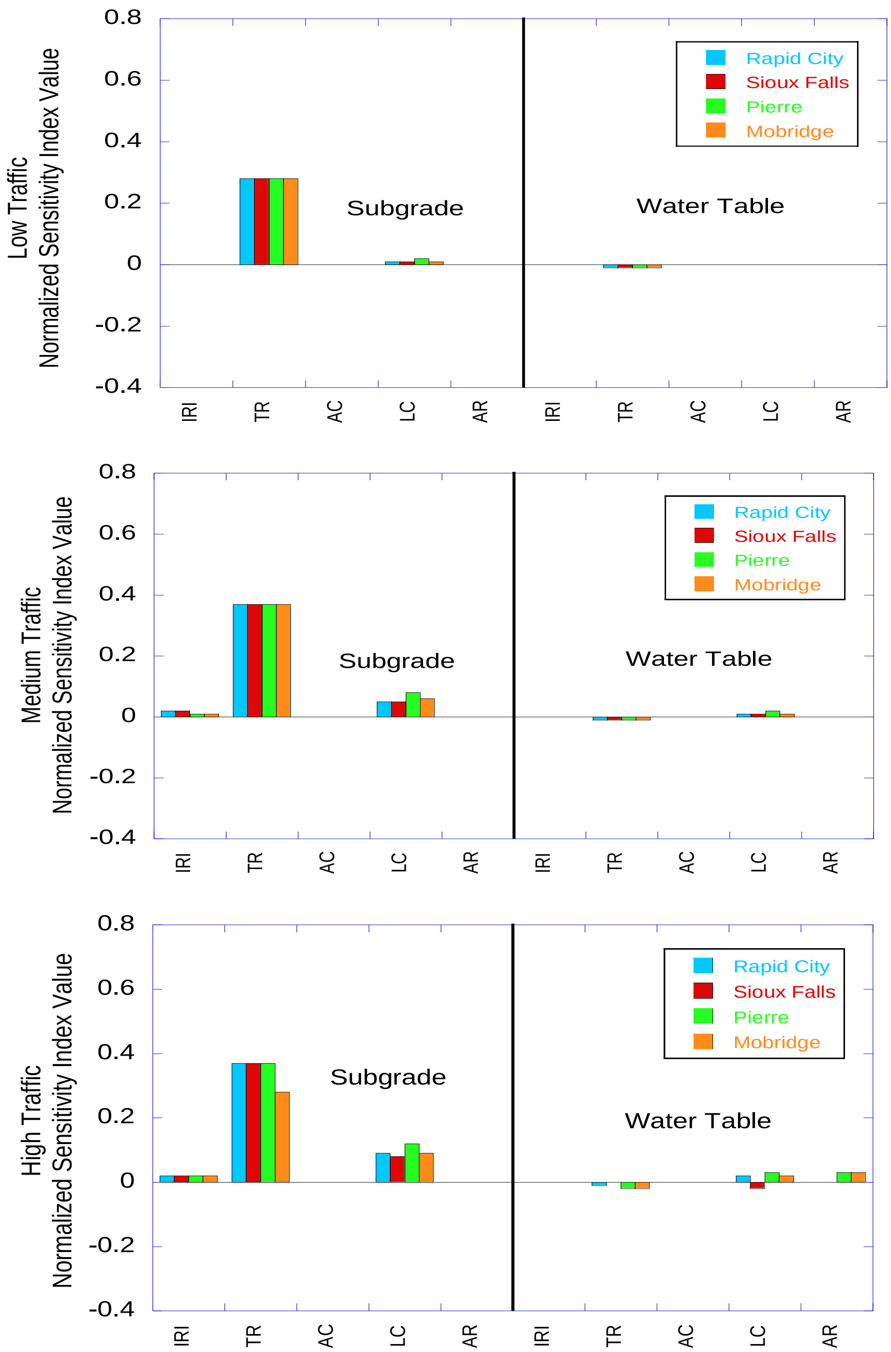

Figure 4.5. Sensitivity analysis for asphalt over JPCP (subgrade and groundwater table level).

IRI: International Roughness Index, TR: Total Rutting, AC: Alligator Cracking, LC: Longitudinal Cracking, AR: Asphalt Rutting

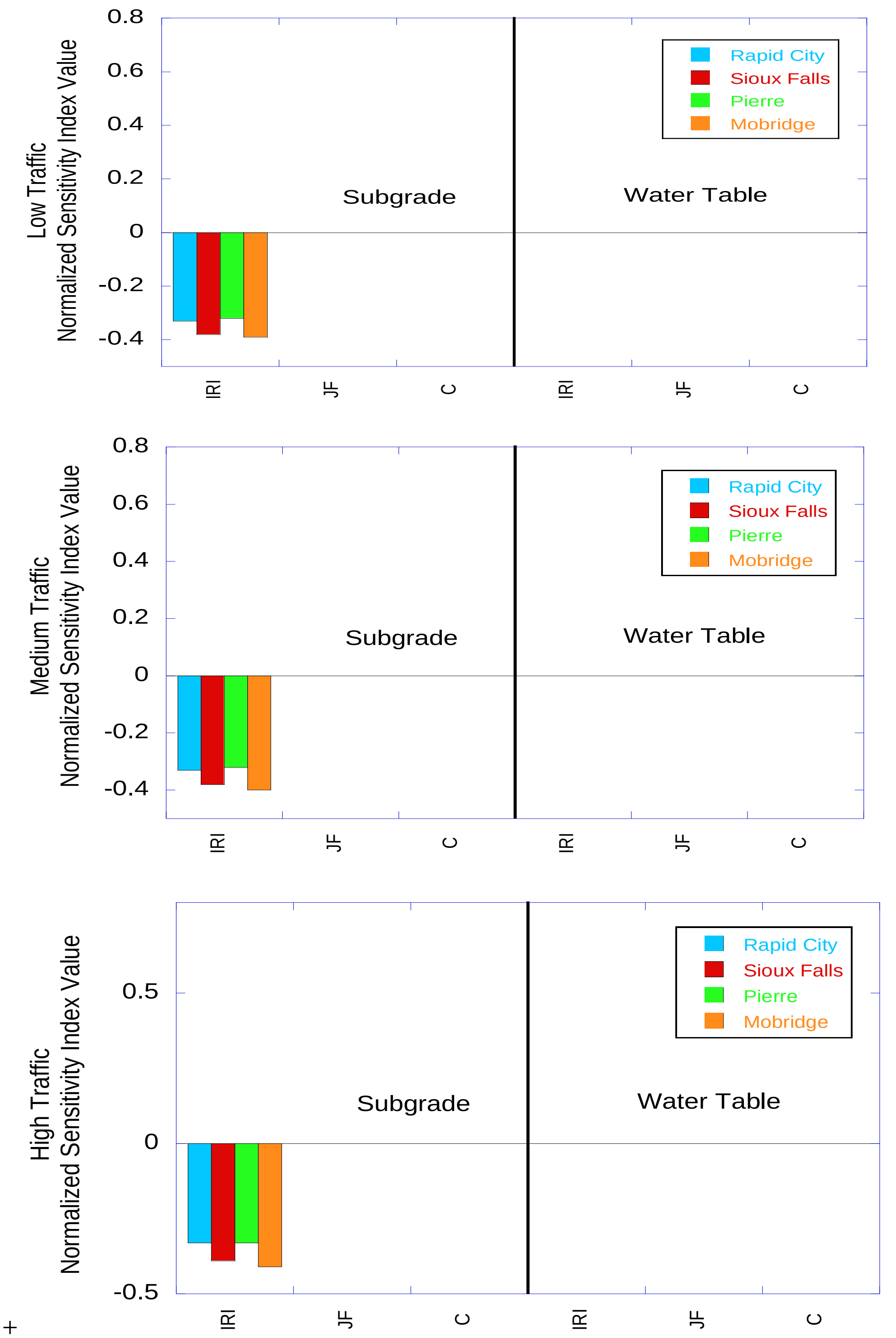

Figure 4.6. Sensitivity analysis for JPCP (subgrade and groundwater table). IRI: International Roughness Index, JF: Joint Faulting, C: Transverse Cracking.

4.4 Task 4 – Assess the adequacy of climate and groundwater data currently embedded in the MEPDG Software

One of the main goals for this study is to determine which weather data source should be used for future pavement performance analyses. Three aspects should be considered: spatial coverage, data quality, and total time duration. There are 11 ground-based weather stations in South Dakota provided with the MEPDG software which are mainly located on the eastern part of the state. Figure 4.7 shows the distribution of these stations. As shown in Figure 4.7, the spatial coverage of the data included with the MEPDG software is very low and use of this data for pavement performance predictions that are far from these stations may lead to significant over or under pavement design. In addition, the MEPDG requires a minimum of 2 years of continuous climate data; this may not well-represent the climatic conditions for a particular location, since in any given year a particular season can be unusually warm or cold or have above or below average precipitation. Even 10 years of data may be highly sensitive to outliers and may not be sufficient to represent the climatic conditions at a specific project site. This research found out that average of 8.9 years of climate data was collected from these 11 stations. These findings indicate that the 11 stations included in the MEPDG software are not sufficient to represent the climatic conditions of the entire state due to low spatial coverage areas and insufficient time duration. Therefore, the research team investigated the other alternative climate data sources, including ground-based weather station (GBWS), environmental sensing stations (ESS), and NASA's Modern-Era Retrospective Analysis for Research and Applications.

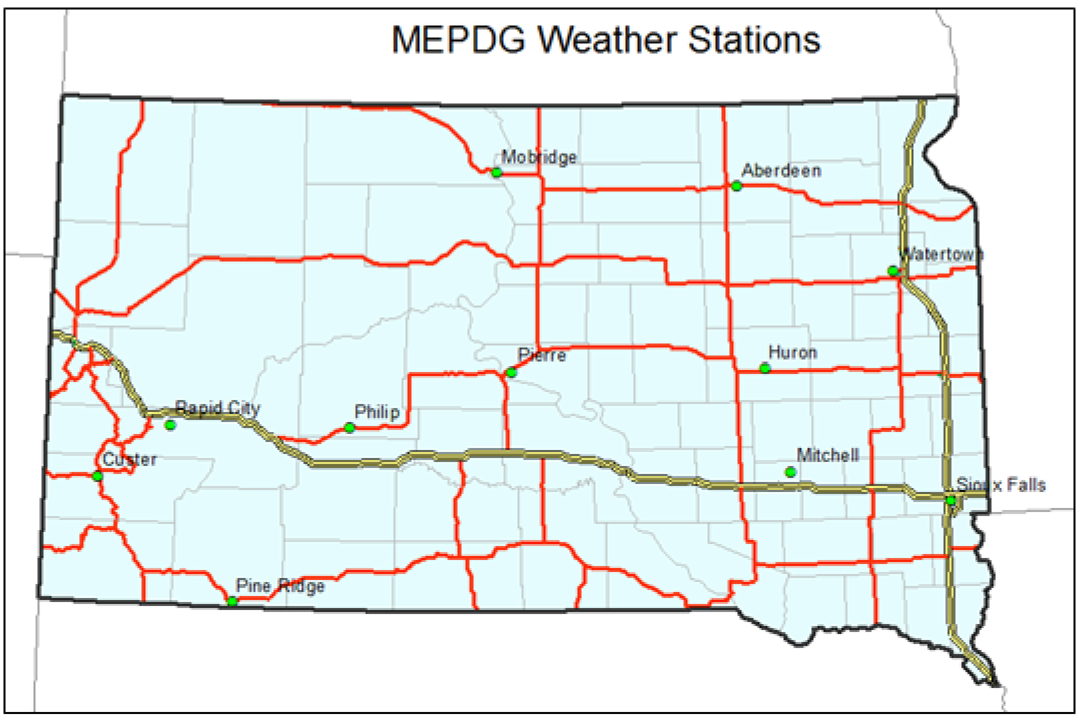

Figure 4.7. Locations of weather stations in South Dakota embedded in the MEPDG software.

4.5 Task 5 - Identify other existing sources of climate and groundwater data to evaluate the availability and quality of data for use in M-E design.

Under this task, the research team accomplished the first objective. The team investigated NASA`s Modern-Era Retrospective Analysis for Research and Applications (MERRA) product and climate data collected from ground-based weather stations throughout South Dakota as alternative climate data sources to be used as inputs in the MEPDG analysis. Then, the pavement performance predictions from the MEPDG analysis conducted with MERRA climate data were compared with those obtained using ground-based weather station data and climate data embedded in the MEPDG software. This process is summarized as shown in Figure 4.8.

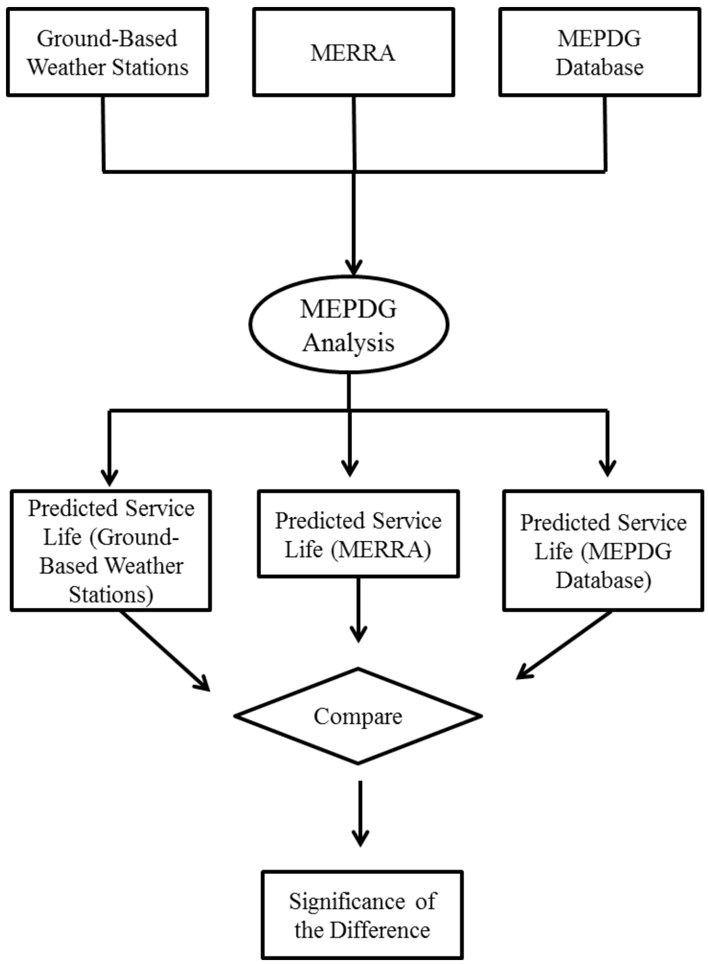

Figure 4.8. Schematic diagram of the MEPDG pavement design approach by MERRA, ground-based weather stations and MEPDG data.

Alternative Climate Data Sources

Four weather data sources were investigated in this study: (1) climate data embedded in the MEPDG software; (2) ground-based weather stations (GBWS); (3) Environmental Sensing Stations (ESS); and (4) NASA Modern-Era Retrospective Analysis for Research and Applications (MERRA). Each weather data source must include hourly air temperature, wind speed, percent sunshine, precipitation, and relative humidity data. The environmental sensing stations were eliminated from further consideration after preliminary research due to lack of percent sunshine data in the entire climate data sets.

Climate Data Embedded in the MEPDG Software

The first weather data source evaluated was supplied with the Mechanistic-Empirical Pavement Design Guide (MEPDG) software. It consists of 11 stations throughout South Dakota. The data is provided by the National Climate Data Center using the Unedited Local Climatological Data (ULCD) and the Quality Controlled Local Climatological Data (QCLCD). The MEPDG developers performed some quality control on ULCD and QCLCD for use with the MEPDG software. There are still some measurement errors, data errors, and very small gaps despite the quality control checks done. The average time period available with MEPDG weather data is 8.2 years for South Dakota stations. The MEPDG weather data was used in a sensitivity study to determine how small changes in each weather parameter affect the pavement performance parameters. Table 4.4 summarizes the meteorological data used in this study from all climate data sources described in the subsequent sections.

Table 4.4. Meteorological data used in this study from each climate data source.

Input Data	GBWS	MEPDG	MERRA
Air Temperature	X	X	X
Relative Humidity	X	X	X
Wind Speed	X	X	X
Precipitation	X	X	X
Shortwave Radiation			X
Cloud Cover Fraction[1]		X	X
Sky Condition[2]	X		
X = measurement/estimate is available at the majority of locations. 1 = cloud cover fraction serves as a proxy for shortwave radiation. 2 = sky condition serves as a proxy for cloud cover fraction, and hence, shortwave radiation.			

Climate Data from Ground-Based Weather Stations (GBWS)

The second weather data source is ground-based weather stations (GBWS). This network consists of 47 weather stations typically found at local airports. This network has limited quality control on the weather data. There are several gaps in the data varying from hours to days to months. The average time period available with GBWS weather data is 12.9 years.

The majority of the GBWS are located at local airports, and hence, they are mostly located in the eastern and southern part of South Dakota. There are not an adequate number of stations to represent the climatic conditions in the northwestern part of the state. Figure 4.9 shows the geographical distributions of the GBWS in South Dakota and nearby states. GBWS data possess significant data quality issues. 11 of 47 GBWS could not be used as an input data since either relative humidity or percent sunshine data have not been measured in these stations.

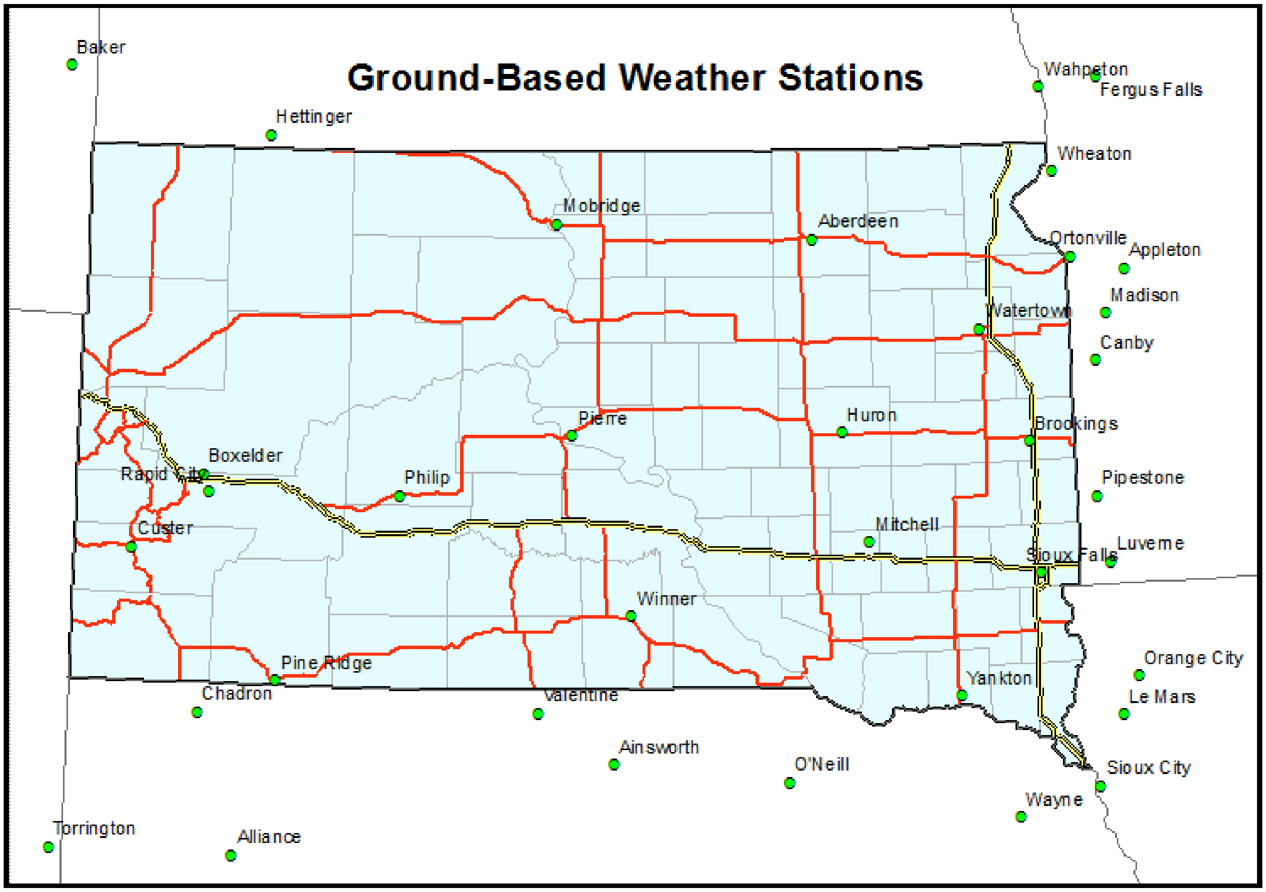

Figure 4.9. Locations of ground-based weather stations in South Dakota and nearby states.

In addition, the data quality of GBWS is very poor. In some cases, particular data are missing and there are large gaps (monthly, weekly, daily) in the climate data. Each station has a significant amount of hourly gaps. Table 4.5 summarizes the missing climate data percentages in the GBWS of South Dakota. Appendix B provides the detailed information regarding missing data in GBWS in South Dakota. The following methodology was used to fill the gaps in GBWS so that they could be used in MEPDG analyses:

1. GBWS is eliminated if it has 100% missing data.
2. If the GBWS is missing data for more than 24 consecutive hours, then the time period that has the highest continuous data was used as an input during pavement performance predictions.
3. Hourly gaps in GBWS data were filled using linear interpolation.

Table 4.5. Summary of the data gaps in ground-based weather stations in South Dakota

GBWS	City	State	Temperature Percent Missing	Wind Speed Percent Missing	Sunshine Percent Missing	Precipitation Percent Missing	Relative Humidity Percent Missing	Total Percent Missing
Q4918	Madison	MN	6.5%	6.2%	7.0%	8.0%	8.2%	7.2%
Q4922	Wheaton	MN	6.1%	6.1%	6.4%	7.9%	7.8%	6.9%
Q4942	Le Mars	IA	11.3%	11.3%	11.4%	10.8%	12.9%	11.6%
Q4957	O'Neill	NE	6.2%	6.0%	6.0%	8.1%	7.8%	6.8%
Q4959	Orange City	IA	11.6%	11.5%	11.8%	11.3%	13.1%	11.9%
Q4965	Pipestone	MN	7.5%	7.4%	8.4%	8.0%	9.1%	8.1%
Q4982	Ortonville	MN	6.3%	6.4%	6.8%	8.0%	8.0%	7.1%
Q4990	Garretson	SD	7.8%	13.1%	100.0%	9.6%	100.0%	46.1%
Q14929	Aberdeen	SD	0.5%	0.5%	0.5%	2.3%	0.5%	0.8%
Q14936	Huron	SD	0.7%	0.8%	1.1%	4.3%	2.7%	1.9%
Q14943	Sioux City	IA	1.2%	1.0%	1.1%	2.7%	1.2%	1.4%
Q14944	Sioux Falls	SD	0.5%	0.3%	0.5%	2.3%	0.6%	0.8%
Q14946	Watertown	SD	0.7%	0.6%	0.7%	2.3%	0.7%	1.0%
Q24006	Boxelder	SD	10.2%	4.4%	6.1%	6.5%	10.5%	7.5%
Q24017	Chadron	NE	1.2%	0.7%	0.7%	2.9%	1.3%	1.4%
Q24024	Philip	SD	0.9%	0.9%	1.1%	2.6%	1.0%	1.3%
Q24025	Pierre	SD	8.5%	4.7%	8.1%	26.4%	24.7%	14.5%
Q24032	Valentine	NE	1.0%	1.0%	1.1%	2.8%	1.0%	1.4%
Q24044	Alliance	NE	0.9%	1.0%	0.9%	2.3%	0.9%	1.2%
Q24090	Rapid City	SD	0.8%	0.6%	0.7%	2.4%	1.0%	1.1%
Q54917	Appleton	MN	2.7%	2.7%	3.0%	5.1%	3.9%	3.5%
Q54922	Wahpeton	ND	4.2%	3.4%	7.5%	5.6%	5.5%	5.2%
Q54923	Canby	MN	2.6%	2.8%	2.7%	5.6%	3.2%	3.4%
Q54925	Wayne	NE	2.6%	2.3%	2.4%	5.6%	3.0%	3.2%
Q54926	Luverne	MN	1.9%	1.9%	1.9%	5.6%	2.1%	2.7%
Q54933	Leola	SD	6.2%	11.7%	100.0%	5.6%	100.0%	44.7%
Q94032	Custer	SD	1.4%	1.4%	1.7%	3.4%	1.6%	1.9%
Q94037	Buffalo	SD	2.6%	2.7%	100.0%	4.4%	3.0%	22.5%
Q94038	Hettinger	ND	1.2%	1.4%	1.2%	2.8%	1.3%	1.6%
Q94039	Pine Ridge	SD	1.9%	1.8%	2.2%	3.5%	1.9%	2.3%
Q94052	Mobridge	SD	1.2%	1.1%	1.2%	3.0%	1.2%	1.5%
Q94053	Torrington	WY	2.7%	2.4%	2.5%	4.3%	2.8%	2.9%
Q94055	Baker	MT	1.8%	2.2%	2.0%	3.3%	1.8%	2.2%
Q94056	Faith	SD	2.8%	3.2%	100.0%	3.2%	3.2%	22.5%
Q94077	HWY 29	NE	8.5%	13.7%	100.0%	9.6%	100.0%	46.3%
Q94079	HWY 2	NE	9.2%	14.5%	100.0%	9.6%	100.0%	46.7%
Q94081	HWY 20	SD	8.6%	13.9%	100.0%	9.6%	100.0%	46.4%
Q94085	Vivian	SD	5.0%	10.4%	100.0%	5.6%	100.0%	44.2%
Q94088	Sundance	WY	4.8%	10.3%	100.0%	5.6%	100.0%	44.2%
Q94902	Brookings	SD	7.1%	6.5%	6.4%	8.0%	8.9%	7.4%
Q94911	Yankton	SD	9.3%	9.0%	8.6%	9.3%	11.0%	9.4%
Q94943	Chamberlain	SD	1.7%	1.5%	100.0%	3.2%	2.0%	21.7%
Q94950	Mitchell	SD	1.4%	1.4%	1.7%	3.4%	1.5%	1.9%
Q94966	Fergus Falls	MN	5.8%	5.8%	6.4%	7.7%	7.4%	6.6%
Q94975	Ainsworth	NE	5.5%	5.4%	5.5%	7.6%	7.2%	6.2%
Q94990	Winner	SD	4.5%	4.5%	4.2%	5.8%	4.6%	4.7%
Q94993	Sisseton	SD	1.6%	1.6%	100.0%	3.5%	1.9%	21.7%

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

The third weather data source is the Modern-Era Retrospective Analysis for Research and Applications (MERRA) product from the National Aeronautics and Space Administration (NASA). MERRA weather data is distributed in a grid spaced every 0.5 degrees latitude and every 0.67 degrees longitude and is provided at an hourly temporal resolution. MERRA weather data is derived using a physically based model along with atmospheric, oceanic, and satellite-based observations. The physically based model is named the NASA Goddard Earth Observing System Model Version 5 (GEOS-5). The MERRA product utilizes the Grid-point Statistical Interpolation (GSI) algorithm which is used to merge observations with a forecast (i.e., GEOS-5) model (Rienecker et al. 2011). In short, GSI computes the difference (or analysis increment) between the model and the observations. An Incremental Analysis Update (IAU) is then used to gradually apply the analysis increment to the forecast model, which has served to ameliorate precipitation "spin-down" during early stages of the forecast as well as significantly improved aspects of atmospheric circulation within the forecast model (Rienecker et al., 2011). For the MERRA product, the analysis is performed in 6-hour increments. The first 6-hour run is used to produce an "analysis tendency" called the "corrector" segment. The run is then continued without an analysis tendency for the next 6 hours. This is called the "predictor" segment. This cycle is then repeated (Rienecker et al., 2011). Figure 4.10 displays this IAU process. The updated model variables from the IAU process make up the variables ultimately provided in the MERRA product.

There are 70 MERRA grid points within South Dakota. MERRA has significant quality control checks to ensure continuity and consistency within the weather data (Schwartz et al. 2014). MERRA data has the longest time period available at 35 years. It is available since 1979 to present date.

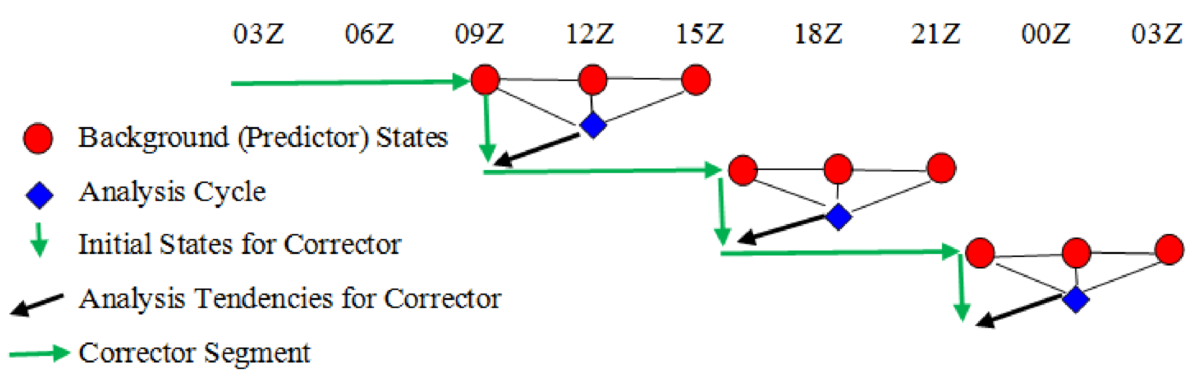

Figure 4.10. Incremental Analysis Update for MERRA

Elevation differences can result in differences in the measured air temperature. These differences are greatest in mountainous or complex terrain. Since not all MERRA measurement locations are at the same elevation as their ground-based counterparts, a correction needs to be made to the air temperature before comparing the two weather data sources. Where elevation differences exist, air temperature is adjusted using an adiabatic lapse rate. One of two lapse rates (γ) are used; -8°K/km when the ground station is higher than the MERRA elevation or -6.5°K/km when the ground station is lower than the MERRA elevation. The following equation is used for air temperature correction where T is air temperature and Δz is elevation difference.

$$T_{corrected} = T_{air} + \gamma * \Delta z \qquad \text{(Schwartz et al. 2014).}$$

Measurement Product Collocation

In order to compare measurements from one measurement network against another, it is first necessary to collocate the ground-based stations (i.e., GBWS and MEPDG) and MERRA prior to synchronizing the measurement sequences in time. The collocation process was conducted relative to the MEPDG station locations. That is, all computed distances treat the given MEPDG station as located at the center of the search area. Next, for a given MEPDG station, the horizontal distance was computed for every MERRA grid cell location as well as every GBWS in and near South Dakota. A minimum separation distance of 0.5 degrees (~50 km at mid-latitudes) was specified so each collocated set of ground-based observations and MERRA would be representative of the same local topographic and climate conditions. In addition, given the spatial resolution of the MERRA product, this guaranteed that at least one MERRA location (grid cell) would correspond to every available ground-based station location. Typical separation distances between the center of the MERRA grid cell and the collocated MEPDG station location ranged between 10 and 40 km. Separation distances between the GBWS and MEPDG stations are shown below in Table 4.6.

Comparisons of GBWS and MERRA Hourly Data

As part of this task the research team compared the MEPDG weather input data (air temperature, wind speed, percent sunshine, precipitation, and relative humidity) from ground-based weather stations to the nearest MERRA grid cell. The differences between the MERRA and GBWS data are generally small for hourly temperatures. Figure 4.11 shows a typical comparison of air temperature values for a location near Huron, South Dakota in which the MERRA data matches MEPDG data and captures the diurnal cycle quite well. The relative frequency plot in Figure 4.11 for all data between 1996 and 2007 at the same location shows that hourly air temperature estimates from MERRA match the MEPDG software data across both seasonal and annual time scales. There are somewhat larger discrepancies and anomalies for wind speed and percent sunshine (results not shown), but these weather inputs have less influence on pavement performance as predicted by the MEDPG.

Advantages of MERRA over Other Available Climate Sources

1. **Greater and more uniform spatial coverage area:** Unlike GBWS data that are compiled at irregularly spaced geographic locations, the hourly MERRA data are provided at a 0.5 degrees (latitude) by 0.67 degrees (longitude) horizontal spatial grid cell resolution (approximately 50 by 66 kilometers at mid-latitudes) and at multiple atmospheric elevations ranging from the ground surface up to the outer atmosphere. Figure 4.12 shows the spatial distribution of MERRA grid cells in South Dakota.

2. **Longer continuous climate data:** MERRA provides continuous hourly climate data from 1979 onwards while most suitable ground-based weather station data span only the last 10-20 years and often have gaps in the time series data.
3. **High quality data:** Unlike ground-based weather stations data, MERRA data do not require any additional quality checks since NASA performs rigorous and sophisticated quality checks for its own internal purposes.

Table 4.6. Distance between GBWS and MEPDG.

	MEPDG (closest)		MEPDG (second closest)	
GBWS	Station	Distance (miles)	Station	Distance (miles)
Winner	Pierre	72	Mitchell	94.1
Brookings	Watertown	46.7	Sioux Falls	50.2
Boxelder	Rapid City	7.3	Custer	38.7
Yankton	Sioux Falls	55.5	Mitchell	67.9
Alliance	Pine Ridge	68.1	Cheyenne	120.8
Sioux City	Sioux Falls	84.1	Estherville	108.4
Chadron	Pine Ridge	31.8	Rapid City	83.4
Valentine	Philip	97.7	Pierre	106.1
Hettinger	Hettinger	0	NA	NA
Baker	Dickinson	75.1	Miles City	78.1
Luverne	Sioux Falls	27.1	Estherville	75.1
Torrington	Torrington	0	NA	NA
Wayne	Sioux Falls	92.9	Mitchell	118.7
Canby	Watertown	45.7	Sioux Falls	83.1
Appleton	Alexandria	54.1	Watertown	59.6
Wahpeton	Fargo	48	Alexandria	63.3
Ainsworth	Pierre	125.5	Mitchell	128.2
Fergus Falls	Alexandria	45.9	Fargo	53.9
O’Neill	Mitchell	95.9	Sioux Falls	123.8
Wheaton	Alexandria	55.4	Watertown	65.9
Ortonville	Watertown	43.8	Alexandria	72.4
Madison	Watertown	48.3	Alexandria	72.4
Pipestone	Sioux Falls	36	Redwood Falls	71.7
Le Mars	Sioux Falls	62.2	Estherville	84.6
Orange City	Sioux Falls	53.8	Estherville	71.7
	Average	54.9	Average	82.3

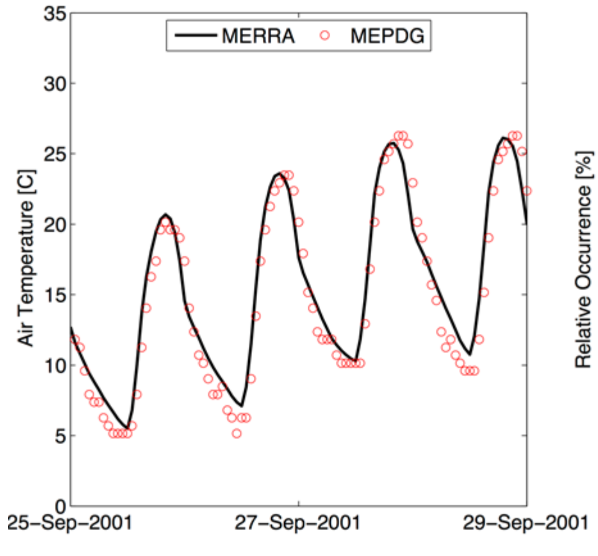

Figure 4.11. Air Temperature data comparisons between MERRA Data and MEPDG Data. Time series (left) and relative frequency distributions (right) highlight the agreement between MERRA and MEPDG across daily, season, and annual timescales.

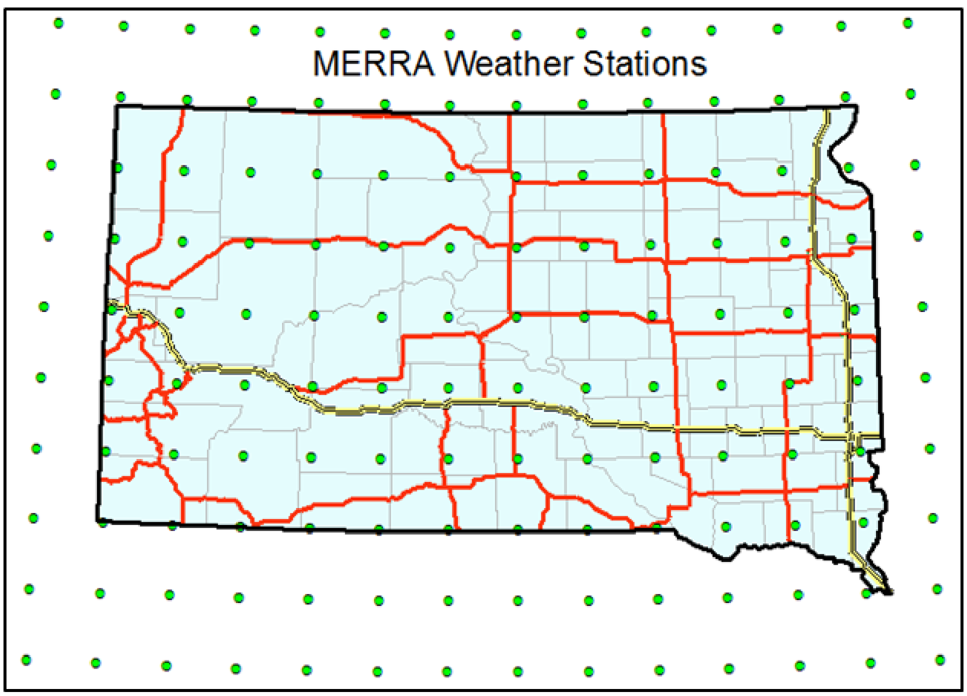

Figure 4.12. Locations of MERRA grid cell centers in South Dakota

Average Weather Data Comparisons

Figure 4.13 compares average annual air temperature, percent sunshine, wind speed, annual precipitation, and relative humidity between the three weather data sources for eleven of the stations embedded in the MEPDG software. MEPDG and GBWS were very comparable for air temperature. MERRA was consistently a few degrees warmer than the MEPDG and GBWS weather data. The GBWS wind speed is typically higher than the MEPDG wind speed while the MERRA data is lower.

The GBWS percent sunshine values are slightly higher than MEPDG data. MERRA percent sunshine is nearly ten percent lower than the MEPDG percent sunshine. It is important to mention that MERRA does not estimate percent sunshine directly, but instead computes downwelling radiation at the land surface, which is a more physically-based metric relative to percent sunshine. Percent sunshine is computed as a function of downwelling radiation along with some empirical coefficients derived from ground-based observations not located in South Dakota. Percent sunshine in the MEDPG weather data is derived from laser ceilometer measurements, but these include only lower atmosphere clouds. Therefore, it is not surprising that the percent sunshine values derived from the MERRA estimates do not exactly agree with the percent sunshine values obtained from the ground-based measurement networks.

In terms of precipitation, most stations were very comparable for average annual precipitation between the three data sources. The GBWS and MEPDG average relative humidity match very well. The MERRA relative humidity was lower than the MEPDG by up to ten percent. Differences between MERRA and the ground-based stations are due, in part, to spatial scale disparities (i.e., satellite-pixel scale versus ground-based point scale) as well as separation distances between the MERRA cell center and the ground-based station location, which at times was upwards of 30 km.

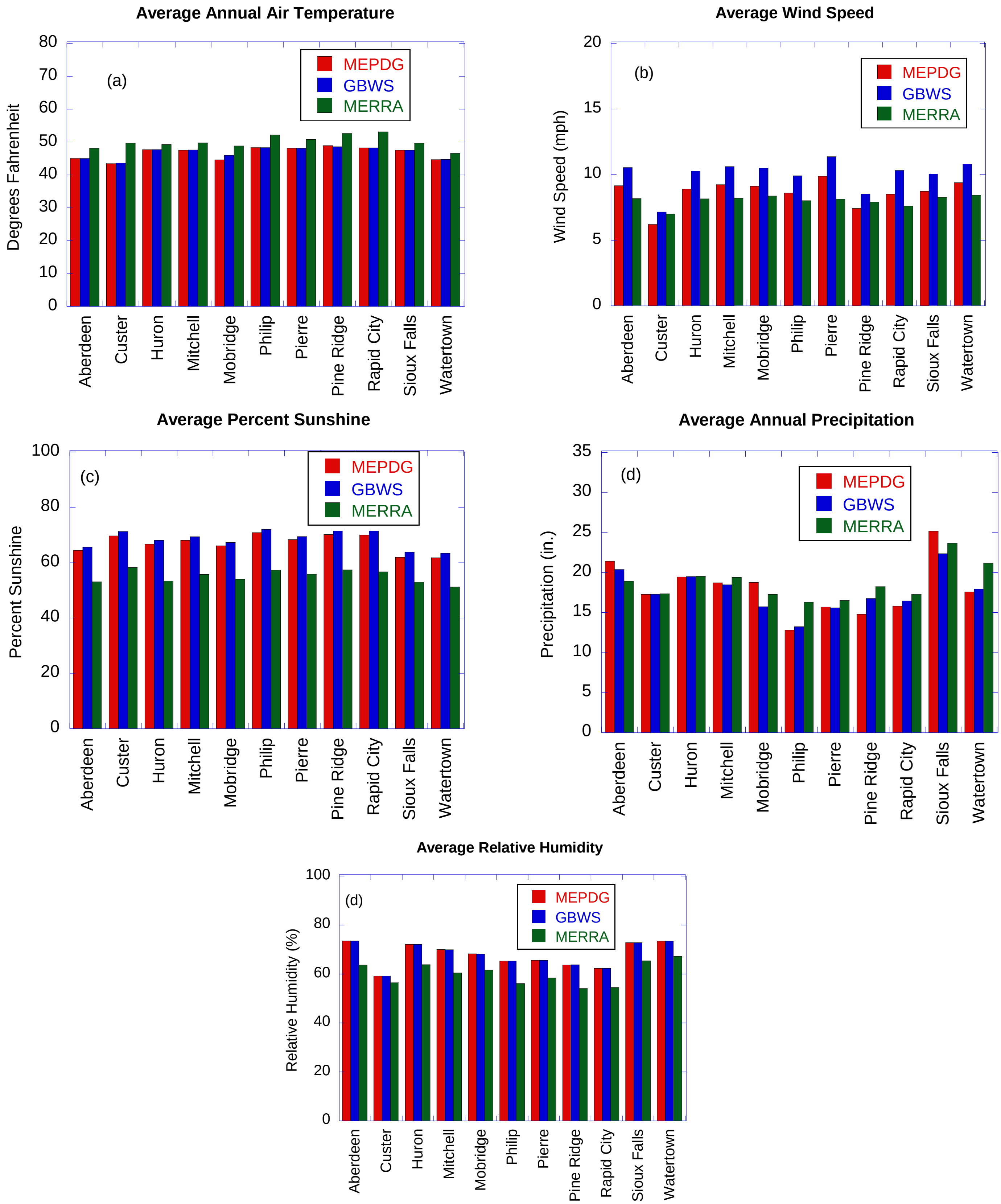

Figure 4.13. Comparisons of (a) air temperature, (b) wind speed, (c) percent sunshine, (d) annual precipitation, and (e) relative humidity from MEPDG, GBWS and MERRA sources.

Groundwater Data Collection

Locations of the groundwater monitoring wells were identified and evaluated to determine whether these wells can provide data that would be adequate for M-E pavement design. The quality and adequacy of the groundwater level data were checked via the criteria listed below:

1. Determine if the groundwater well monitoring data is well-distributed and uniform throughout South Dakota.

   There are 1572 groundwater monitoring wells recorded by the South Dakota United States Geological Survey (SD USGS) and South Dakota Department of Environment and Natural Resources. However, the majority of the wells are located in the southern and eastern parts of South Dakota. The western (northwestern in particular) side of South Dakota does not have adequate number of groundwater monitoring wells to represent the actual groundwater table level in these specific areas. Figure 4.14 shows the locations of the groundwater monitoring wells in South Dakota.

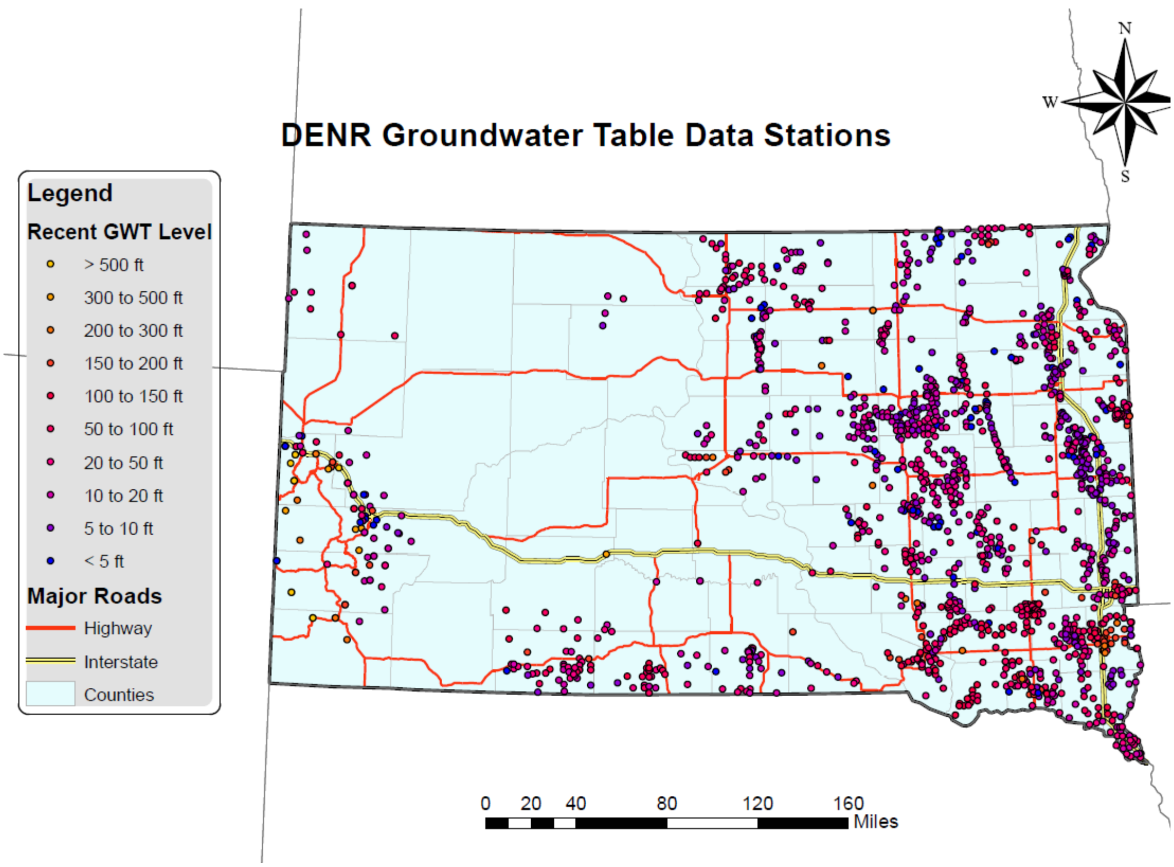

Figure 4.14. Locations of groundwater monitoring wells in South Dakota.

2. Determine the availability of groundwater and water elevation data for the entire state.

   Table 4.7 summarizes the well depths (ft), service years, average depths (ft), minimum depths (ft), and maximum depths (ft) of some of these groundwater monitoring wells. Data from all other monitoring wells were also downloaded and extracted and were provided along with this report in an Excel file.

Table 4.7. Limited sample of the groundwater monitoring wells in South Dakota.

USGS Groundwater Sites								
Site #	**Latitude**	**Longitude**	**County**	**Well Depth (ft)**	**Time in Service (years)**	**Minimum Depth (ft)**	**Maximum Depth (ft)**	**Average Depth (ft)**
430027102311801	43°00'27"	102°31'18"	Shannon	180	22	37.8	44.3	41.3
430027102311806	43°00'27"	102°31'18"	Shannon	835	25	34.3	66.0	41.1
430314100372001	43°03'14"	100°37'20"	Todd	140	3	46.6	47.7	47.4
430415100451501	43°04'15"	100°45'15"	Todd	150	3	20.2	21.2	20.5
431158100461002	43°11'58"	100°46'10"	Todd	263	2	82.4	89.3	85.3
433726096444501	43°37'26"	96°44'45"	Minnehaha	31.14	10	0.0	14.1	10.0
433752096432701	43°37'52"	96°43'27"	Minnehaha	35	10	0.4	10.6	7.3
434329096521201	43°43'29"	96°52'12"	Minnehaha	27.43	9	0.5	8.5	5.5
434330096434801	43°43'30"	96°43'48"	Minnehaha	29	27	0.2	10.0	5.3
440326103180702	44°03'26"	103°18'07"	Pennington	640	28	0.2	10.0	5.3
440544103180001	44°05'44"	103°18'05"	Pennington	175	14	8.0	64.1	33.2
440544103180002	44°05'44"	103°18'05"	Pennington	826	25	0.0	73.2	36.8
441759103261201	44°18'00"	103°26'12"	Meade	302	32	0.0	62.9	3.9
441759103261202	44°17'59"	103°26'12"	Meade	840	24	0.0	55.0	0.0
441759103261203	44°17'59"	103°26'12"	Meade	180	19	0.0	57.9	30.1
452115097110601	45°21'15"	97°11'09"	Roberts	21.6	32	12.1	14.8	13.6
452304097083901	45°23'04"	97°08'39"	Roberts	57.4	38	10.0	23.2	14.9
453358098260101	45°33'58"	98°26'01"	Brown	38	5.8	3.9	11.3	8.0
453515097083801	45°35'15"	97°08'38"	Roberts	19	19	1.3	8.5	4.6

3. Determine whether large gaps are present within the data collection times and determine whether spatial continuity of the data exists.

   There are large gaps in the majority of the monitoring groundwater wells data as shown in Figures in Appendix C with few examples. All this data can be found in the Excel file submitted along with this report. Moreover, as mentioned previously spatial continuity does not exist throughout the state.

4. Determine how long the data has been collected. Data collected less than 2 years will be classified as inadequate.

   All groundwater monitoring wells satisfy this requirement. However, there are large temporal gaps within the data for almost all of the monitoring wells.

5. Determine the depth of elevation that has been monitored. The monitoring wells that do not have water within 20 feet of the ground surface will not be used.

   Based on the data collected from groundwater monitoring wells in South Dakota, it could be concluded that majority of the monitoring wells satisfy this criterion. A few stations indicate that ground water level is very close to the ground surface, which could be very detrimental to pavement performance. However, it should be noted that these minimum depths that are lower than 2 feet below the ground surface typically only occur every 7-14 years. Some of these stations that had ground water table levels within 2 feet of the ground surface were located near surface water (river, water pond or lake). This may yield a significant rise in the groundwater table level for that particular location. Figure 4.15 shows the proximity of the locations of these stations that are located nearby surface waters.

Figure 4.15. Proximity of the locations of the few groundwater monitoring wells to the surface waters.

Comparisons of Predicted Pavement Performances

MEPDG analyses were conducted using climate data collected from 3 different sources. The goal of this comparison is to determine how well pavement performance agrees using the three climate data sources. Once the inputs were determined for each pavement system, the only thing changed was the climate data source. These sources include the data embedded in MEPDG, ground based weather station (GBWS) data, and MERRA data. The results were differentiated between flat or mountainous terrain. The locations considered mountainous for this study were Custer, SD; Philip, SD; Pierre, SD; Pine Ridge, SD; Rapid City, SD; Boxelder, SD; Chadron, NE; Baker, MT; and Torrington, WY. These locations were selected because of the result of the literature review where difference in elevation proved to have an impact on climate data impacting pavement performance.

Prediction analyses were completed in 2 phases. In the first phase, analyses were conducted to compare the pavement distresses results for the 11 weather stations that are supplied with the MEPDG software by comparing MERRA, GBWS and MEPDG weather station data. The locations of these stations are shown in Figure 4.16.

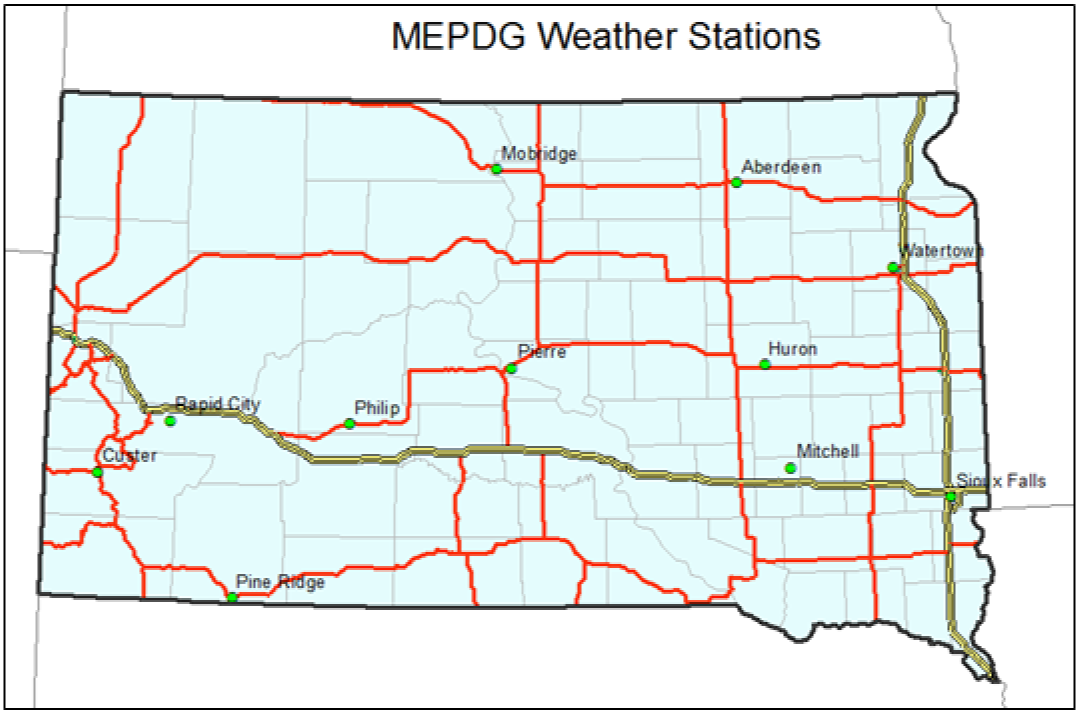

Figure 4.16. Locations of weather stations used for comparison analyses in the first phase.

In the second phase, comparison analyses were conducted for the 36 GBWS locations along with MERRA and MEPDG virtual weather stations. The locations of these stations were shown in Figure 4.17. Analyses were conducted for both AC and JPCP pavements using Version 2.0 of the Pavement ME Design® software. Input data of the pavement structures, traffic loads, materials properties, and other information are summarized in Tables 4.8, 4.9 and 4.10.

All GBWS data had missing data. Hourly gaps were filled using linear interpolation. Furthermore, GBWS data that had data gaps greater than a 24-hour period (daily gaps) were not used in the analyses. The longest period of time available in the GBWS data that did not have daily gaps was identified and MEPDG analyses were conducted on this period of time for the specific location. MEPDG and MERRA weather data corresponding to the same time period of the continuous GBWS data was used for comparison.

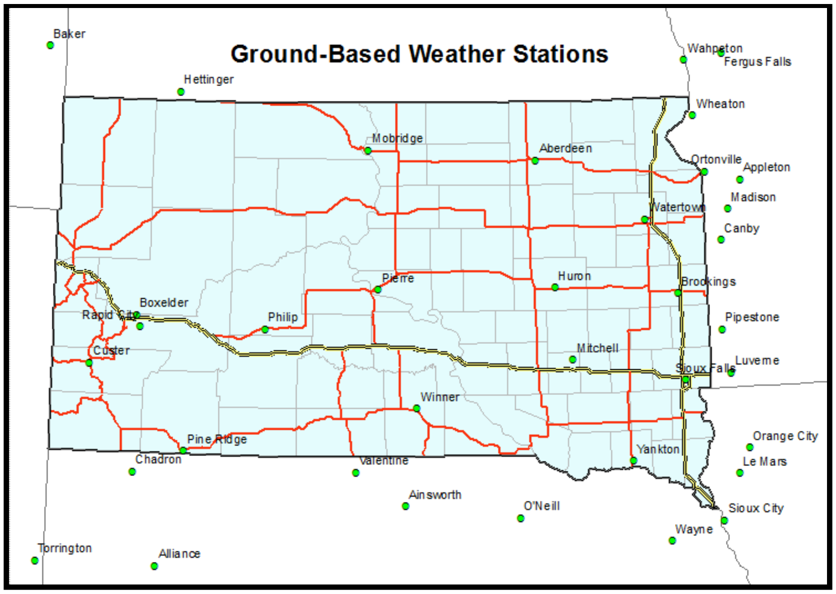

Figure 4.17. Locations of weather stations used for comparison analyses in the second phase.

Table 4.6. Traffic and pavement layer thickness for AC and JPCP pavement designs

Traffic Level for AC/JPCP	High
Nominal AADTT for AC	450
Nominal AADTT for JPCP	7,500
AC Thickness (in.)	6
Base Thickness for AC (in.)	7
JPCP Thickness (in.)	10
Base Thickness for JPCP (in.)	6

Table 4.7. AC and JPCP Pavement design properties

Input Parameter	Value
Design Life	10 years for flexible pavements 20 years for rigid pavements
Construction Month	June 2014
Reliability	90%
AADTT Category	Rural
Number of Lanes in Design Direction	1
Truck Direction Factor	50%
Truck Lane Factor	55%
Default Growth Rate	None
First Layer Material Type	Jointed Plain Concrete Pavement / Asphalt Concrete
Second Layer Material Type	Crushed Gravel
Subgrade Material Type	A-4
Base Resilient Modulus	25000 psi
Base Poisson's Ratio	0.35
*Subgrade Resilient Modulus	15000 psi
Subgrade Poisson's Ratio	0.35

Table 4.8. Surface layer properties for base cases in AC and JPCP pavement design.

		Value
Asphalt Properties	Surface Shortwave Absorption	0.85
	Unit Weight	149 pcf
	Poisson's Ratio	0.35
	Thermal Conductivity	0.67 (BTU/hr-ft-˚F)
	Heat Capacity	0.23 (BTU/lb-˚F)
	Effective Binder Content	7%
	Air Void	7%
	Binder Type	64-34
	Voids in Mineral Aggregate	14 (%)
Concrete Properties	Design Lane Width	12 feet
	Joint Spacing	15ft
	Dowel Diameter	1.25 in.
	Dowel Spacing	12 in.
	Erodibility Index	5
	Surface Shortwave Absorption	0.85
	Unit Weight	150 pcf
	Poisson's Ratio	0.2
	Coefficient of Thermal Expansion	5.5 (in./in./˚Fx10^{-6})
	Thermal Conductivity	1.25 (BTU/hr-ft-˚F)
	Cement Content	600 lb/yd^3
	W/C ratio	0.2

Comparisons of asphalt concrete (AC) pavement performance as predicted by the MEPDG using MEPDG vs. MERRA, MEPDG vs. GBWS, and GBWS vs. MERRA data are shown in Figures 4.18 and 4.19 for total rutting, AC rutting, alligator cracking, International Roughness Index (IRI), and thermal cracking. (Top-down longitudinal fatigue cracking was not considered because this model is generally viewed as unreliable.) Based on the Figures 4.18 and 4.19 following conclusions are drawn:

1. As demonstrated in Figure 4.18, in all cases the MERRA and MEPDG predictions are broadly similar, as shown by their location near the line of equality.
2. As shown in Figure 4.19, the GBSW data resulted in slightly lower pavement distresses than predicted using the MEPDG data. Table 4.11 shows the comparison of the data quality of the MEDPG weather stations and the GBWS, both of which were collected from the same weather stations. Figure 4.19 suggests that the MEPDG predictions could be different using the weather data supplied with the MEPDG software or from GBWS, even though the data were collected from the same source. This could be due to the higher level of quality checking and data cleanup performed on the MEPDG data by the Pavement ME Design® software developers.

Table 4.9. MEPDG Weather Station Data and GBWS Weather Station Data used in the pavement distress comparison analyses.

City	Statio ID #	MEPDG Weather Data		GBWS Weather Data			*Time Period (years)
		Start	End	Start	End	Total Missing Data (%)	
Aberdeen	14929	07/1996	02/2006	07/1996	02/2006	0.8	10
Custer	94032	04/1999	02/2006	08/2002	02/2006	1.9	4
Huron	14936	11/1996	02/2006	11/1996	02/2006	1.9	10
Mitchell	94950	09/1999	02/2006	09/2002	02/2006	1.9	4
Mobridge	94052	01/1998	02/2006	09/2002	02/2006	1.5	4
Philip	24024	07/1998	02/2006	07/1998	02/2006	1.3	8
Pierre	24025	09/2000	02/2006	09/2000	02/2006	14.5	6
Pine Ridge	94039	06/1997	02/2006	07/1997	08/2002	2.3	5
Rapid City	24090	07/1996	02/2006	11/1996	02/2006	1.1	10
Sioux Falls	14944	07/1996	02/2006	07/1996	02/2006	0.8	10
Watertown	14946	07/1996	02/2006	07/1996	02/2006	1	10

Similar analyses were also conducted on AC at 36 GBWS weather station locations. The comparisons here are between measured GBWS and virtual MEDPG weather station data, MERRA vs. MEPDG virtual weather station data, and MERRA vs. measured GBWS data. Figure 4.20 and 4.21 show the comparisons of the results for total rutting, AC layer rutting, alligator cracking, IRI and thermal cracking. The following conclusions were observed:

1. The results showed that total rutting, AC rutting and alligator cracking pavement distresses predicted via MERRA and MEPDG virtual stations at GBWS sites were close in value (Figure 4.20).
2. The predictions of IRI predicted via the three different climate sources were slightly different from each other. Figure 4.21 shows that there are discrepancies in the comparison of the IRI results calculated via GBWS and MEPDG virtual stations. In many cases IRI predictions calculated via MERRA resulted in closer values to the ones calculated via GBWS than the ones calculated via MEDPG virtual stations.
3. Predicted thermal cracking values via the three different climate sources aligned well with the respective lines of equality (Figure 4.21) with few exceptions.
4. Figures 4.20 and 4.21 show that the predicted pavement distresses are very similar when using MERRA and MEPDG virtual stations.

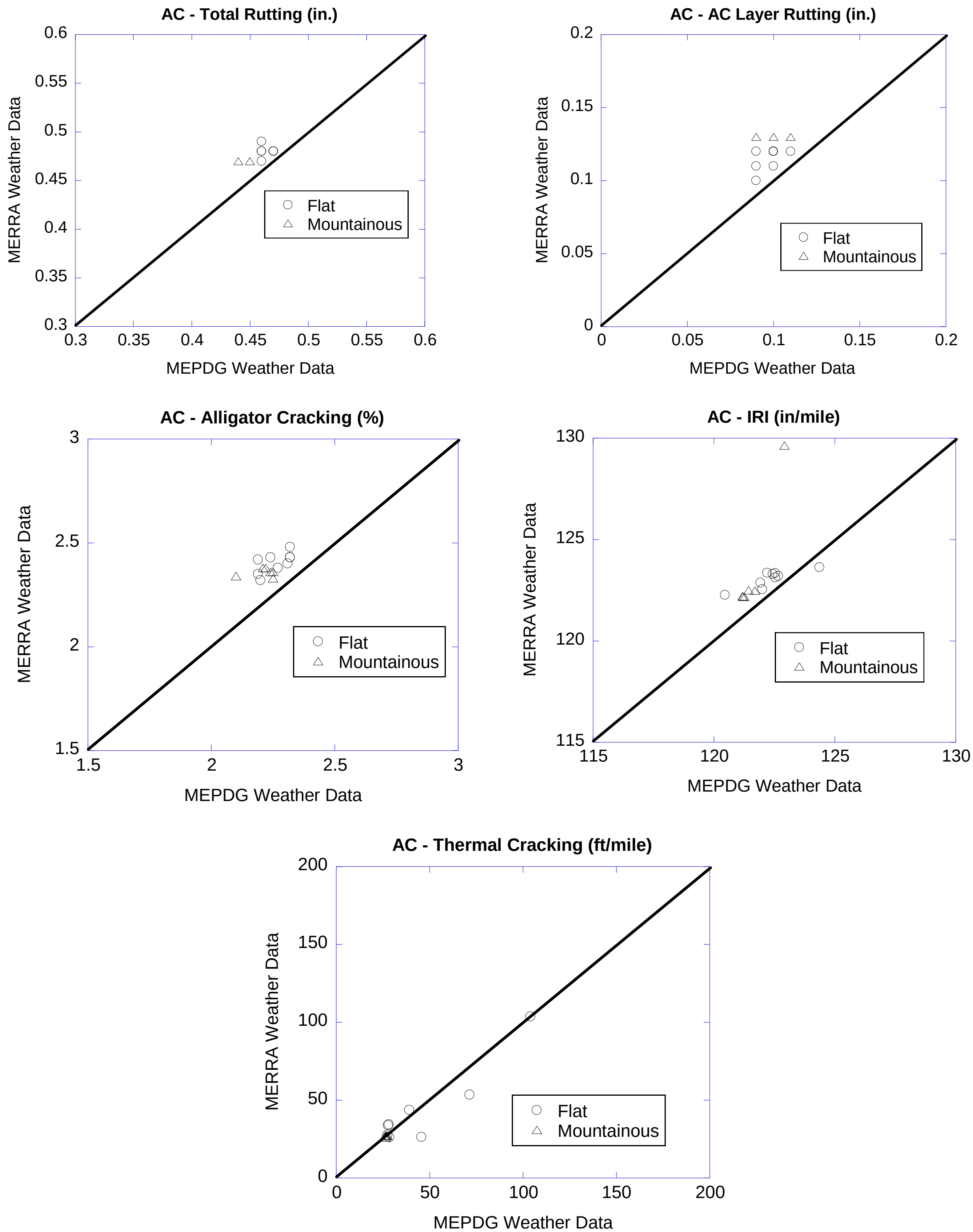

Figure 4.18. Comparisons of MEPDG asphalt concrete predictions for total rutting. AC rutting, alligator fatigue cracking, International Roughness Index (IRI), and thermal cracking using MERRA vs. MEPDG weather data.

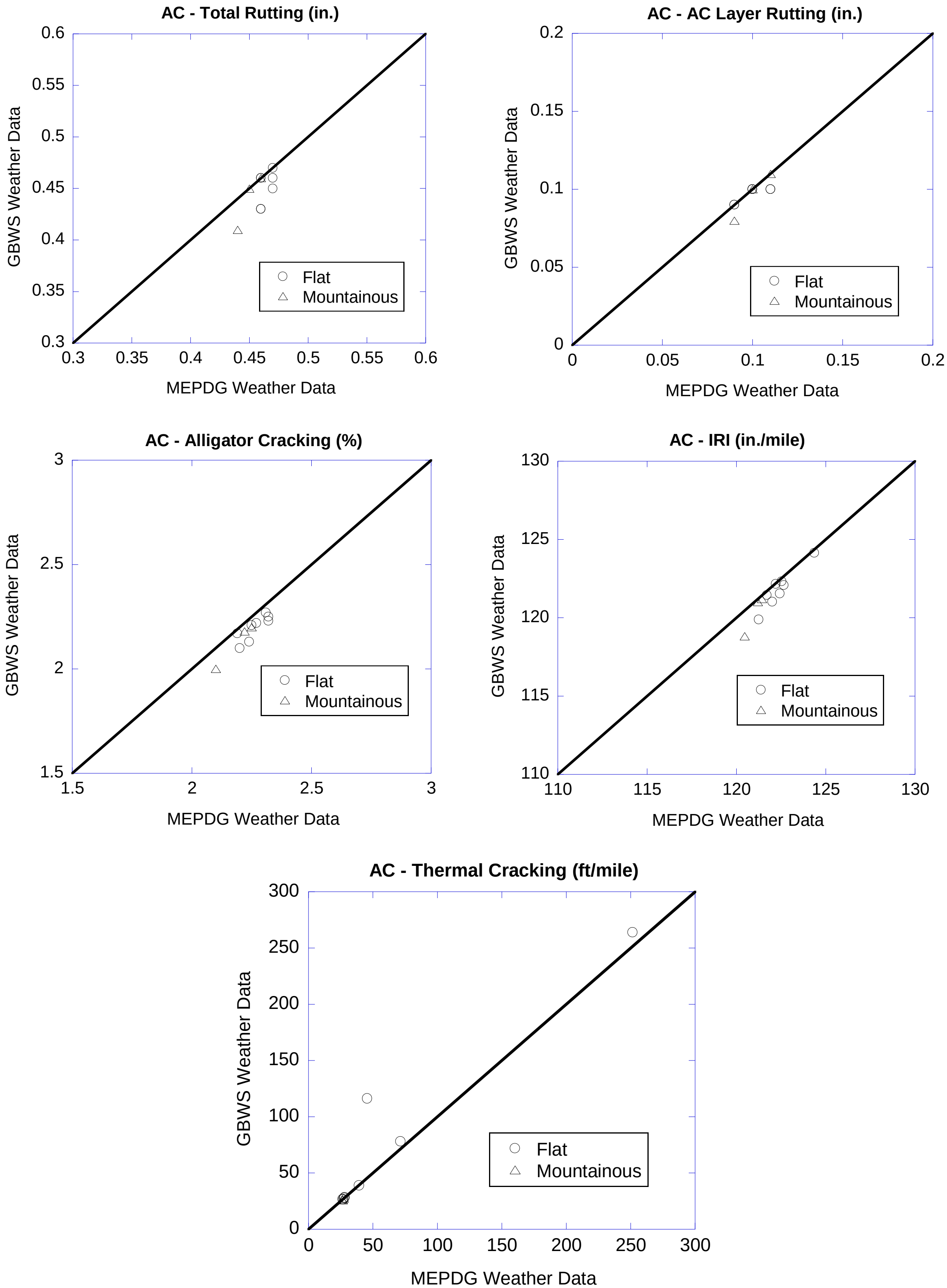

Figure 4.19. Comparisons of MEPDG asphalt concrete predictions for total rutting. AC rutting, alligator fatigue cracking, International Roughness Index (IRI) and thermal cracking using GBWS vs. MEPDG weather data.

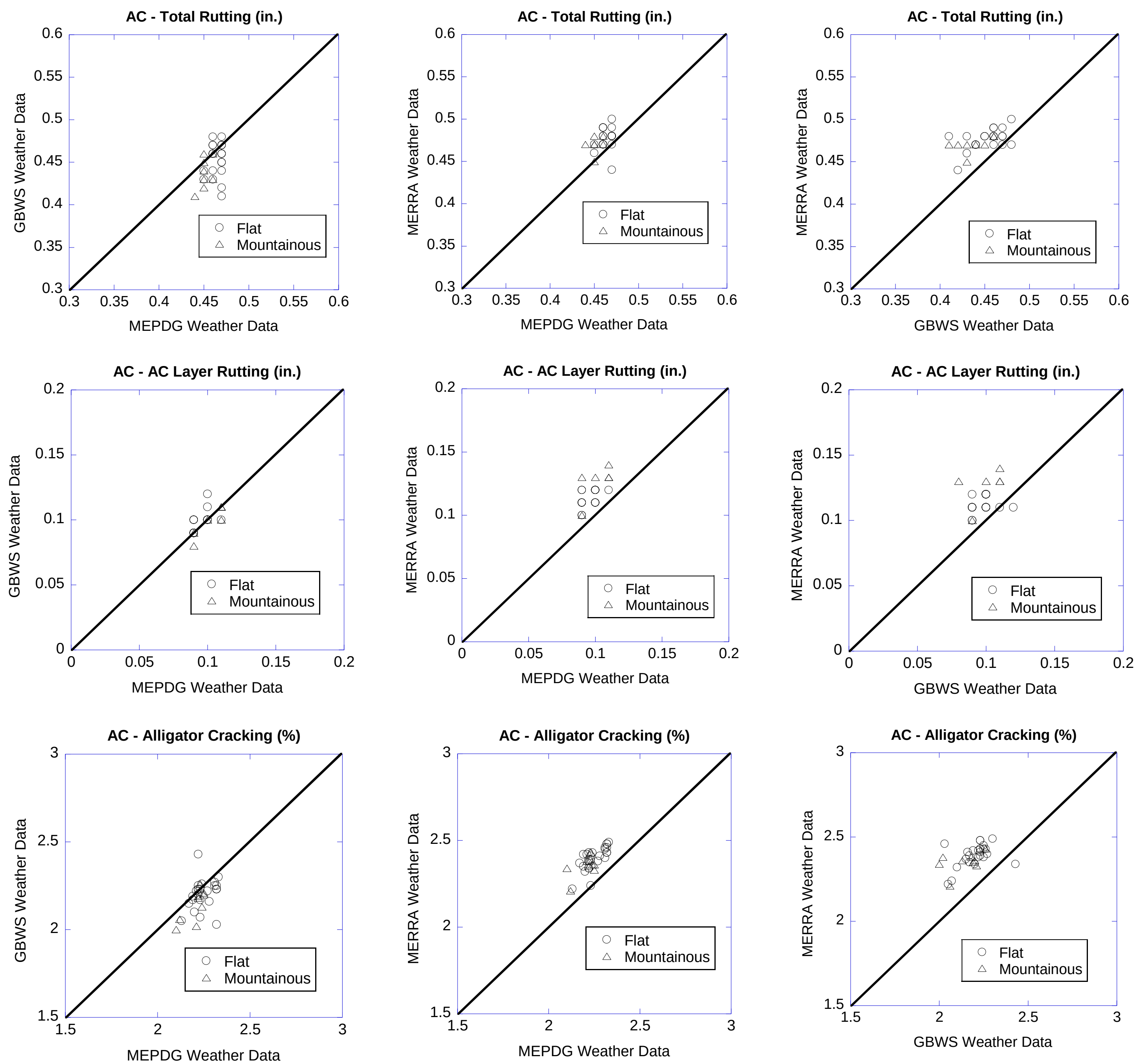

Figure 4.20. Comparisons of MEPDG asphalt concrete predictions for total rutting, AC rutting, alligator fatigue cracking, using GBWS vs. MEPDG weather data, MERRA vs. MEPDG weather data, and MERRA vs GBWS weather data.

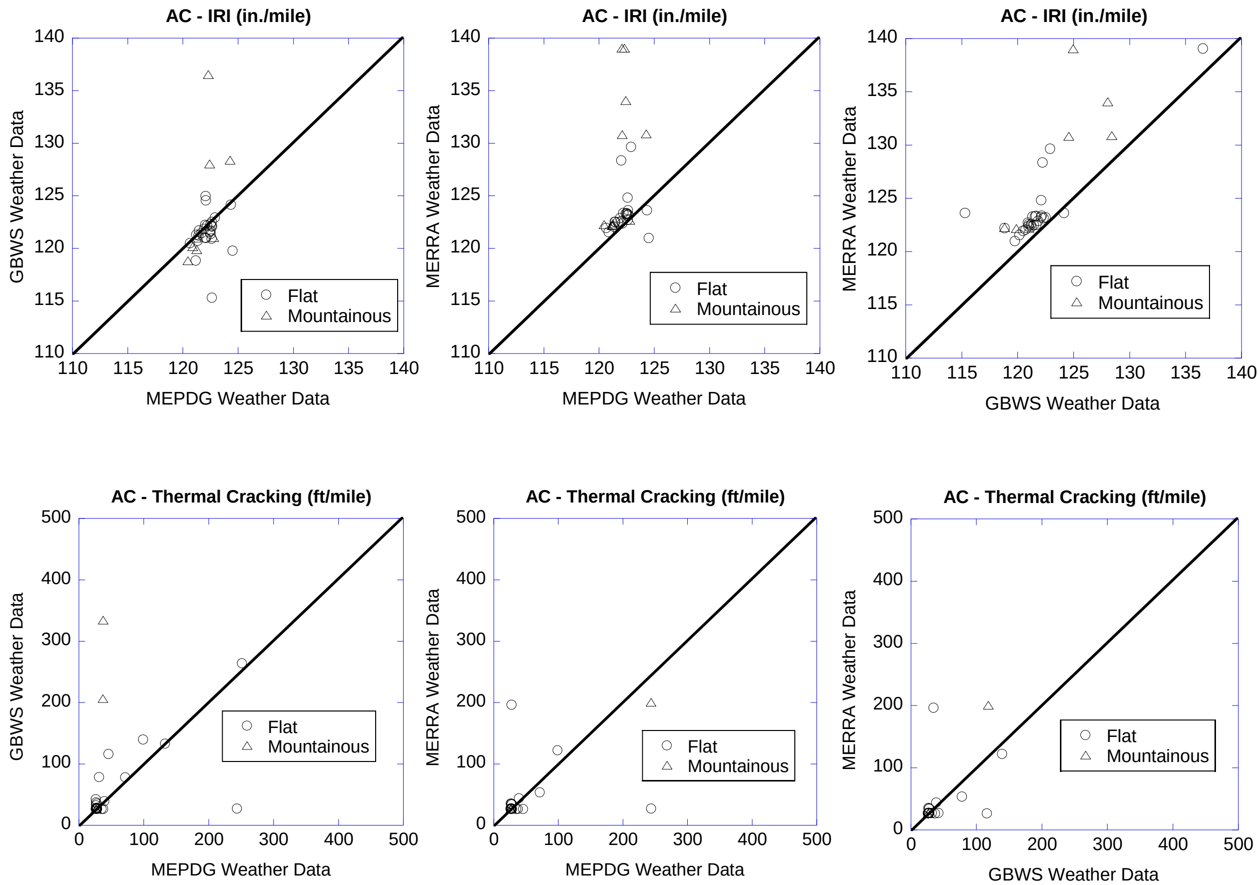

Figure 4.21. Comparisons of MEPDG asphalt concrete predictions for International Roughness Index (IRI) and thermal cracking using GBWS vs. MEPDG weather data, MERRA vs. MEPDG weather data, and MERRA vs GBWS weather data.

Comparisons of rigid JPCP pavement performance as predicted by the MEPDG using MEPDG vs. MERRA, MEPDG vs. GBWS, and GBWS vs. MERRA are shown in Figures 4.22 and 4.23 for transverse cracking, joint faulting, and International Roughness Index (IRI). Based on the Figures 4.22 and 4.23, the following conclusions are drawn:

1. In all cases, the MERRA and MEPDG predictions are similar in value, as shown by their location near the line of equality, and are in most cases clustered. However, the agreement among the three climate data cases for rigid pavements is slightly less than that observed for asphalt concrete pavements.
2. Figure 4.22 shows that the IRI values predicted using MERRA are slightly lower than those predicted using the MEPDG weather data. Joint faulting and transverse cracking pavement distresses predicted using MERRA were slightly higher than predicted using the MEPDG weather data.
3. Figure 4.23 shows that the GBWS climate data produced lower pavement distresses than predicted using the MEPDG weather stations. Similar trends were observed in the AC analyses as mentioned above. Also similar to the AC analyses, Figure 4.23 suggests that the MEPDG predictions could be different using the weather data supplied with the MEPDG software or from GBWS, even though the data were collected from the same source.

Similar analyses were also conducted on JPCP at 36 GBWS weather station locations. The comparisons here are between measured GBWS and virtual MEDPG weather station data, MERRA vs. MEPDG virtual weather station data, and MERRA vs. measured GBWS data. Figure 4.24 shows the comparisons of the results of the analyses for IRI, joint faulting and transverse cracking. The following conclusions were observed:

1. Figure 4.24 shows that the predicted IRI values comparisons between MERRA vs. MEPDG virtual stations, MERRA vs. GBWS, and GBWS vs MEPDG virtual stations were more scattered than for the AC pavements. This was expected, since it was previously determined that predictions of IRI in JPCPs were more sensitive to slight climate data changes than were joint faulting and transverse cracking.
2. Joint faulting predicted using MERRA was slightly lower than as predicted using MEPDG virtual stations and GBWS. In many cases, joint faulting predictions calculated using MERRA resulted in values similar to those calculated using GBWS and MEDPG virtual stations.
3. Overall, transverse cracking values predicted using MERRA aligned better than the ones calculated using MEPDG virtual stations and GBWS.

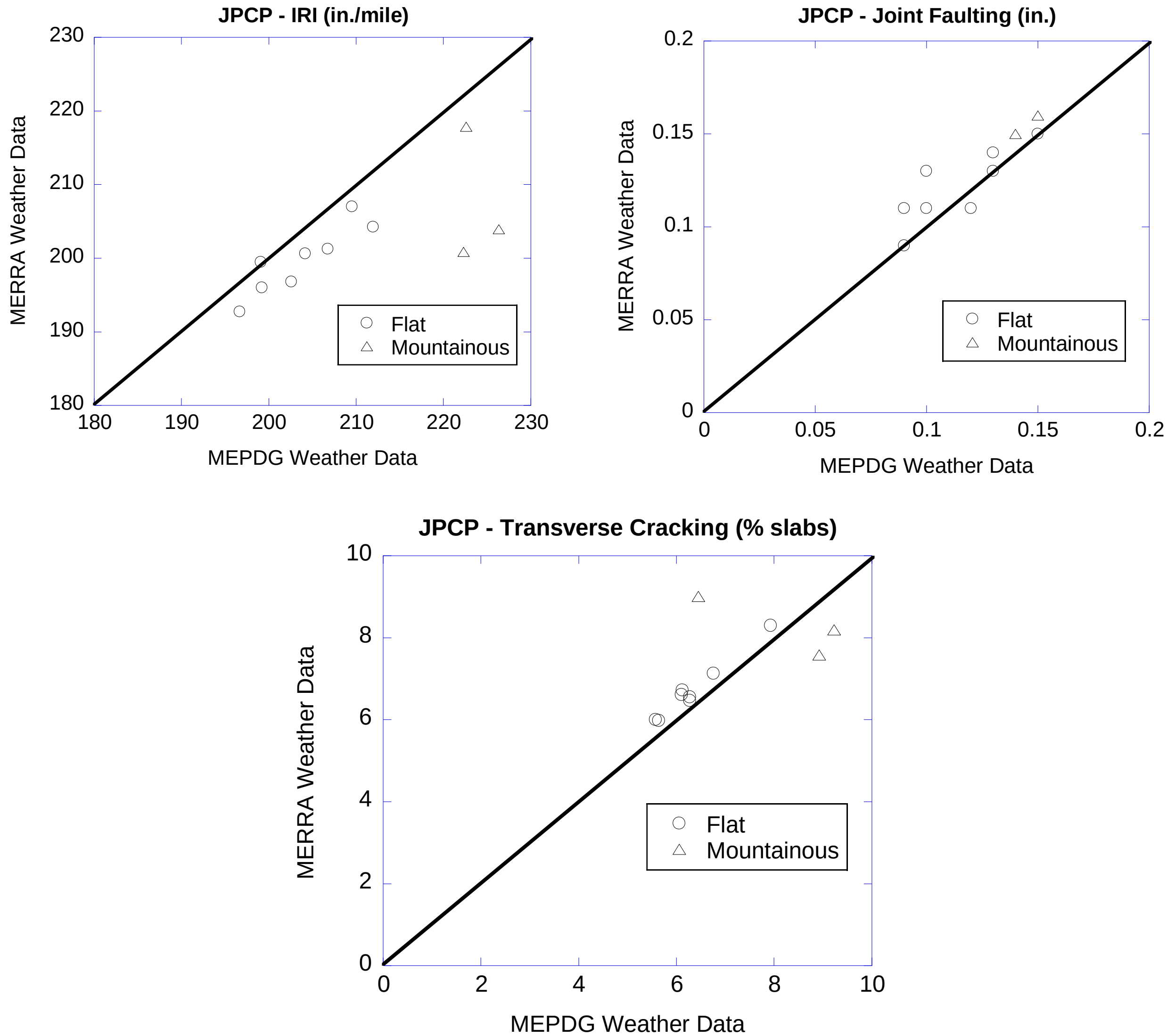

Figure 4.22. Comparisons of MEPDG JPCP predictions for International Index Roughness (IRI), joint faulting (in.) and transverse cracking (% slabs) using MERRA vs. MEPDG weather data.

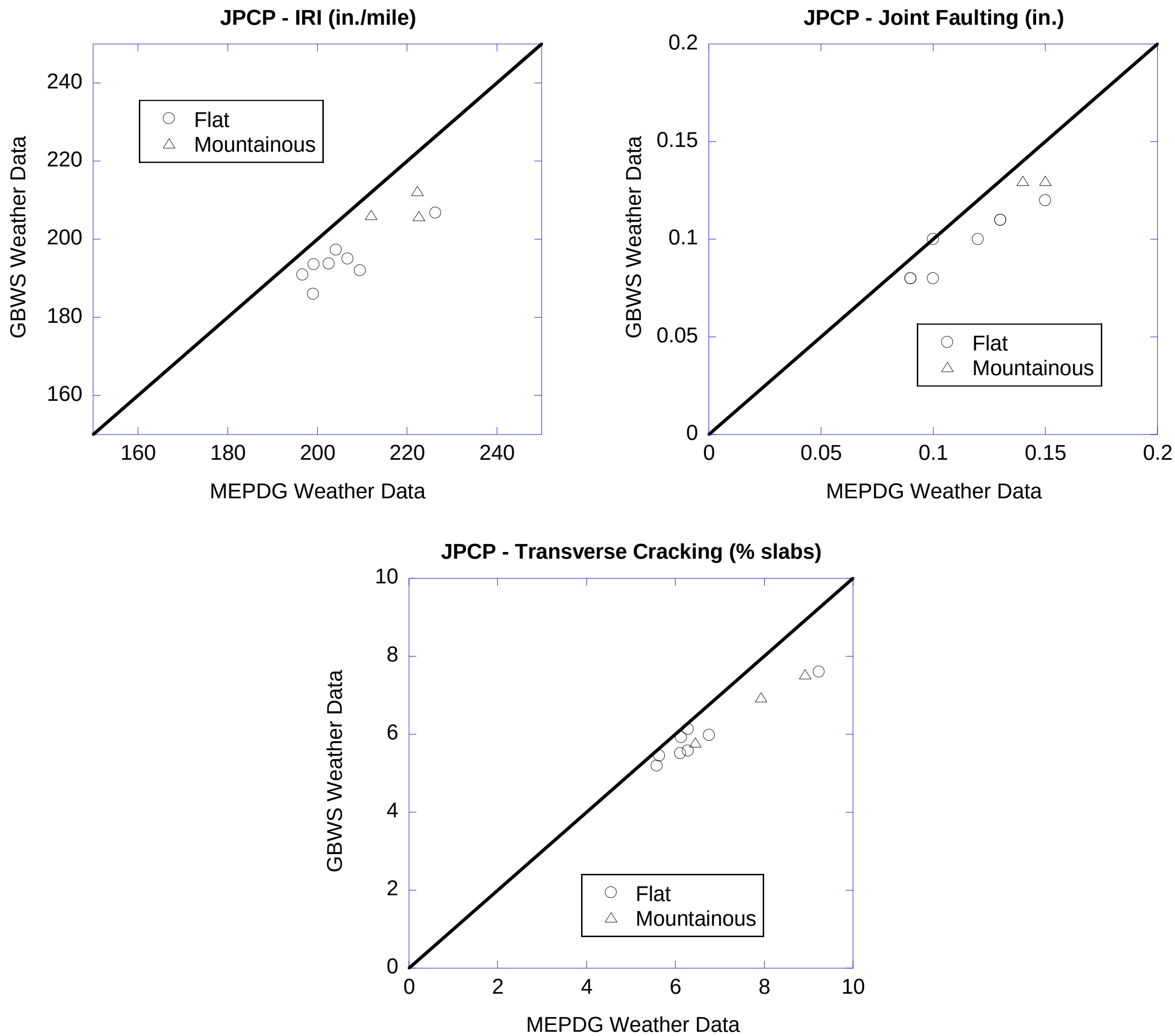

Figure 4.23. Comparisons of MEPDG JPCP predictions for International Index Roughness (IRI), joint faulting (in.) and transverse cracking (% slabs) using GBWS vs. MEPDG weather data.

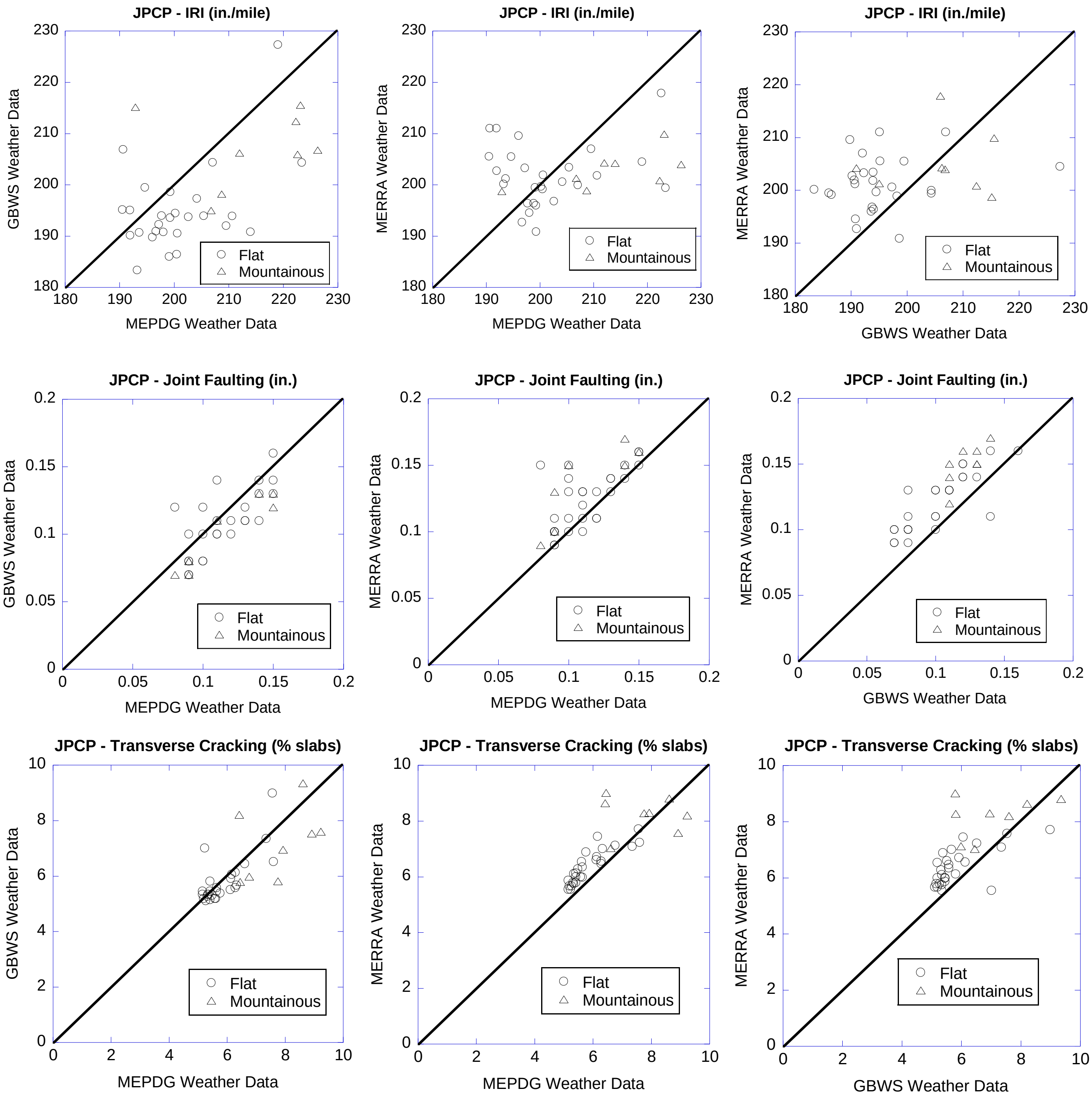

Figure 4.24. Comparisons of MEPDG JPCP predictions for International Index Roughness (IRI), joint faulting (in.) and transverse cracking (%slabs) using GBWS vs. MEPDG weather data, MERRA vs. MEPDG weather data, and MERRA vs GBWS weather data.

Discrepancies in the Predictions of Pavement Performance Calculated via GBWS and Virtual MEPDG Weather Stations

The GBWS data has significantly more stations than MEPDG. There are 25 additional GBWS stations where there are no MEPDG stations. In order to compare these, virtual weather stations needed to be created.. The MEPDG software can create a virtual weather station from stations selected based on their distance from the project site. Table 4.6 shows the nearest MEPDG stations and their distance to the respective GBWS. Pavement performance was determined for the 25 GBWS data for both asphalt and concrete pavement. The following set of graphs (Figures 4.25-4.32) compares the results from the GBWS and the virtual MEPDG stations. The top graph in each set was created using a virtual weather station from the two closest MEPDG stations. The middle graph uses the single closest MEPDG station for comparison. The bottom graph in each set uses the second closest MEPDG station for comparison.

Key findings from the GBWS vs. virtual MEPDG comparisons are as follows:

1. Results for IRI for JPCP were rather scattered. There were only a few stations that matched well. This may be due to the rather long distances between the GBWS and the nearest MEPDG station.
2. Joint faulting for JPCP matched fairly well. The top graph with the virtual weather station created from the two closest MEPDG stations compared the best of the three.
3. Results for transverse cracking for JPCP were quite similar between the three graphs.
4. Results for most asphalt pavement performance parameters showed little difference between the three methods. IRI, total rutting, alligator cracking, thermal cracking, and AC layer rutting changed very little between each method of using MEPDG data. IRI and thermal cracking had a few outliers, which may be due to the large distances between the GBWS and MEPDG stations.

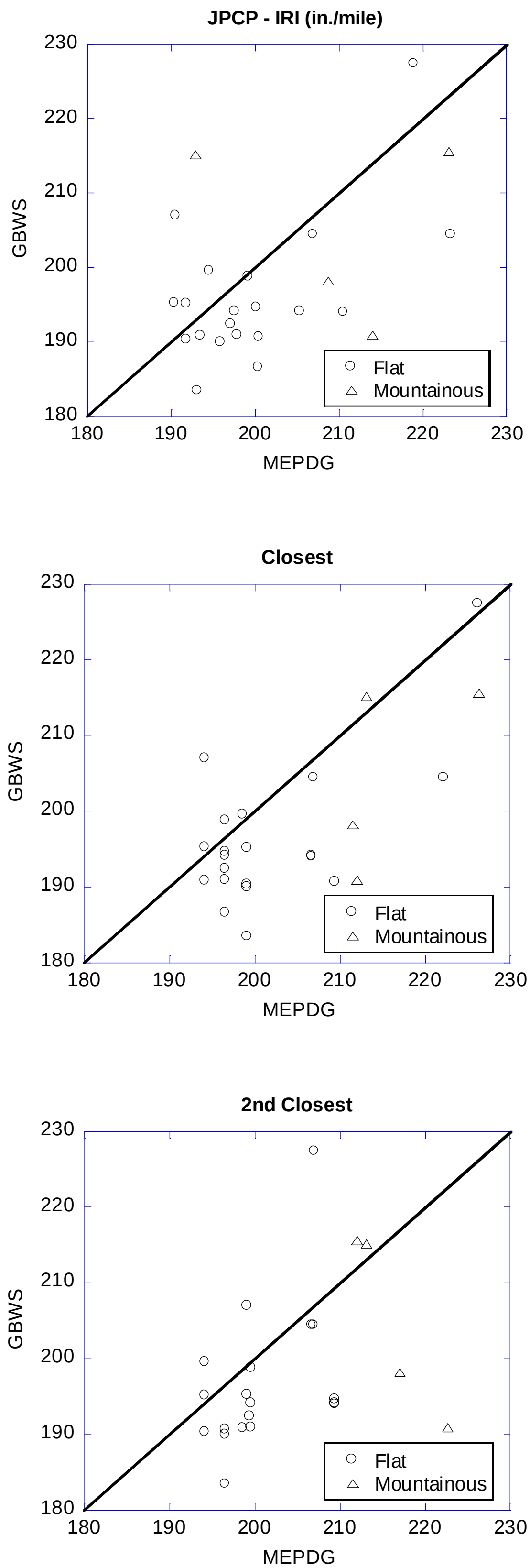

Figure 4.25.GBWS vs. Virtual MEPDG for JPCP IRI

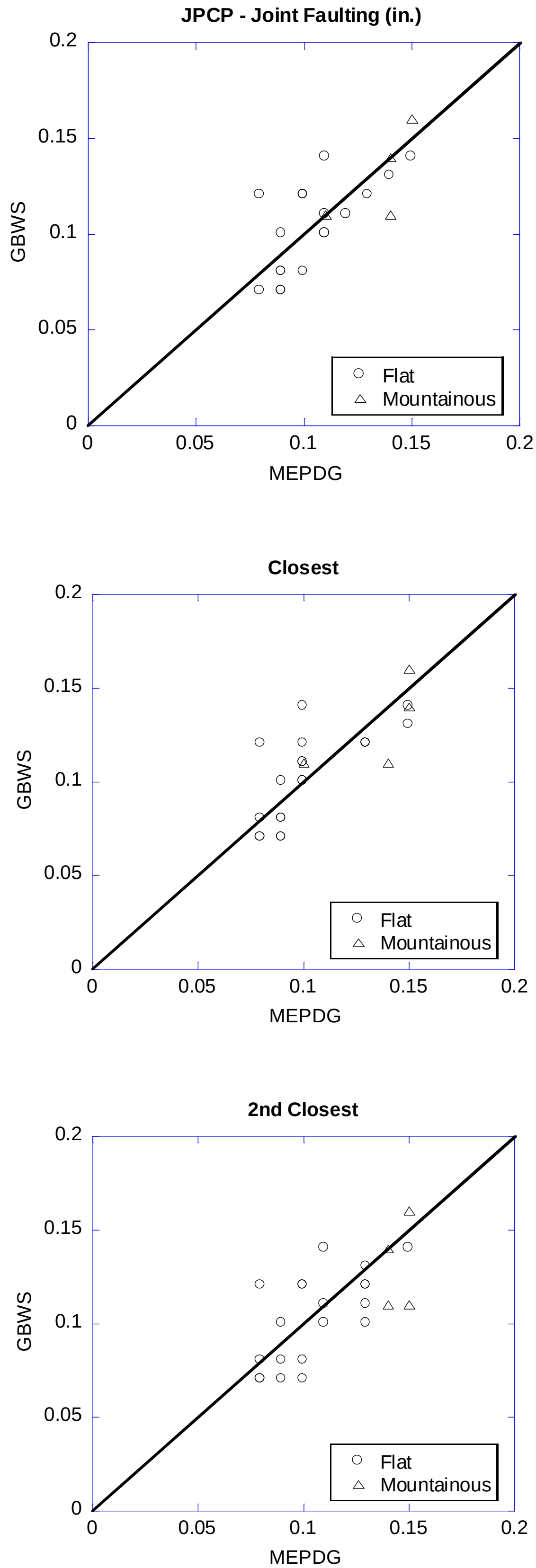

Figure 4.26. GBWS vs. Virtual MEPDG for JPCP Joint Faulting

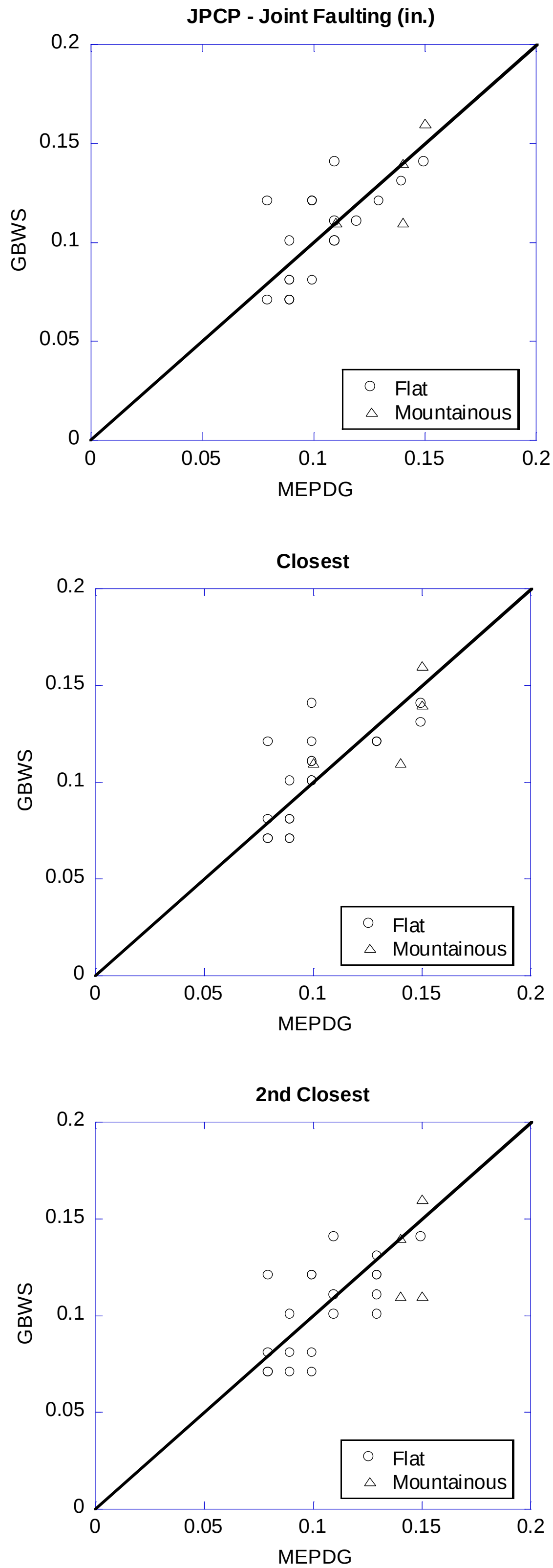

Figure 4.27. GBWS vs. Virtual MEPDG for JPCP transverse cracking

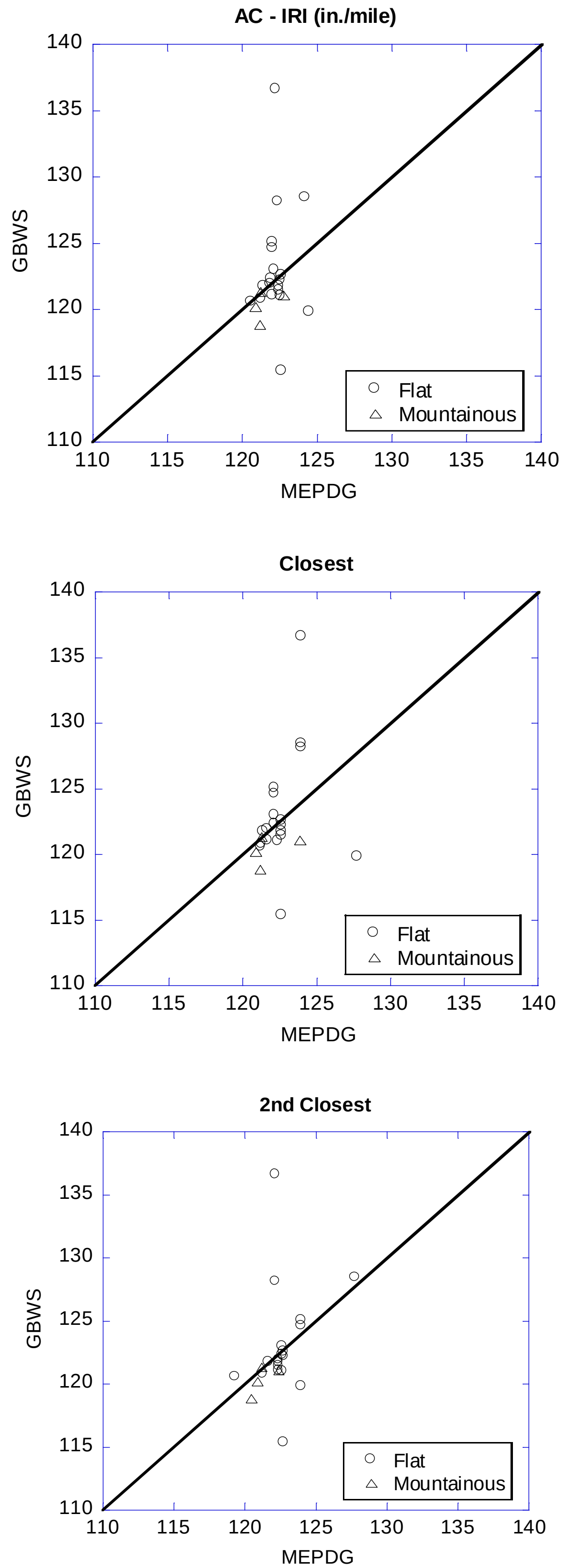

Figure 4.28. GBWS vs. Virtual MEPDG for AC IRI

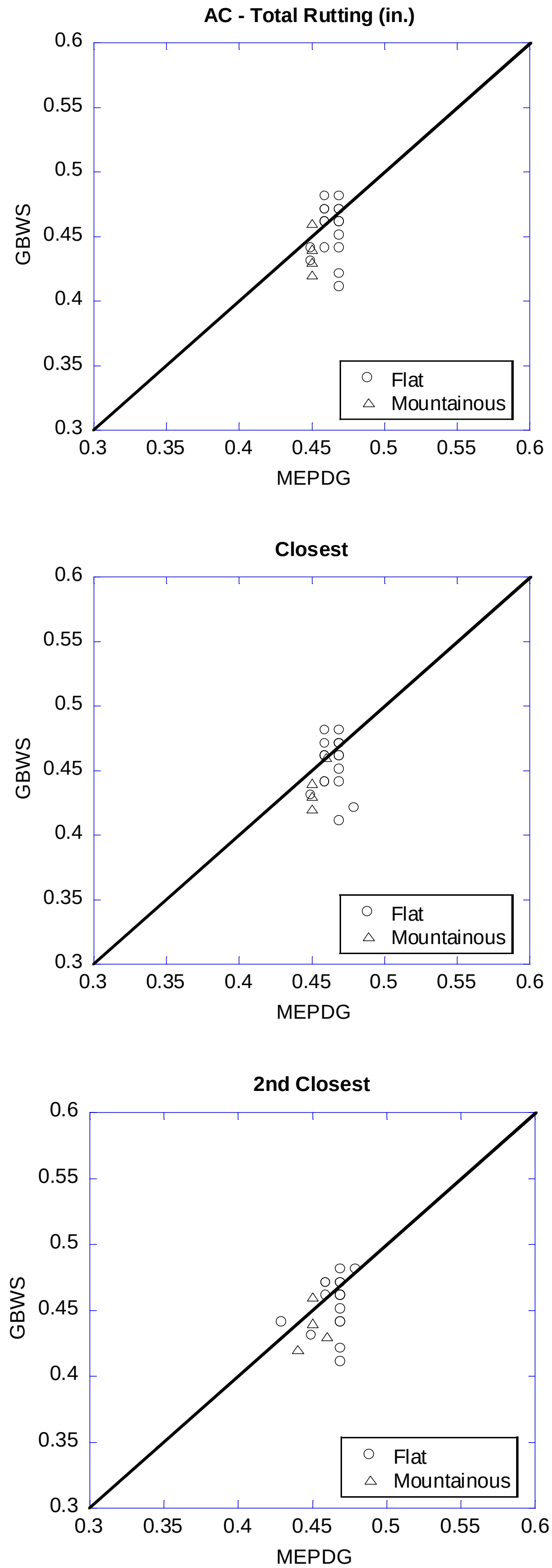

Figure 4.29. GBWS vs. Virtual MEPDG for AC Total Rutting

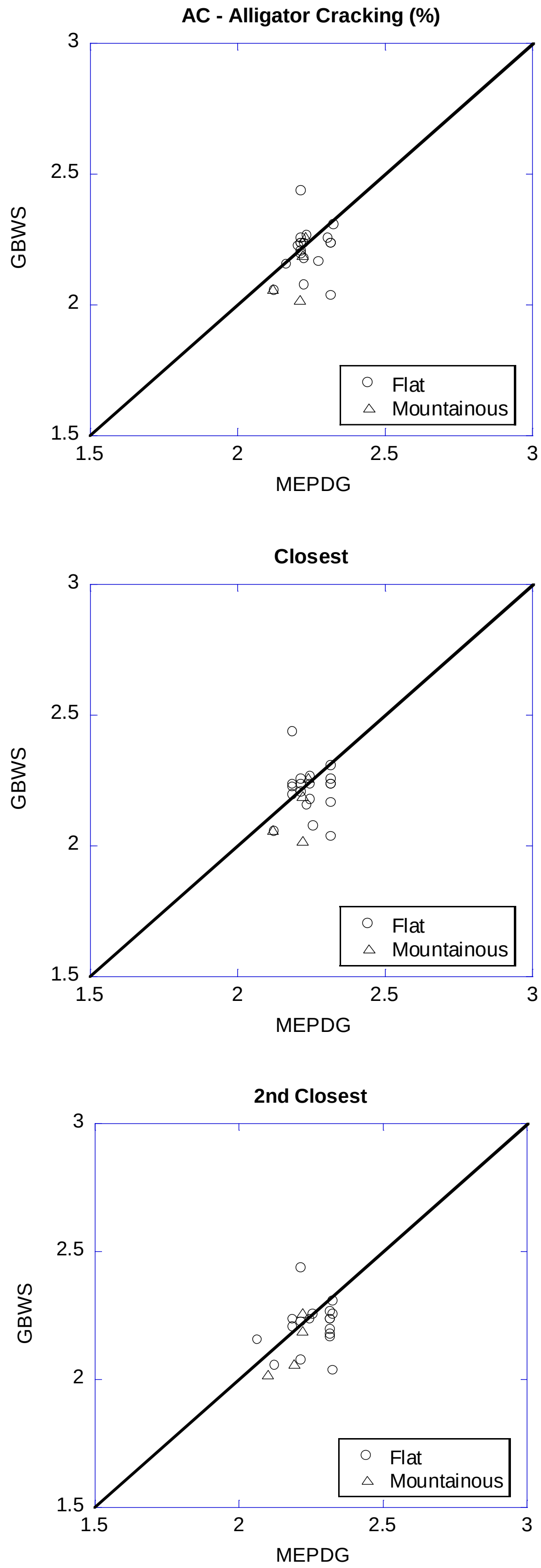

Figure 4.30. GBWS vs. Virtual MEPDG for AC Alligator Cracking

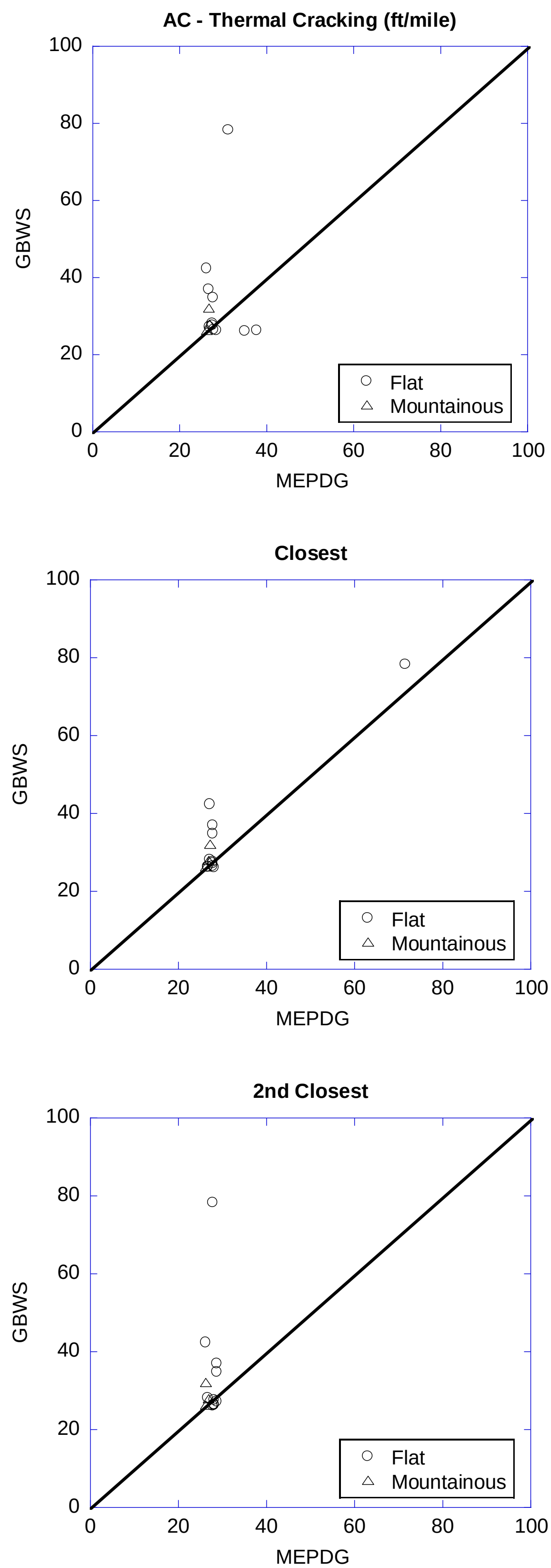

Figure 4.31. GBWS vs. Virtual MEPDG for AC Thermal Cracking

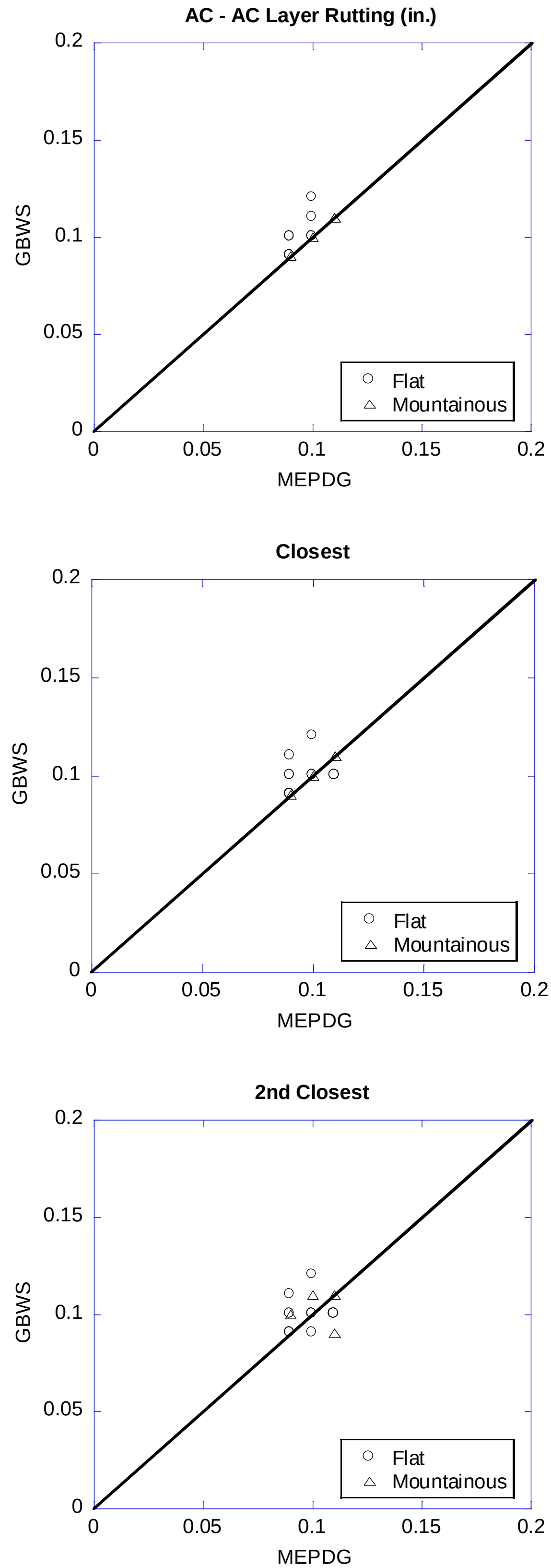

Figure 4.32. GBWS vs. Virtual MEPDG for AC Layer Rutting

4.6 Task 6 - Identify remaining gaps in climate and groundwater data needed to support M-E design in South Dakota

Under this task, the research team accomplished the first objective of this study. Based on the results obtained from the previous task (Task 5), the research team identified the gaps and quality issues that exist in the MEPDG weather data. The research team provided the following suggestions about ground-based weather stations (GBWS), environmental sensing stations (ESS), Modern-Era Retrospective Research and Applications (MERRA) data, and monitoring wells for ground water level.

Identified Gaps in the Climate Sources Investigated in the Current Study

1. Environmental sensing stations cannot be used as a climate input data since they do not collect the percent sunshine data or downwelling radiation at the land surface.
2. Climate data stations (11 stations) provided with the MEPDG software do not cover all areas of South Dakota. This necessitates the creation of virtual weather stations. The results showed that there were discrepancies in the pavement performance predicted by the ground-based weather stations and virtual weather stations in the same locations. This suggests that pavements designed by virtual weather stations may lead to over- or under- designs.
3. Ground-based weather stations (GBWS) had better spatial coverage than the weather data embedded in the MEPDG software. However, the majority of these stations are located in the eastern part of South Dakota while there are very few on the western and northern sides of the state. Furthermore, GBWS data has significant data quality issues. Eleven of the 46 stations located in or nearby South Dakota do not possess any relative humidity, percent sunshine data, or downwelling radiation. The majority of the GBWS data have gaps longer than 24 hours, which decreases the usable time period in the analyses. The average time period available with GBWS weather data is 12.9 years.
4. NASA Modern-Era Retrospective Research and Applications (MERRA) is the best data that can be used as a climate source in the pavement performance predictions in South Dakota. The advantages of MERRA are as follows:
    a. There are 70 uniformly distributed MERRA grid points in South Dakota vs 11 MEPDG stations and 36 GBWS. MERRA provides continuous hourly data from 1979 onward with no spatial or temporal gaps.
    b. There are no local or daylight saving time issues with MERRA, as all data are identified using Universal Time Coordinates.
    c. The extensive data quality checks applied to MERRA data by NASA for its own modeling needs reduces the need for any addition quality checks for use in the MEPDG.
    d. MERRA permits direct use of surface solar radiation rather than requiring an empirical estimate based on percent cloud cover, which is a more robust and physically-based approach to estimating the amount of solar energy incident on the pavement surface.

Identified Gaps in the Groundwater Data Sources Investigated in the Current Study:

This study reveals the following conclusions regarding the groundwater data sources in South Dakota:

1. Even though there are 1572 ground water monitoring wells in the state, the majority of these wells are located in the eastern and southern part of the state. This indicates that data obtained from these wells are not representative of the ground water conditions across the entirety of the state.
2. Sensitivity analyses indicated that the Pavement ME , software does not take ground water effects into account during analysis unless the ground water table level is close to the ground surface (i.e., less than 2 feet below ground surface). The majority of the data collected from 1572 wells in South Dakota were more than 2 feet below the ground surface, indicating that the water table levels will not impact the pavement performance predictions.

4.7 Task 7 – Submit to the project`s technical panel a technical memorandum summarizing the results of tasks 1-6 and recommending the number of climatic stations, climatic record length, and water table data that should be used in the MEPDG

The research team prepared a technical memorandum based on the findings from Tasks 1 through 6. The summary interim report presented the findings of the literature review, summary of the sensitivity analysis, assessment of the adequacy of climate and groundwater data embedded in the MEPDG software, identification of other existing climate and groundwater data sources, and determination of the remaining gaps that need to be filled. The research team also gave a presentation to the technical panel. This meeting was held on October 15, 2014 in Pierre, South Dakota.

The following conclusions were drawn at this meeting:

1. GBWS, ESS and the weather data embedded in the MEPDG software are inadequate climate sources. MERRA data should be implemented as the primary climate data source.
2. GBWS possess many data quality issues. Therefore, it was decided that no GIS map of climate data was required.
3. A GIS map to update groundwater data was not necessary to be developed since the MEPDG software does not take the impact of groundwater into account unless the water level is less than 2 feet below ground surface level.

4.8 Task 8 – Update M-E design climatic files for appropriate weather stations based on panel recommendations

This task accomplished the second objective of this project. The research team updated the MEPDG climatic files both for GBWS and MERRA climate data. These files are provided in a format required by the MEPDG software. This is accomplished by the MATLAB® code that is developed by the research team.

4.9 Task 9 and 11 – Develop a Procedure and Map and Software Tools for Dividing the State into Climate Zones and Selecting One or More Weather Stations for Interpolation to a Specific Location / to Assist with the Selection of Water Table Depth at a Specific Location

Under this task, the research team originally planned to develop a tool to accomplish the second objective of the project. The research team planned to create a GIS map of South Dakota using ArcGIS software and publicly available geospatial data for South Dakota to extract and download climate data from the online sources depending on the availability of these sources. However, it was decided that MERRA data should be implemented as the primary climate data source at the technical memorandum meeting which was held on October 15, 2014 in Pierre, South Dakota.

The results of this study showed that groundwater table did not impact the pavement performance analysis in the recent version of the MEPDG software. Therefore, it was also decided that a GIS map to update groundwater data was not necessary to be developed at the technical memorandum meeting.

4.10 Task 10 – Provide a Methodology and Automated Means to Automatically Update Climatic Files in the Format Required by M-E Design

A code in MATLAB® for downloading and extracting the data from NASA servers for MERRA was developed. Climate data from MERRA were extracted, formatted to meet .hcd file format requirements, and written in ASCII format for eventual use by the MEPDG model. This code will be provided to the SDDOT technical panel upon their request. However, the purchase of a software license and personnel training may be required to use the code. The FHWA Long Term Pavement Performance (LTPP) program is working on the development of online source for the extraction of MERRA data in a format required by the MEPDG software for the entire United States. It is expected to be available in the second half of 2015.

4.11 Task 12 – Prepare a Final Report Summarizing the Research Methodology, Findings, Conclusions and Recommendations

The research team prepared a final report that included a comprehensive summary of the project and document the project results, findings, and conclusions related to the improvement of the climate and groundwater data to support mechanistic-empirical pavement design in South Dakota after the draft final report was submitted to the Project Technical Panel for review and comment and revised per comments and edits of the project technical panel.

4.12 Task 13 – Make an Executive Presentation to the SDDOT Research Review Board at the Conclusion of the Project.

The research team made an executive presentation to the SDDOT Research Review Board and Project Technical Panel that summarized all research activities and presented any conclusions and recommendations that resulted from this research.

5 CONCLUSIONS

A research study was conducted to identify alternative climate data sources to be used as an input in the MEPDG software. The research team used three different climate data sources: (1) Ground-based weather stations included with the MEPDG software; (2) ground-based weather stations throughout South Dakota; and (3) NASA's Modern-Era Retrospective Analysis for Research and Applications (MERRA) product. Extensive comparisons of MEPDG pavement predictions were made with the data collected from these three sources. The conclusions from these analyses are summarized below:

1. This research suggests that MERRA should be used as a primary climate data source for MEPDG pavement analyses.
2. MERRA provides 70 uniformly distributed grid points throughout South Dakota as a weather station, whereas there are only 11 MEPDG and 36 GBWS weather stations in South Dakota and nearby states. In addition, the GBWS are not spread out uniformly. Discrepancies in the pavement distresses calculated using MEPDG vs. GBWS data derived for the same source suggests that there are quality issues with the GBWS data.
3. MERRA has continuous hourly climate data from 1979 to the present and does not have gaps in the data. Moreover, extensive data quality checks are applied to MERRA data by NASA.
4. MERRA provides direct use of surface solar radiation instead of using percent cloud cover in GBWS to estimate the percent sunshine.
5. NASA has plans to move to ~10 km horizontal spatial resolution in the future, which will greatly increase the MERRA grid cell density.
6. Sensitivity analyses indicate that the groundwater table does not have any impact on the pavement performance unless it is very close to the ground surface.

6 RECOMMENDATIONS

The purpose of this research project was to identify the best climate sources to use in MEPDG pavement performance predictions. The results of this study showed that MERRA is as reliable as ground-based weather stations for critical weather data. In addition, MERRA has several advantages over currently available ground-based weather sources: denser, more uniform, and broader spatial coverage; better temporal frequency and continuity; excellent data consistency and quality. The results of this study indicate that the MEPDG software is not sensitive to groundwater table unless it is very near the ground surface. The following recommendations are made based on the results of this study.

1.5.1. South Dakota Department of Transportation should adopt MERRA as a primary climate data source for pavement designs.

As mentioned in the previous sections of the report, MERRA possesses many advantages over other available climate data sources including ground-based weather stations (GBWS) and environmental sensing stations (ESS). GBWS data have significant discontinuities in the collected data. It requires significant amounts of effort to fill these gaps if SDDOT decides to use them for pavement performance predictions. Moreover, GBWS does not cover the entire state uniformly.

On the other hand, MERRA provides uniform and more representable climate data with a spatial coverage of the entire state. In addition, there are no gaps in the data which were collected since 1979 and subjected to vigorous and continuous quality check by NASA.

Even though the research team strongly suggests the integration of MERRA as a primary climate data source for pavement performance predictions, it should be emphasized that in mountainous regions none of the climate data sources may provide accurate and reliable pavement performance predictions due to spatial scale issues in complex terrain as well as installation bias of instrumental networks (e.g., preferential installation in lower elevation valleys rather than higher elevation mountain tops).

1.5.2. South Dakota Department of Transportation should initiate a new project to determine the stiffness and the strength of pavement subgrade and base layers under different moisture content conditions (dry, optimum, and wet) and to use these values as input values in the MEPDG pavement performance predictions.

This study showed that the groundwater table depth does not have a significant impact on pavement performance unless it is 1 ft below or lower than the ground surface. The current version of the MEPDG software does not simulate the entire processes occurring in the field during the presence of water such as heaving, and strength loss.

1.5.3. South Dakota Department of Transportation could use the groundwater data from the online sources provided in this report.

These sources can be reached at the following internet links:

http://sd.water.usgs.gov/

http://denr.sd.gov/des/wr/wr.aspx

7 RESEARCH BENEFITS

The end result of this study is expected to improve the performance and life expectancy of the pavement structures in South Dakota significantly via improving the quality of climate. Results of this study showed that the MERRA climate data provided the most accurate and reliable climate data for M-E pavement design.

MERRA is superior to available data embedded in the MEPDG software and data collected from ground-based weather stations (GBWS) and environmental sensing stations (ESS). It is denser, more uniform, has broader spatial coverage; it has better temporal frequency and continuity, and has excellent data consistency and quality. MERRA data can be updated free annually from the NASA webservers with the MATLAB® code provided.

This study also indicated that the impact of groundwater table on the pavement distress predictions in the current version of the MEPDG software was negligible unless it is 1 ft or lower below the ground surface. This is not the case in the field applications. Therefore, the results of this study suggests conducting additional research to determine the stiffness, strength and heaving properties of pavement sublayers under different moist conditions which could provide accurate and reliable input parameters for the MEPDG software. Thus, it yields more proper pavement design and ultimately increases the service life of the pavements.

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APPENDIX A – INPUT DATA USED IN MEPDG PAVEMENT DISTRESS SENSITIVITY ANALYSES

Table A1. Design Values for Sensitivity Analyses - JPCP

Design Type	Jointed Plain Concrete Pavement (JPCP)
Design Life	10 years
PCC Layer	
Thickness	10 inches
Base Layer	Crushed Gravel
Thickness	6 inches
Poisson's ratio	0.35
Coefficient of lateral earth pressure	0.5
Resilient Modulus	25000 psi
Subgrade	
Thickness	Semi-infinite
Poisson's ratio	0.35
Coefficient of lateral earth pressure	0.5

Table A2. Design Values for Sensitivity Analyses - AC

Design Type	Flexible Pavement
Design Life	10 years
AC Layer	
Thickness	10 inches
Base Layer	Crushed Gravel
Thickness	7 inches
Poisson's ratio	0.35
Coefficient of lateral earth pressure	0.5
Resilient Modulus	25000 psi
Subgrade	
Thickness	Semi-infinite
Poisson's ratio	0.35
Coefficient of lateral earth pressure	0.5

Table A3. Subgrade Levels for Sensitivity Analyses

Subgrade	Type	Resilient Modulus
Low	A-7-6	13000 psi
Medium	A-6	14000 psi
High	A-4	15000 psi

Table A4. Traffic Levels for Sensitivity Analyses

Traffic	AADTT
Low	50
Medium	250
High	450

Table A5. Water Table Levels for Sensitivity Analyses

Water Table	Depth
Low	10 feet
Medium	5 feet
High	2 feet

Table A6. Design Values for Comparison Analyses - JPCP

Design Type	Jointed Plain Concrete Pavement (JPCP)
Design Life	20 years
PCC Layer	
Thickness	10 inches
Base Layer	Crushed Gravel
Thickness	6 inches
Poisson's ratio	0.35
Coefficient of lateral earth pressure	0.5
Resilient Modulus	25000 psi
Subgrade	A-4
Thickness	Semi-infinite
Poisson's ratio	0.35
Coefficient of lateral earth pressure	0.5
Traffic (AADTT)	7500

Table A7. Design Values for Comparison Analyses - AC

Design Type	Flexible Pavement
Design Life	10 years
AC Layer	
Thickness	10 inches
Base Layer	Crushed Gravel
Thickness	7 inches
Poisson's ratio	0.35
Coefficient of lateral earth pressure	0.5
Resilient Modulus	25000 psi
Subgrade	A-4
Thickness	Semi-infinite
Poisson's ratio	0.35
Coefficient of lateral earth pressure	0.5
Traffic (AADTT)	450

Table A8. Surface Layer Properties for AC and JPCP Design

		Value
Asphalt Properties	Surface Shortwave Absorption	0.85
	Unit Weight	150 pcf
	Poisson's Ratio	0.35
	Thermal Conductivity	0.67 (BTU/hr-ft-˚F)
	Heat Capacity	0.23 (BTU/lb-˚F)
	Effective Binder Content	7%
	Air Void	7%
	Binder Type	64-34
	Voids in Mineral Aggregate	14 (%)
Concrete Properties	Design Lane Width	12 feet
	Joint Spacing	15ft
	Dowel Diameter	1.25 in.
	Dowel Spacing	12 in.
	Erodibility Index	5
	Surface Shortwave Absorption	0.85
	Unit Weight	150 pcf
	Poisson's Ratio	0.2
	Coefficient of Thermal Expansion	5.5 (in./in./˚Fx10^{-6})
	Thermal Conductivity	1.25 (BTU/hr-ft-˚F)
	Cement Content	600 lb/yd^3
	W/C ratio	0.42

Table A9. Traffic Properties for AC and JPCP Design

Traffic Properties	Value
Number of Lanes in Design Direction	2
Percent of Trucks in Design Direction	50%
Percent of Trucks in Design Lane	55%
Operational Speed	65 mph
Traffic Growth	None
Mean Wheel Location	18 in.
Traffic Wander Standard Deviation	10 in.
Design Lane Width	12 feet
Average Axle Width	8.5 feet
Dual Tire Spacing	12 in.
Tire Pressure	120 psi
Tandem Axle Spacing	52 in.
Tridem Axle Spacing	54 in.
Quad Axle Spacing	54 in.

APPENDIX B: GROUND-BASED WEATHER STATION (GBWS) DATA QUALITY

Table B1. Ground Based Weather Stations Data Quality Part A

City	State	Temperature % Missing	Wind Speed % Missing	Sunshine % Missing	Precipitation %Missing	Humidity % Missing	Total % Missing
Aberdeen	SD	0.5%	0.5%	0.5%	2.3%	0.5%	0.8%
Sioux Falls	SD	0.5%	0.3%	0.5%	2.3%	0.6%	0.8%
Watertown	SD	0.7%	0.6%	0.7%	2.3%	0.7%	1.0%
Rapid City	SD	0.8%	0.6%	0.7%	2.4%	1.0%	1.1%
Alliance	NE	0.9%	1.0%	0.9%	2.3%	0.9%	1.2%
Philip	SD	0.9%	0.9%	1.1%	2.6%	1.0%	1.3%
Sioux City	IA	1.2%	1.0%	1.1%	2.7%	1.2%	1.4%
Chadron	NE	1.2%	0.7%	0.7%	2.9%	1.3%	1.4%
Valentine	NE	1.0%	1.0%	1.1%	2.8%	1.0%	1.4%
Mobridge	SD	1.2%	1.1%	1.2%	3.0%	1.2%	1.5%
Hettinger	ND	1.2%	1.4%	1.2%	2.8%	1.3%	1.6%
Huron	SD	0.7%	0.8%	1.1%	4.3%	2.7%	1.9%
Custer	SD	1.4%	1.4%	1.7%	3.4%	1.6%	1.9%
Mitchell	SD	1.4%	1.4%	1.7%	3.4%	1.5%	1.9%
Baker	MT	1.8%	2.2%	2.0%	3.3%	1.8%	2.2%
Pine Ridge	SD	1.9%	1.8%	2.2%	3.5%	1.9%	2.3%
Luverne	MN	1.9%	1.9%	1.9%	5.6%	2.1%	2.7%
Torrington	WY	2.7%	2.4%	2.5%	4.3%	2.8%	2.9%
Wayne	NE	2.6%	2.3%	2.4%	5.6%	3.0%	3.2%
Canby	MN	2.6%	2.8%	2.7%	5.6%	3.2%	3.4%
Appleton	MN	2.7%	2.7%	3.0%	5.1%	3.9%	3.5%
Winner	SD	4.5%	4.5%	4.2%	5.8%	4.6%	4.7%
Wahpeton	ND	4.2%	3.4%	7.5%	5.6%	5.5%	5.2%
Ainsworth	NE	5.5%	5.4%	5.5%	7.6%	7.2%	6.2%
Fergus Falls	MN	5.8%	5.8%	6.4%	7.7%	7.4%	6.6%
O'Neill	NE	6.2%	6.0%	6.0%	8.1%	7.8%	6.8%
Wheaton	MN	6.1%	6.1%	6.4%	7.9%	7.8%	6.9%
Ortonville	MN	6.3%	6.4%	6.8%	8.0%	8.0%	7.1%
Madison	MN	6.5%	6.2%	7.0%	8.0%	8.2%	7.2%
Brookings	SD	7.1%	6.5%	6.4%	8.0%	8.9%	7.4%
Boxelder	SD	10.2%	4.4%	6.1%	6.5%	10.5%	7.5%
Pipestone	MN	7.5%	7.4%	8.4%	8.0%	9.1%	8.1%
Yankton	SD	9.3%	9.0%	8.6%	9.3%	11.0%	9.4%
Le Mars	IA	11.3%	11.3%	11.4%	10.8%	12.9%	11.6%
Orange City	IA	11.6%	11.5%	11.8%	11.3%	13.1%	11.9%
Pierre	SD	8.5%	4.7%	8.1%	26.4%	24.7%	14.5%
Chamberlain	SD	1.7%	1.5%	100.0%	3.2%	2.0%	21.7%
Sisseton	SD	1.6%	1.6%	100.0%	3.5%	1.9%	21.7%
Buffalo	SD	2.6%	2.7%	100.0%	4.4%	3.0%	22.5%
Faith	SD	2.8%	3.2%	100.0%	3.2%	3.2%	22.5%
Vivian	SD	5.0%	10.4%	100.0%	5.6%	100.0%	44.2%
Sundance	WY	4.8%	10.3%	100.0%	5.6%	100.0%	44.2%
Leola	SD	6.2%	11.7%	100.0%	5.6%	100.0%	44.7%
Garretson	SD	7.8%	13.1%	100.0%	9.6%	100.0%	46.1%
HWY 29	NE	8.5%	13.7%	100.0%	9.6%	100.0%	46.3%
HWY 20	SD	8.6%	13.9%	100.0%	9.6%	100.0%	46.4%
HWY 2	NE	9.2%	14.5%	100.0%	9.6%	100.0%	46.7%

Table B2. Ground Based Weather Stations Data Quality Part B

City	State	Summary of types of gaps (relative humidity - RH, percent sunshine - PS, temperature - T, month - M)
Aberdeen	SD	Occasional hourly gaps, one 11 day gap, no major gaps
Sioux Falls	SD	Occasional hourly gaps, 11 day gap,
Watertown	SD	Occasional hourly gaps, 11 day gap,
Rapid City	SD	Occasional hourly gaps, 3 day gap, 12 day gap
Alliance	NE	Occasional hourly gaps, 12 day gap, 17 day gap PS
Philip	SD	Several large hourly gaps , 11 day gap, 7 day gap
Sioux City	IA	Occasional hourly gaps, 1 M missing, 11 day gap,
Chadron	NE	Several large hourly gaps , 11 day gap
Valentine	NE	Occasional hourly gaps, 1 M gap, 12 day gap
Mobridge	SD	Occasional hourly gaps, 1 M gap, 12 day gap
Hettinger	ND	Occasional hourly gaps, 13 day gap
Huron	SD	Occasional hourly gaps, first 3 Ms of precipitation, RH missing, one 11 day gap
Custer	SD	Occasional hourly gaps, several day gaps, 1 M gap, 12 day gap
Mitchell	SD	Occasional hourly gaps, 1 M gap, 12 day gap,
Baker	MT	Occasional hourly gaps, 1 M gap, 12 day gap
Pine Ridge	SD	Occasional hourly gaps, 3 - 1 M gaps, 12 day gap
Luverne	MN	Occasional hourly gaps, several day gaps,
Torrington	WY	Occasional hourly gaps, 1.5 M gap, 1 M gap, 12 day gap
Wayne	NE	Occasional hourly gaps, several day gaps,
Canby	MN	Occasional hourly gaps, 15 days missing of PS, 16 day gap, several day gaps, M gap of PS
Appleton	MN	Occasional hourly gaps, 1 M of RH missing, 12 day gap
Winner	SD	Occasional hourly gaps, 1 M gap, 23 day gap,
Wahpeton	ND	Occasional hourly gaps, several day gaps,
Ainsworth	NE	Occasional hourly gaps, 3 M gap, 2 - 1 M gap RH, 12 day gap,
Fergus Falls	MN	Occasional hourly gaps, 3 M gap, 2 - 1 M gap RH, 12 day gap,
O'Neill	NE	Daily gaps, M missing of RH, occasional day missing, one gap of over 120 days missing
Wheaton	MN	M missing of RH, occasional day missing, one large gap of over 120 days missing
Ortonville	MN	Daily gaps, M missing of RH, occasional day missing, one gap of over 120 days missing
Madison	MN	M missing of RH, occasional day missing, one large gap of 120 days missing
Brookings	SD	Occasional hourly gaps, 3 M gap, 2 - 1 M gap of RH, 1 M gap, 12 day gap
Boxelder	SD	Several large hourly gaps , 12 day gap
Pipestone	MN	Daily gaps, M missing of RH, occasional day missing, one gap of over 120 days missing
Yankton	SD	Occasional hourly gaps, 3 M gap, 1 M gap, 1 M gap RH, 12 day gap,
Le Mars	IA	Daily gaps, M missing of RH, occasional day missing, one gap of over 120 days missing
Orange City	IA	Daily gaps, M missing of RH, occasional day missing, one gap of over 120 days missing
Pierre	SD	first 4 years of precip. and RH missing, 4 - 1 M gaps, 24 day gap T, 2 M gap, 7 M gap of T
Chamberlain	SD	No data for PS, occasional hourly gaps, 1 M gap, 12 day gap,
Sisseton	SD	No data for PS, occasional hourly gaps, 1 M gap, 12 day gap
Buffalo	SD	No data for PS, 3 - 1 M gaps, 12 day gap, occasional hourly gaps
Faith	SD	No data for PS, 2 - 1 M gap, 12 day gap
Vivian	SD	No data for PS or RH, several day gaps, 10 day gap,
Sundance	WY	No data for PS or RH, several day gaps, 12 day gap
Leola	SD	No data for PS, no data for RH, occasional hourly gaps, occasional daily gaps, 15 day gap
Garretson	SD	No data for PS, no data for RH, occasional hourly gaps, occasional daily gaps, 3 M gap
HWY 29	NE	No data for PS or RH, 3 M gap, several day gaps
HWY 20	SD	No data for PS or RH, 2 M gap, several day gaps, 12 day gap
HWY 2	NE	No data for PS or RH, 3 M gap, several day gaps

APPENDIX C: GROUNDWATER DATA

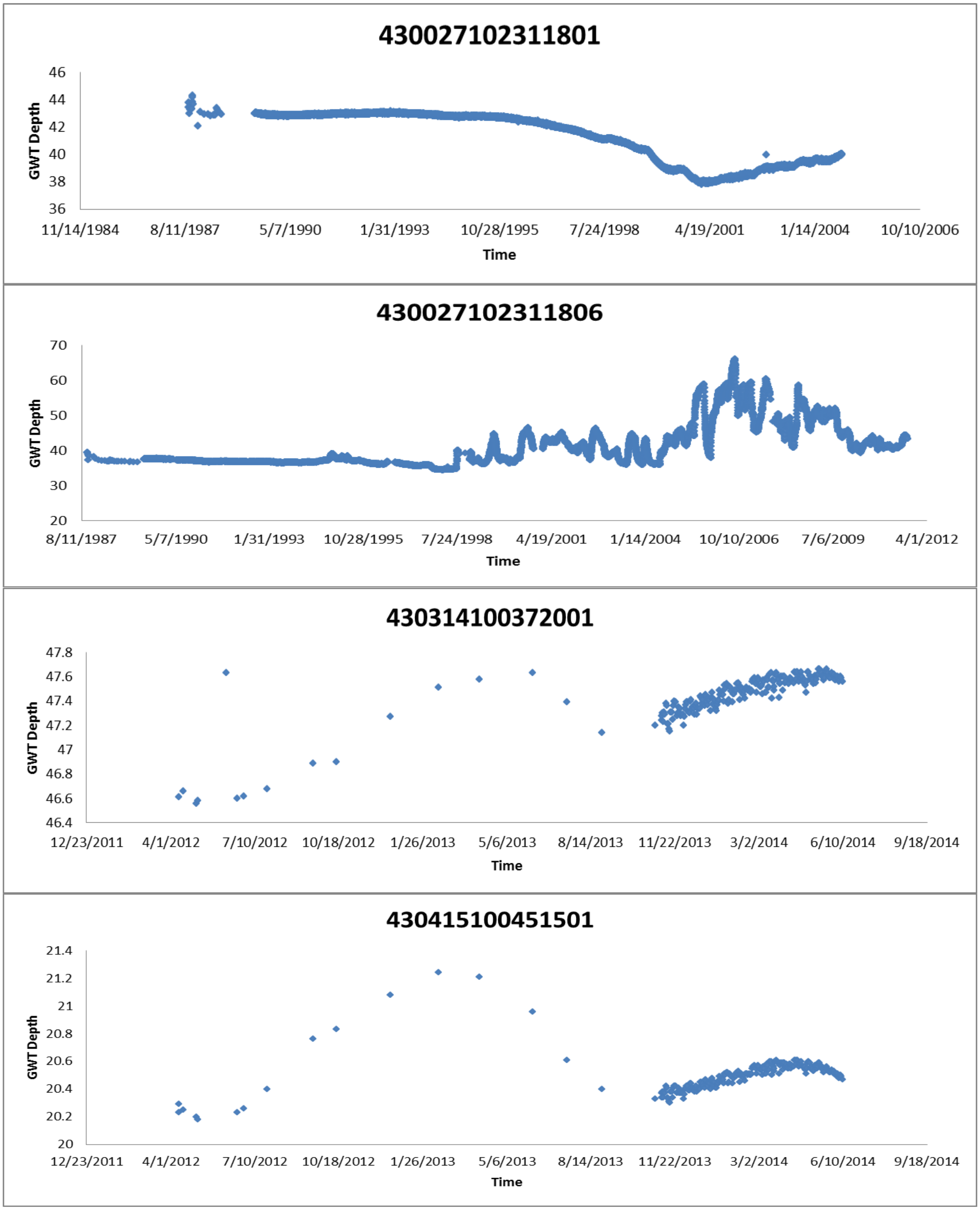
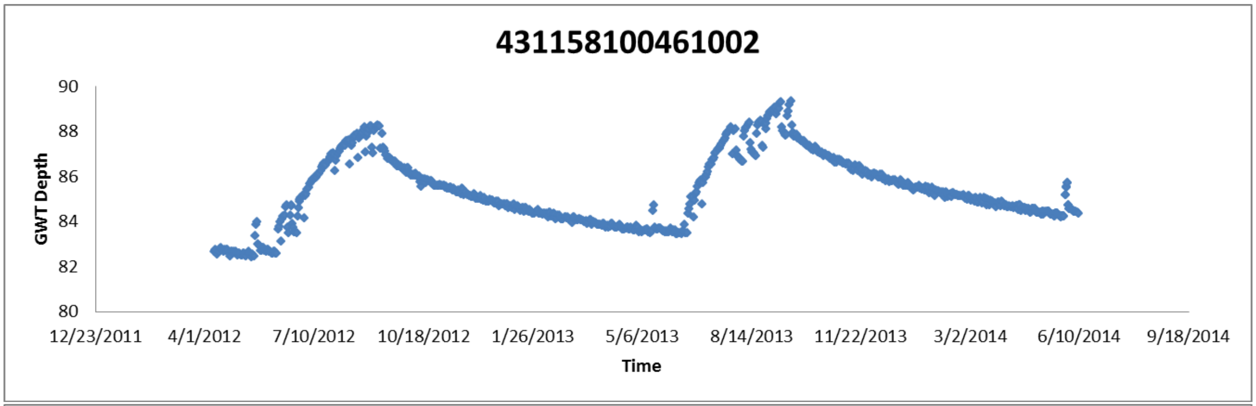
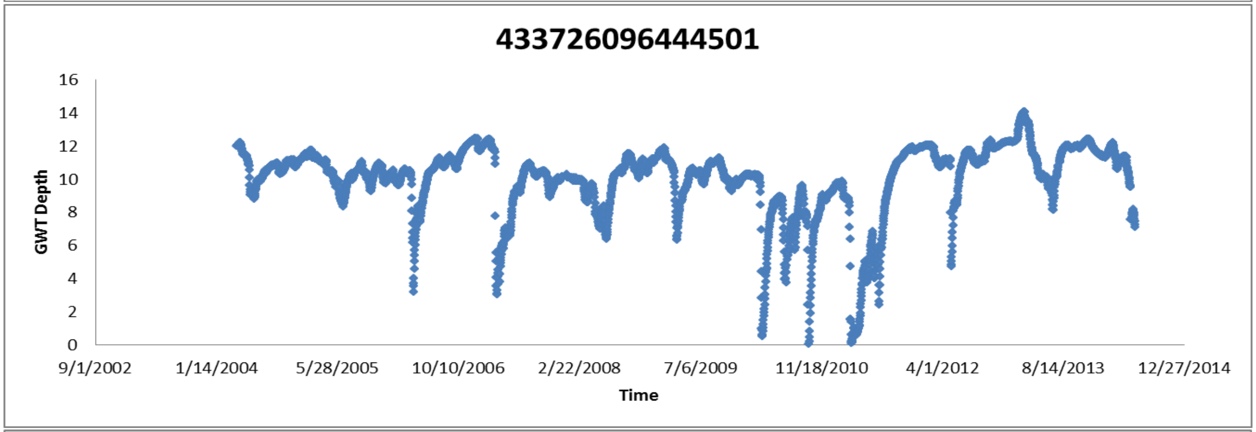


Figure C1. Locations of groundwater monitoring wells





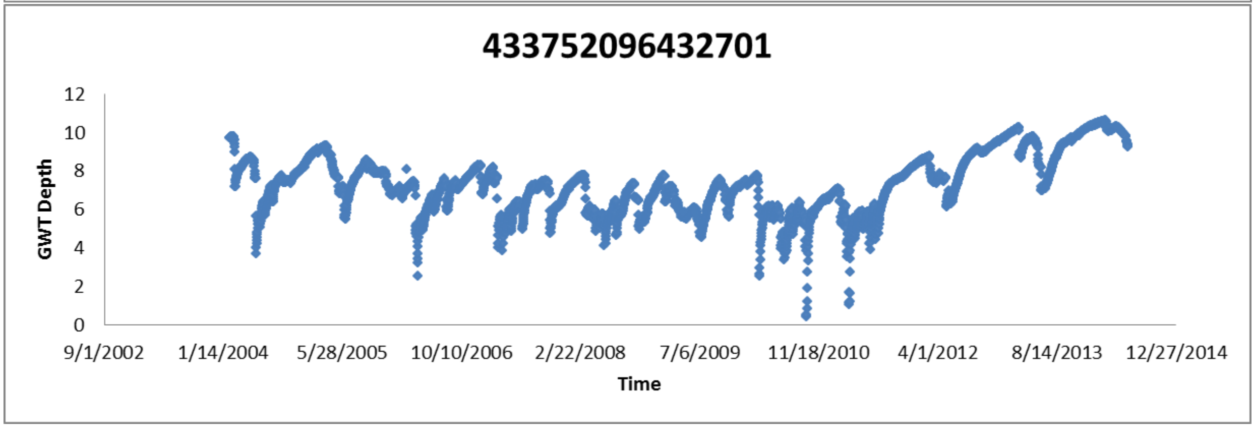


Figure C2. Locations of groundwater monitoring wells

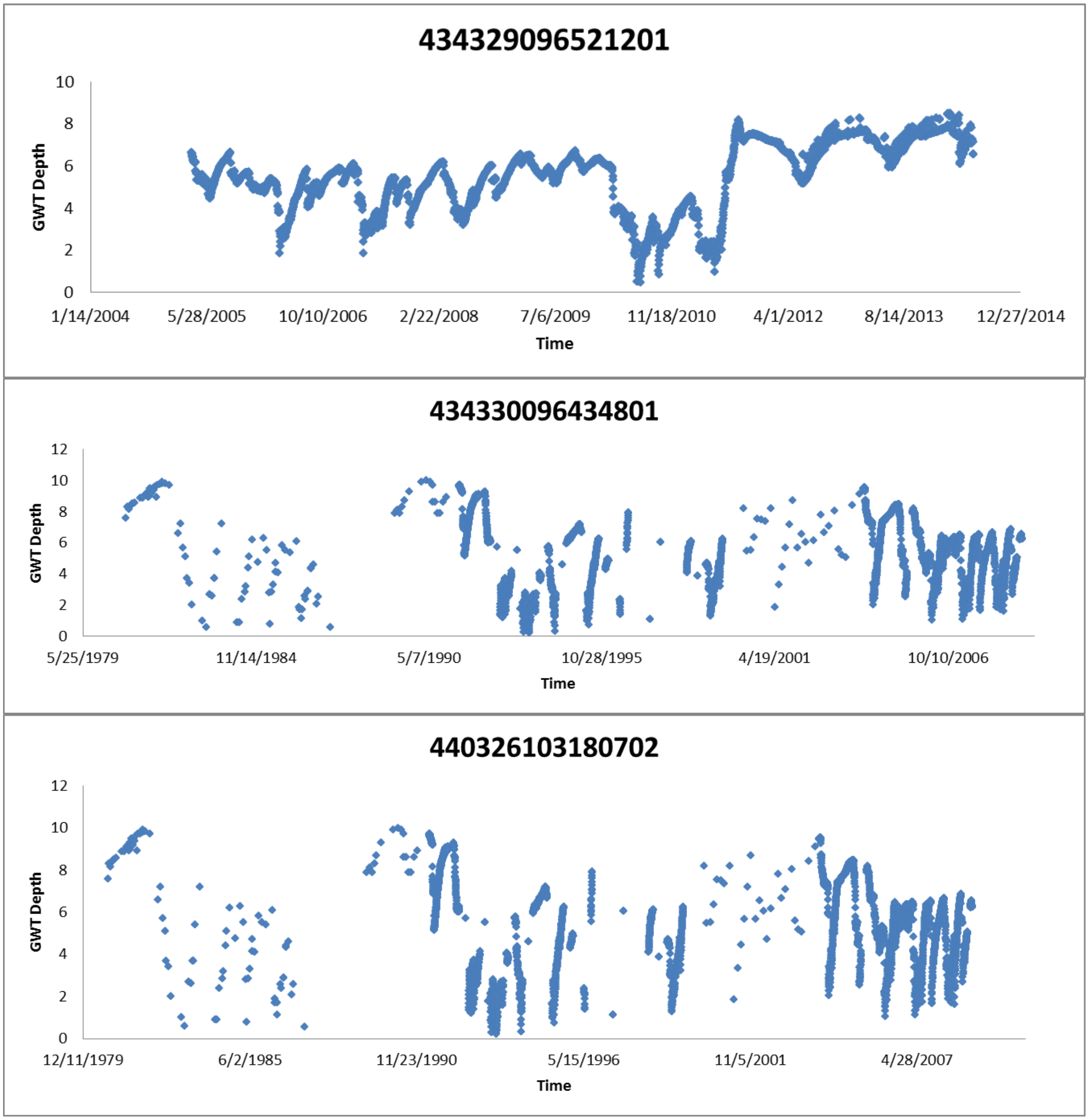
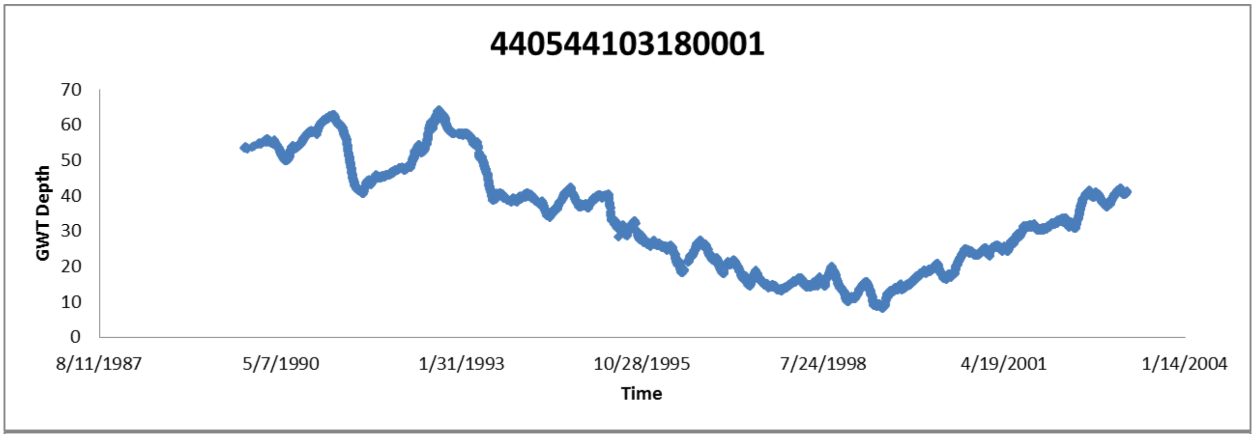


Figure C3. Locations of groundwater monitoring wells



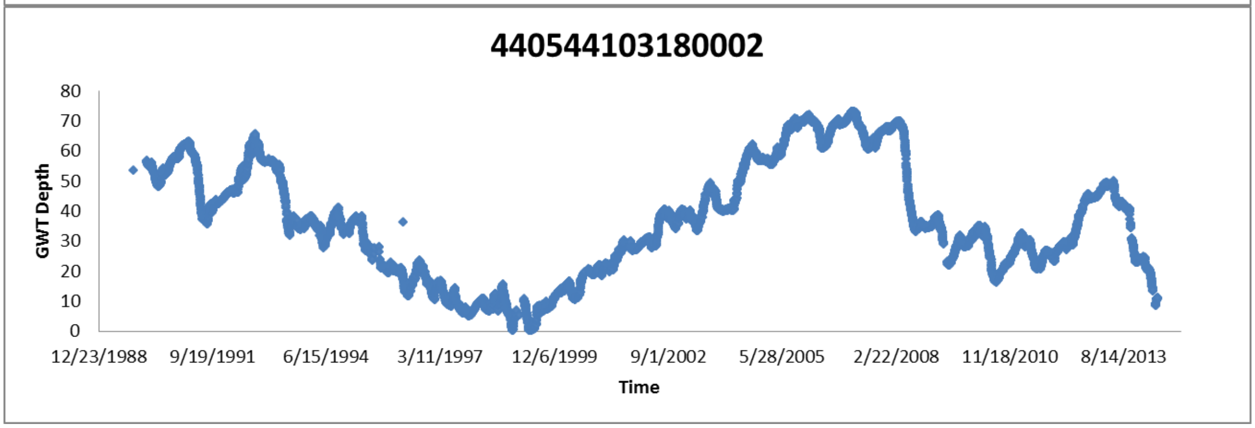


Figure C6. Locations of groundwater monitoring wells

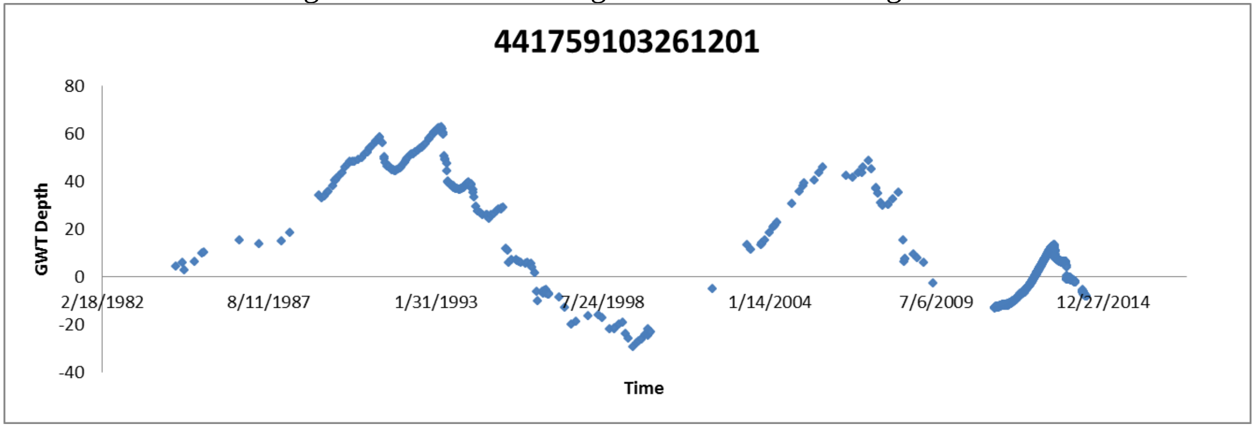


Figure C4. Locations of groundwater monitoring wells

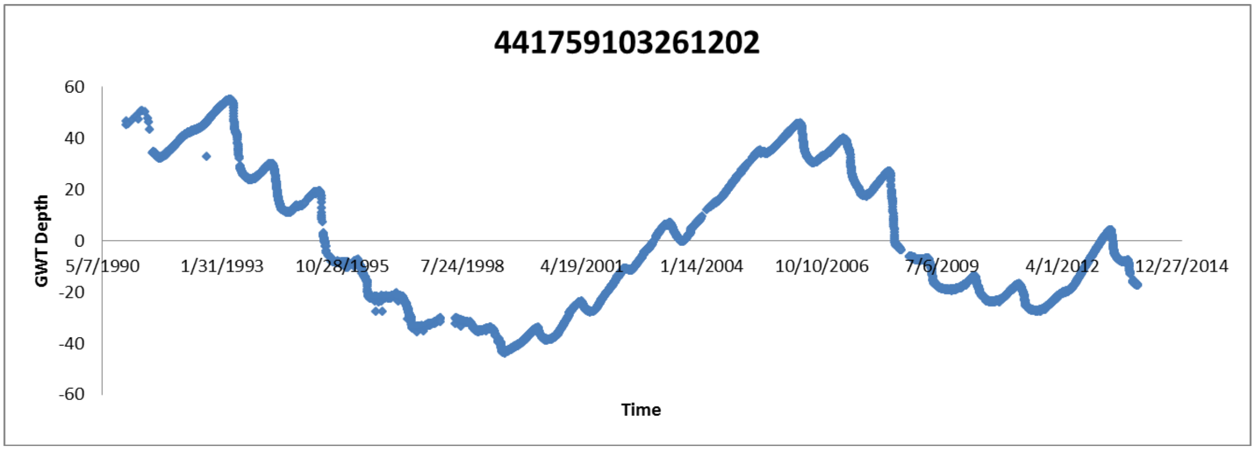


Figure C7. Locations of groundwater monitoring wells

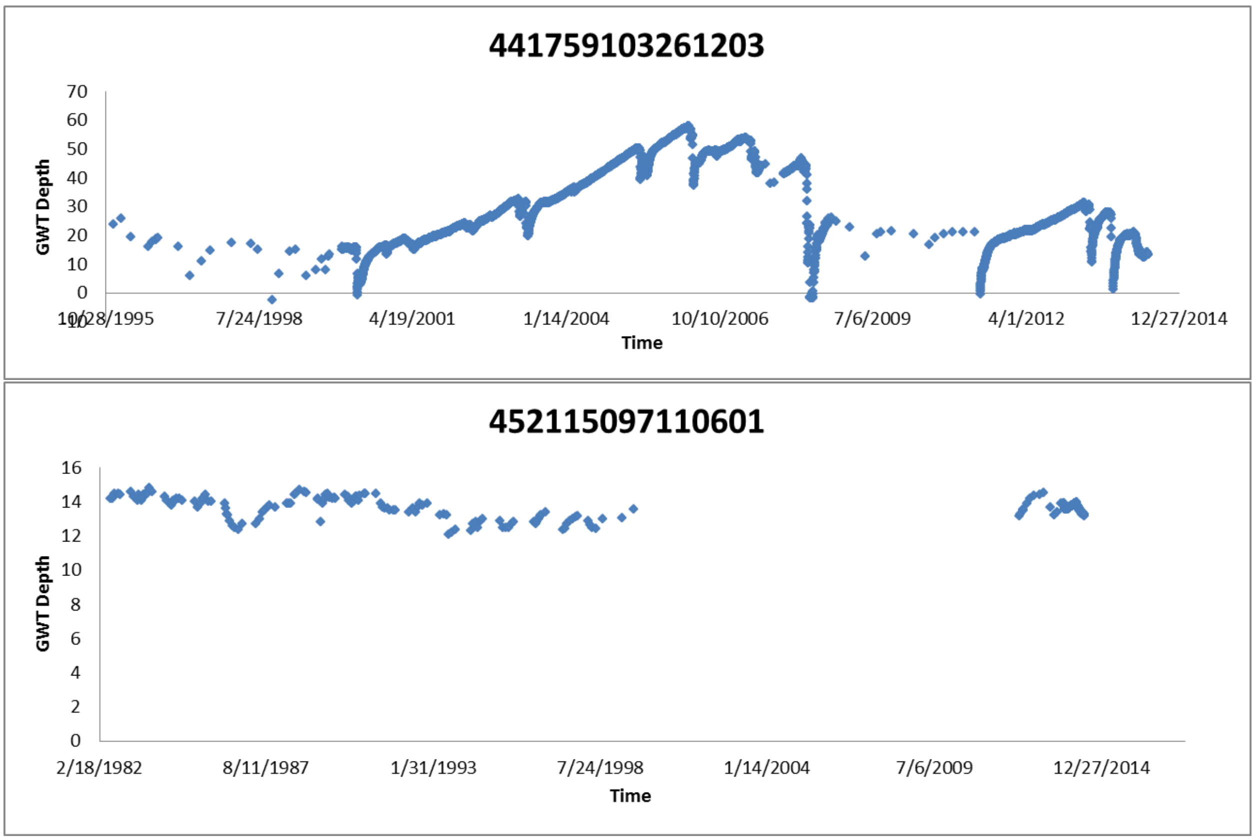


Figure C5. Locations of groundwater monitoring wells

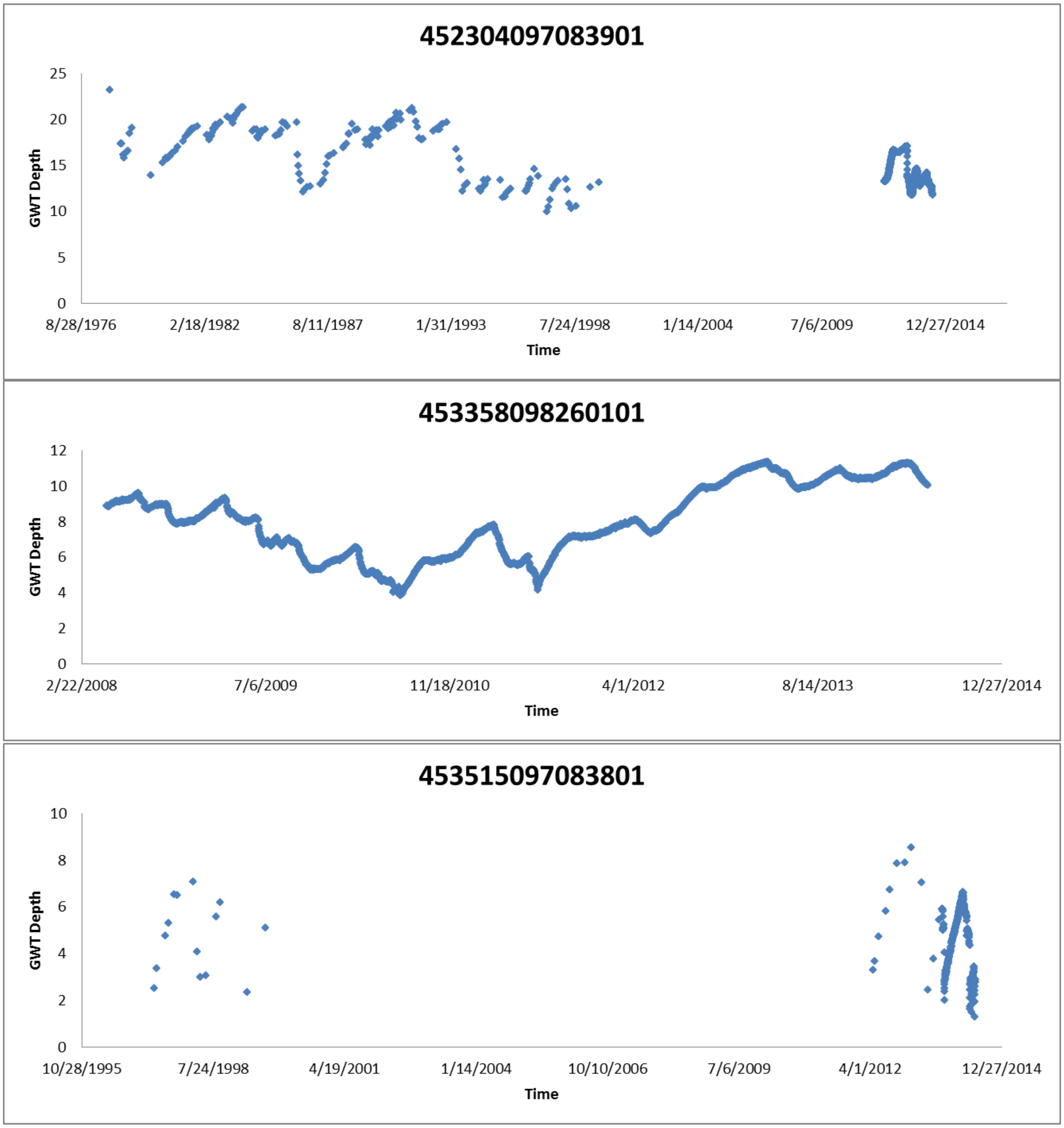


Figure C6. Locations of groundwater monitoring wells

APPENDIX D: SENSITIVITY ANALYSES FOR RAPID CITY AND SIOUX FALLS

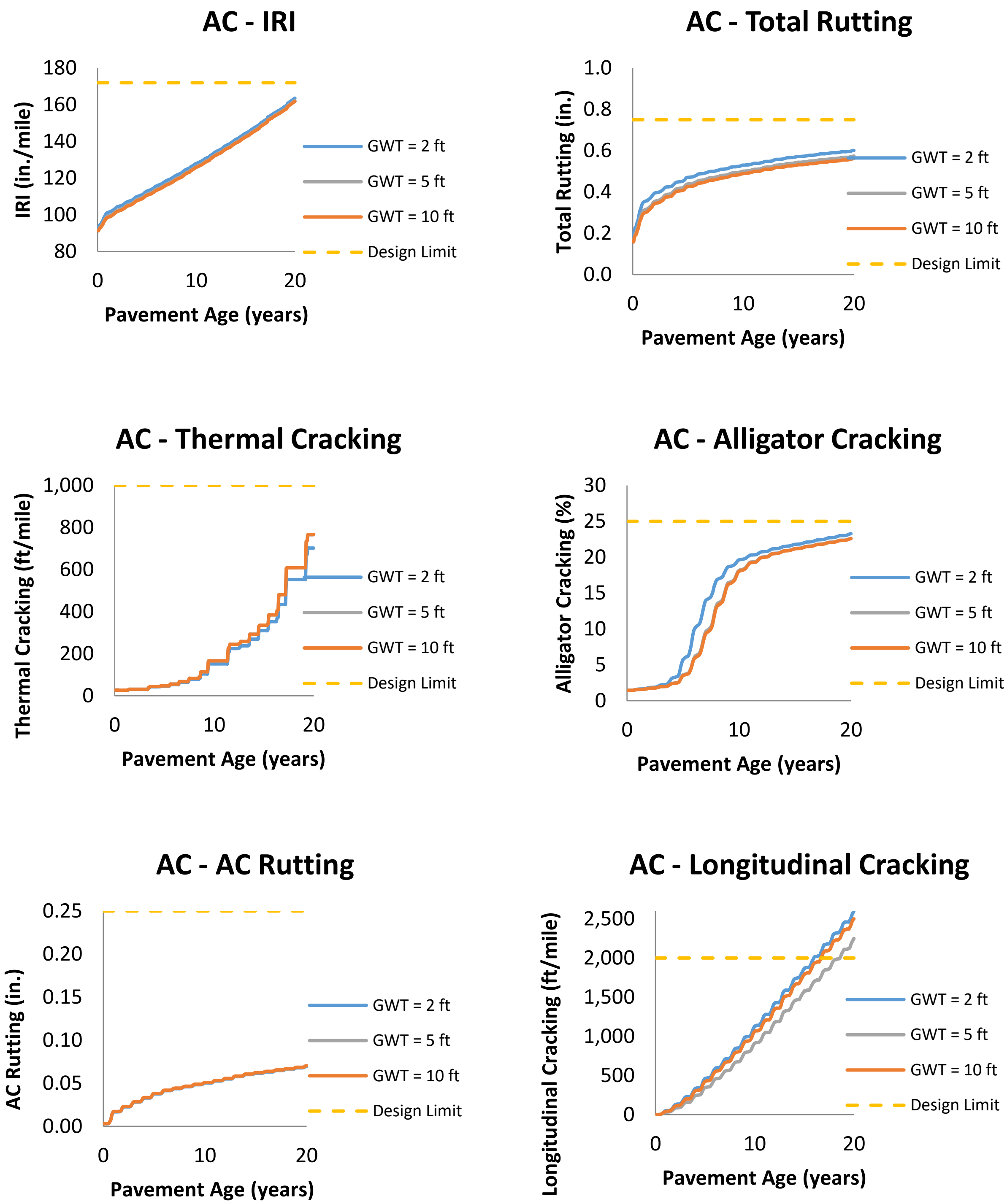


Figure D1. Asphalt Pavement, Varied Groundwater Table for Rapid City

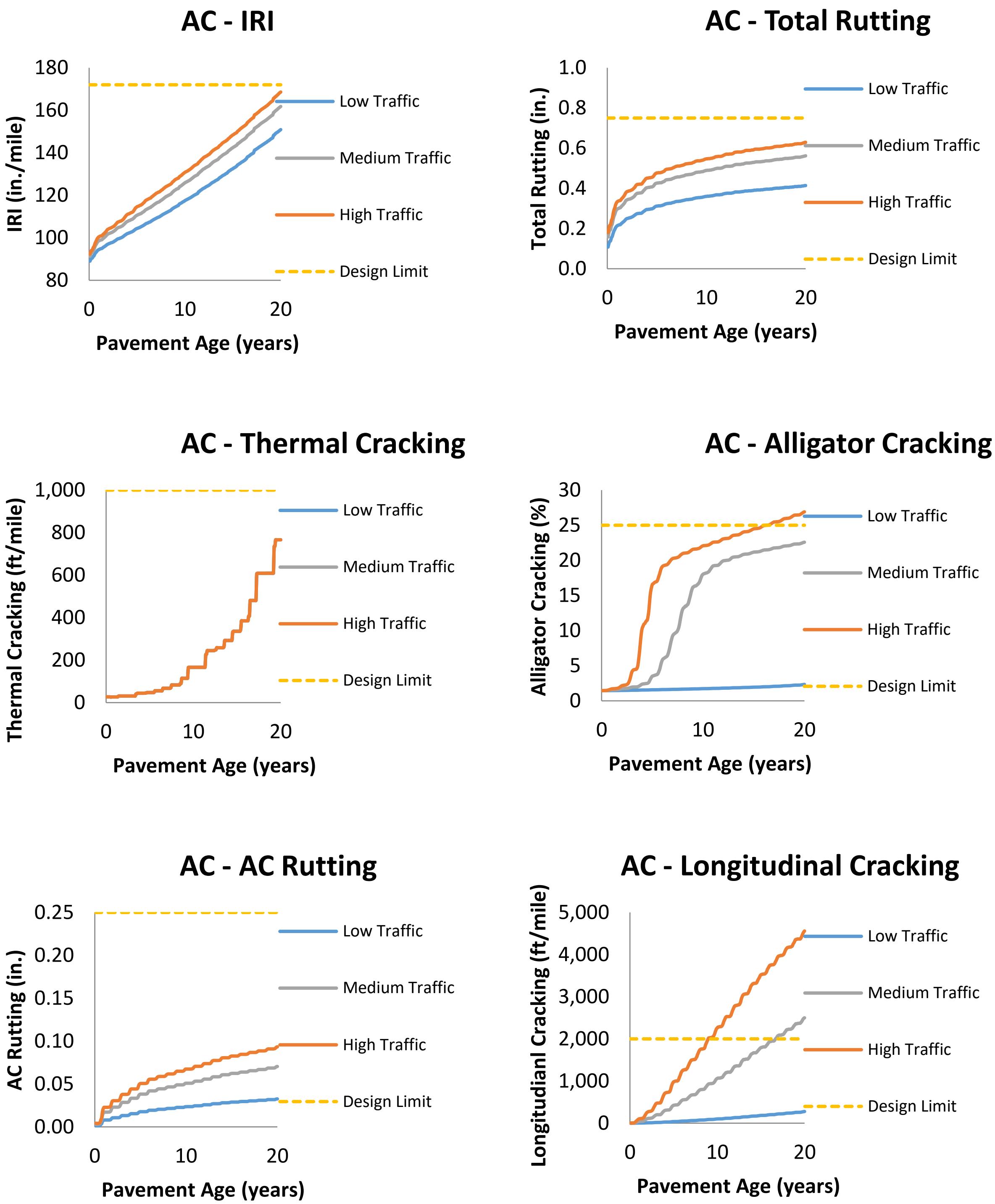


Figure D2. Asphalt Pavement, Varied Traffic Level for Rapid City

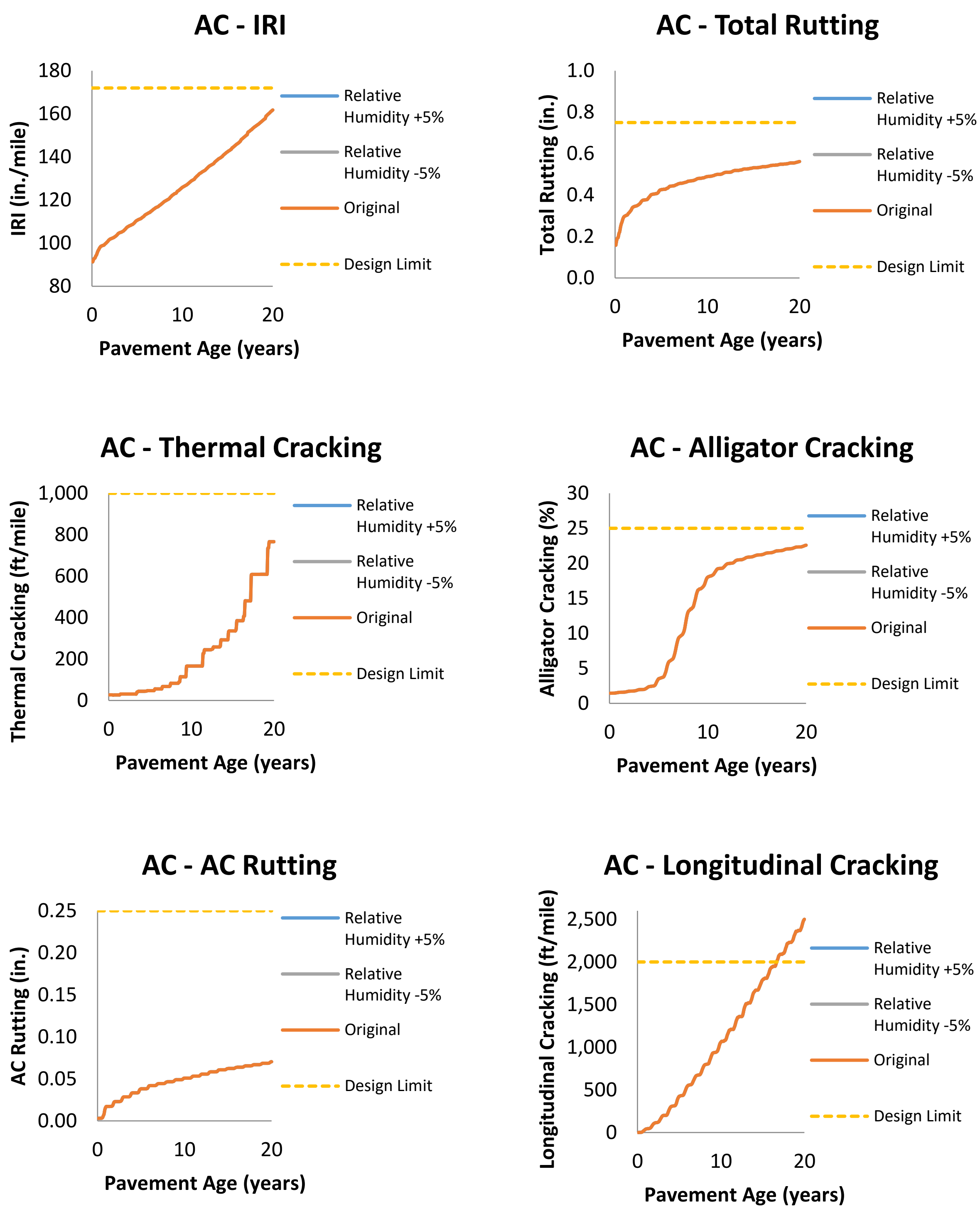


Figure D3. Asphalt Pavement, Varied Relative Humidity for Rapid City

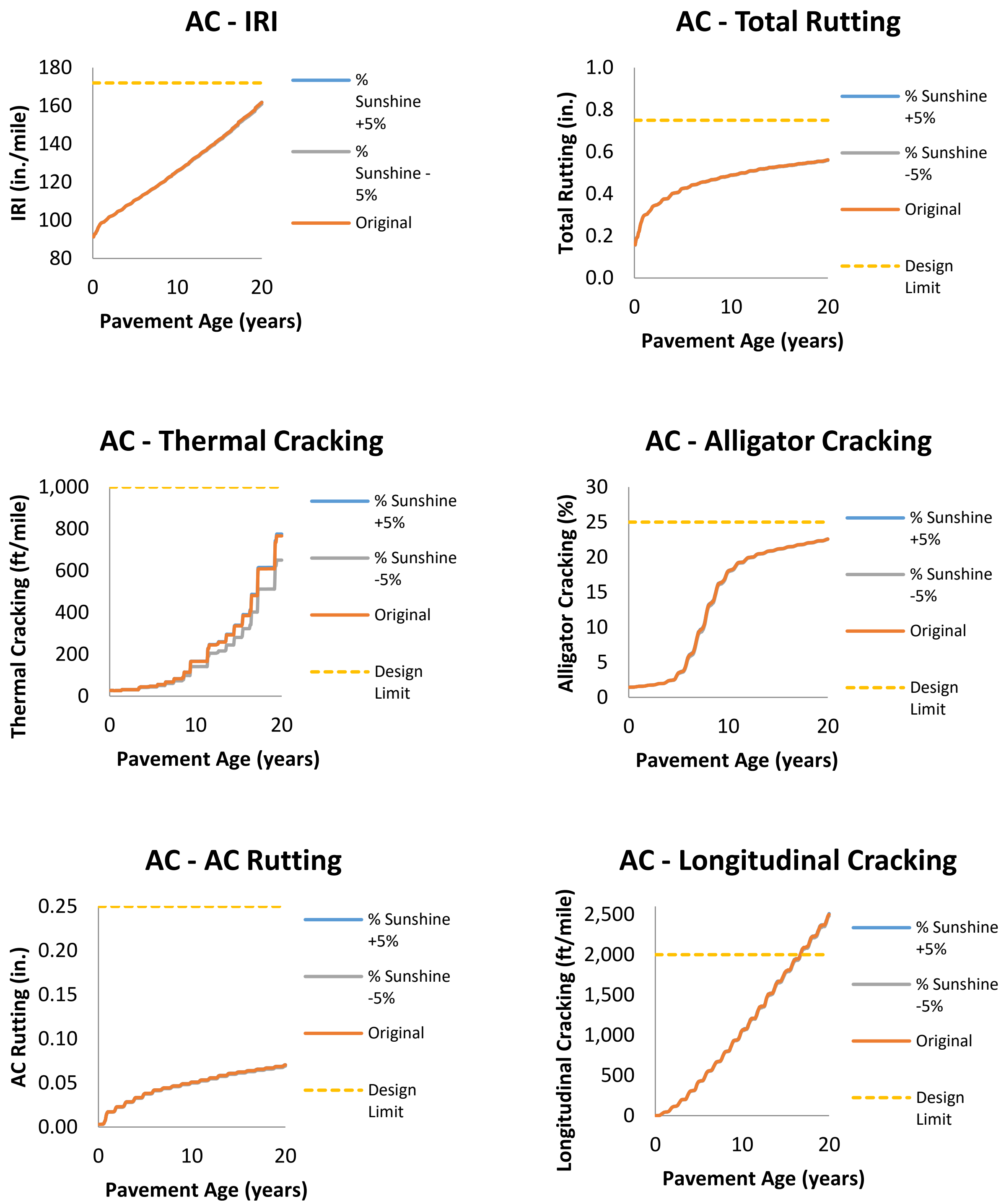


Figure D4. Asphalt Pavement, Varied Percent Sunshine for Rapid City

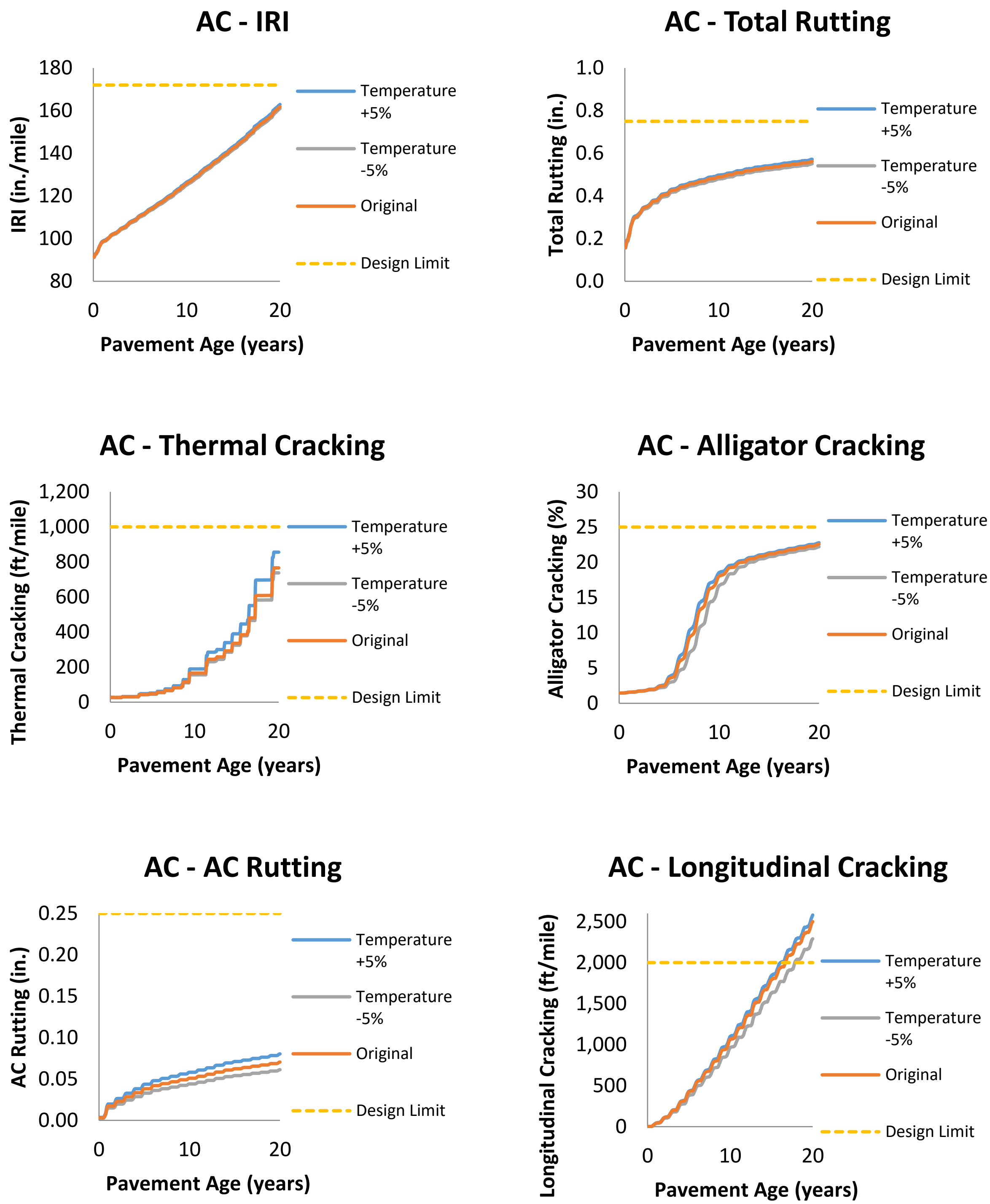


Figure D5. Asphalt Pavement, Varied Annual Air Temperature for Rapid City

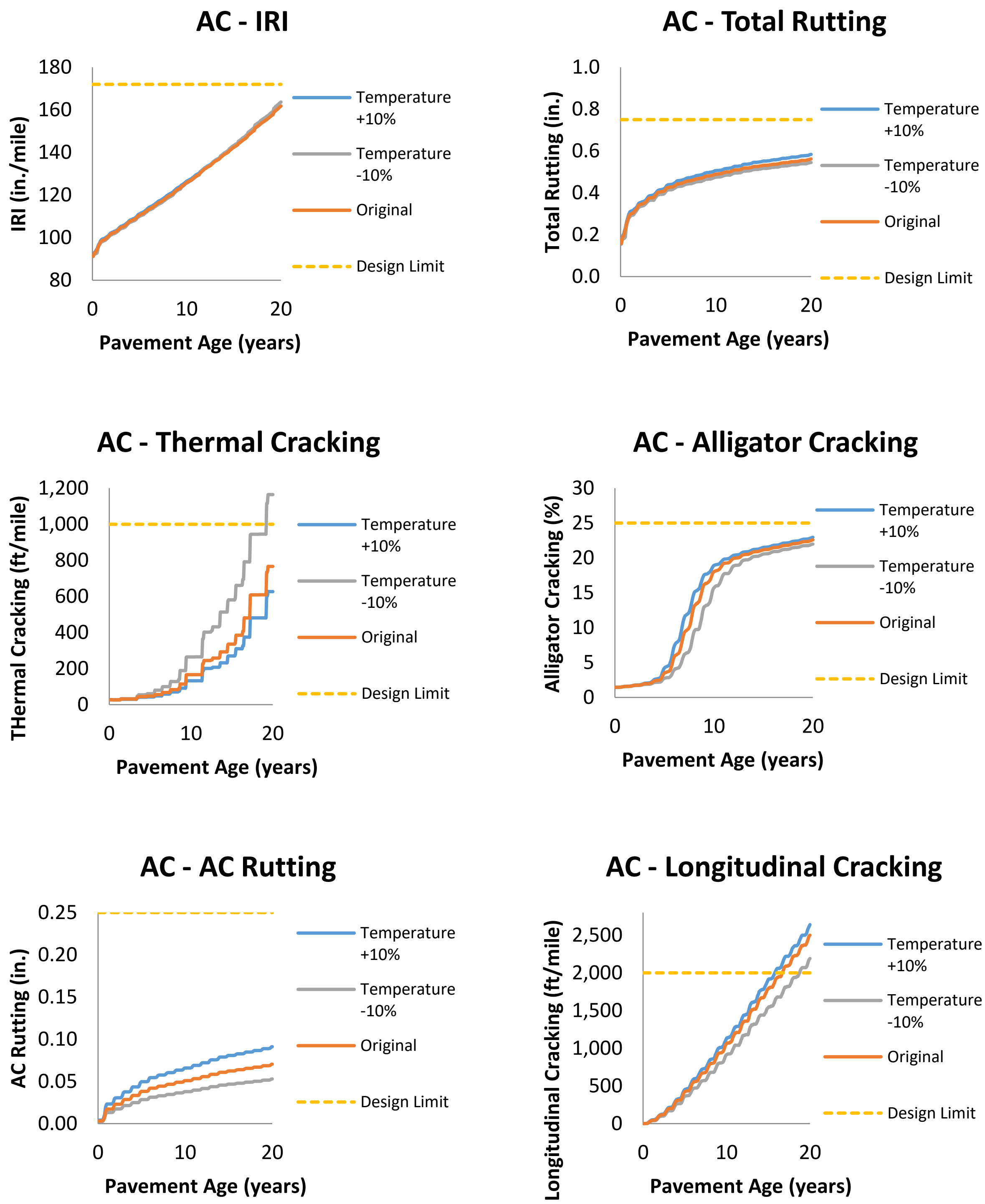


Figure D6. Asphalt Pavement, Varied Daily Air Temperature for Rapid City

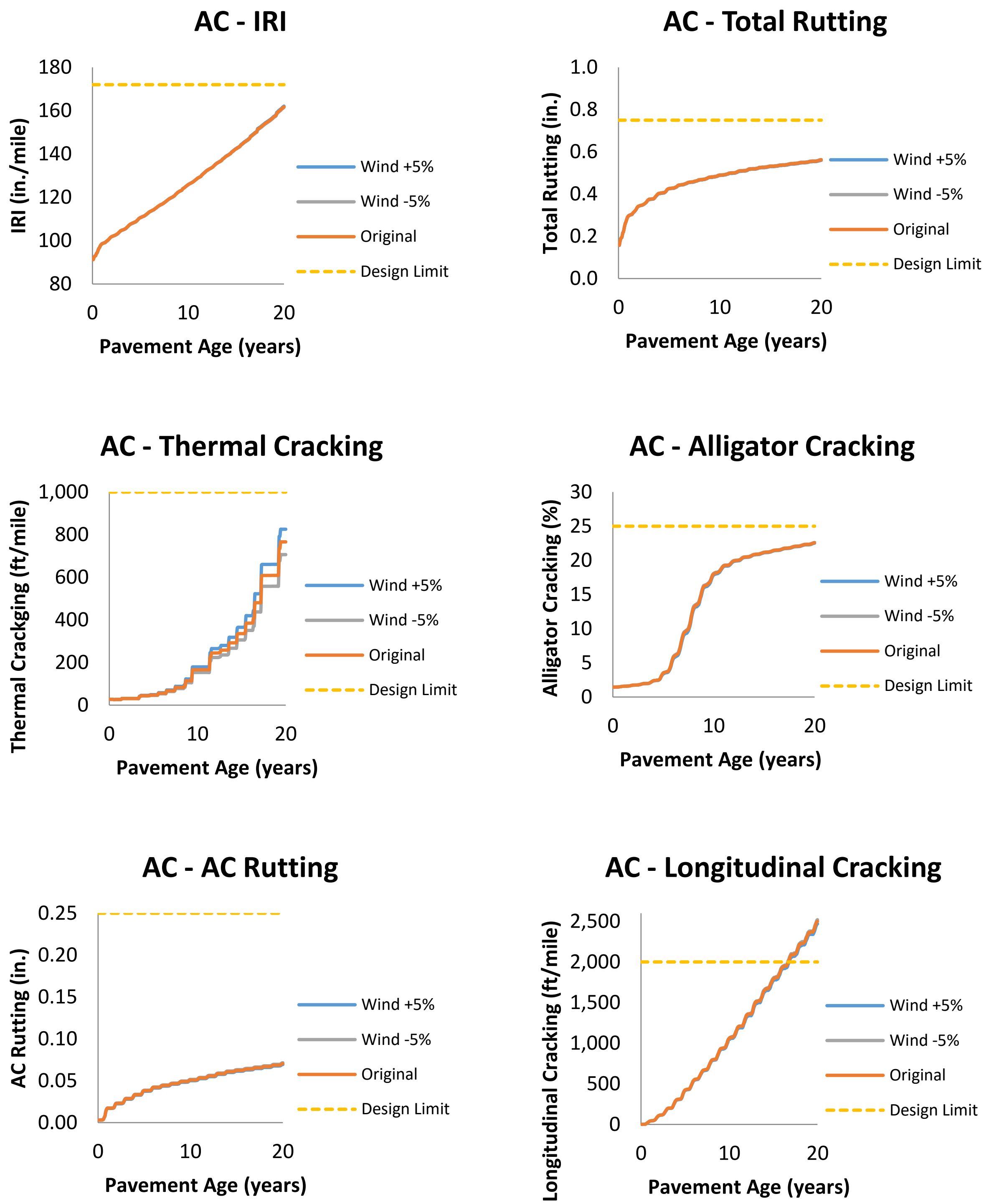


Figure D7. Asphalt Pavement, Varied Wind Speed for Rapid City

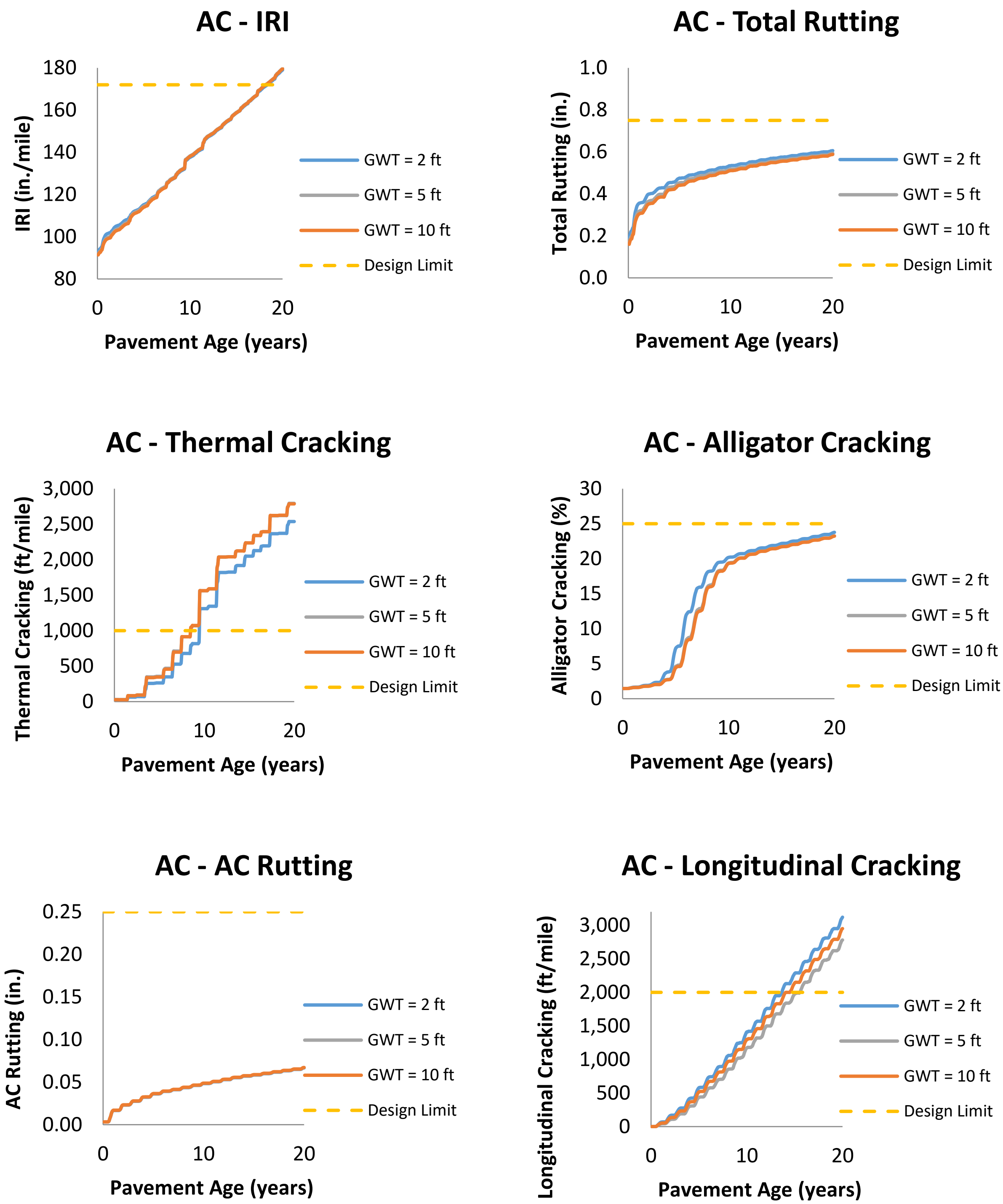


Figure D8. Asphalt Pavement, Varied Groundwater Table for Sioux Falls

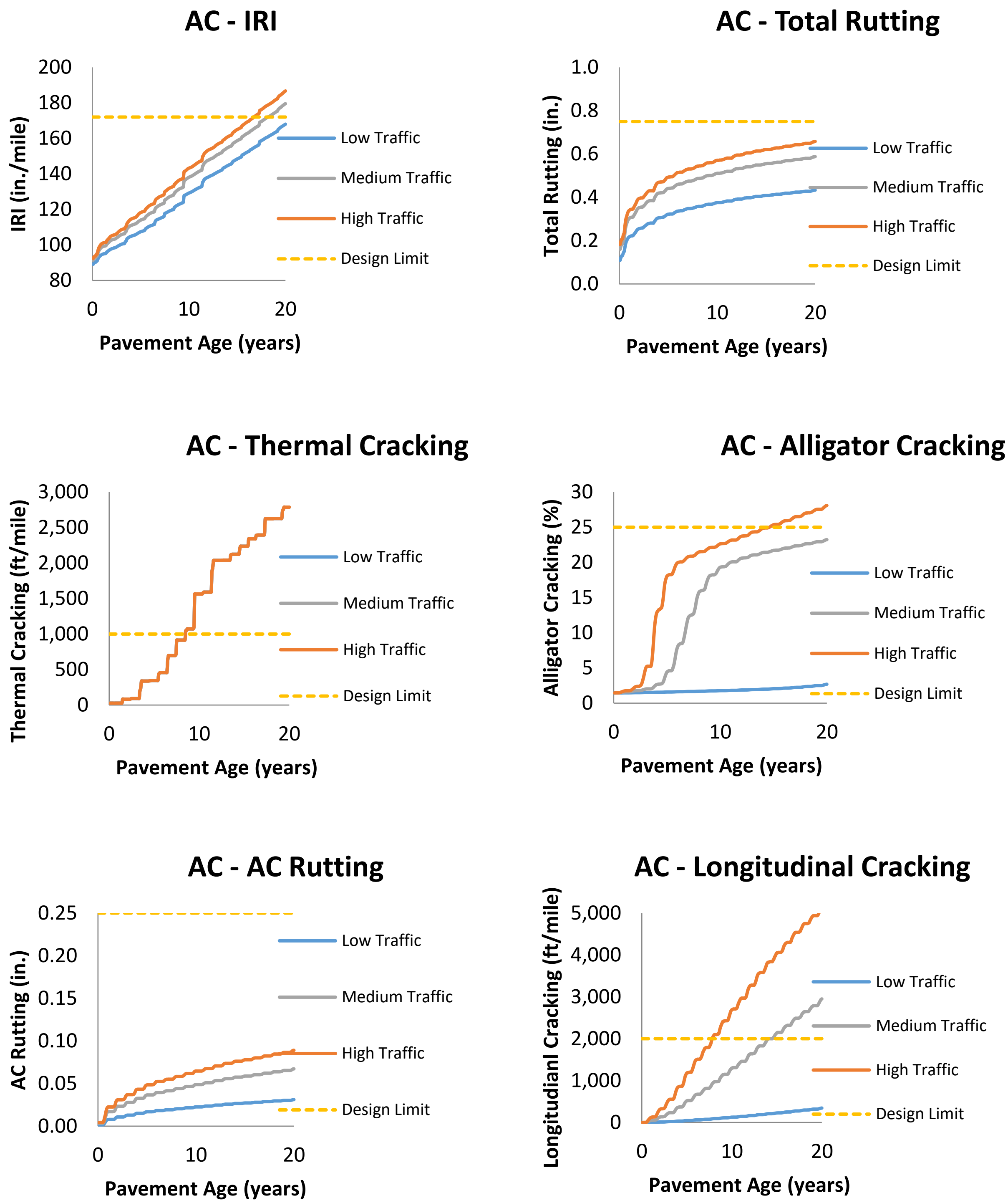


Figure D9. Asphalt Pavement, Varied Traffic Level for Sioux Falls

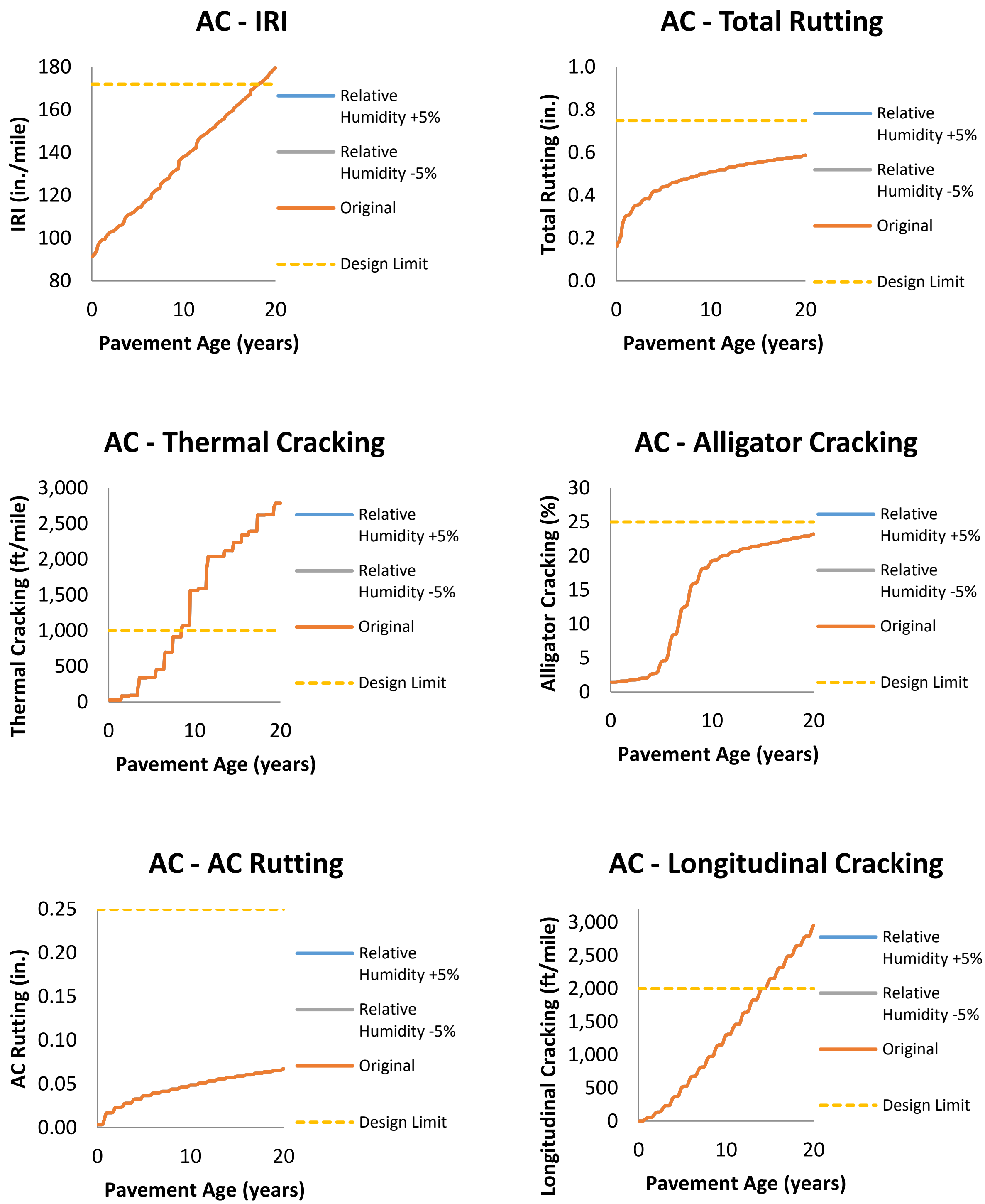


Figure D10. Asphalt Pavement, Varied Relative Humidity for Sioux Falls

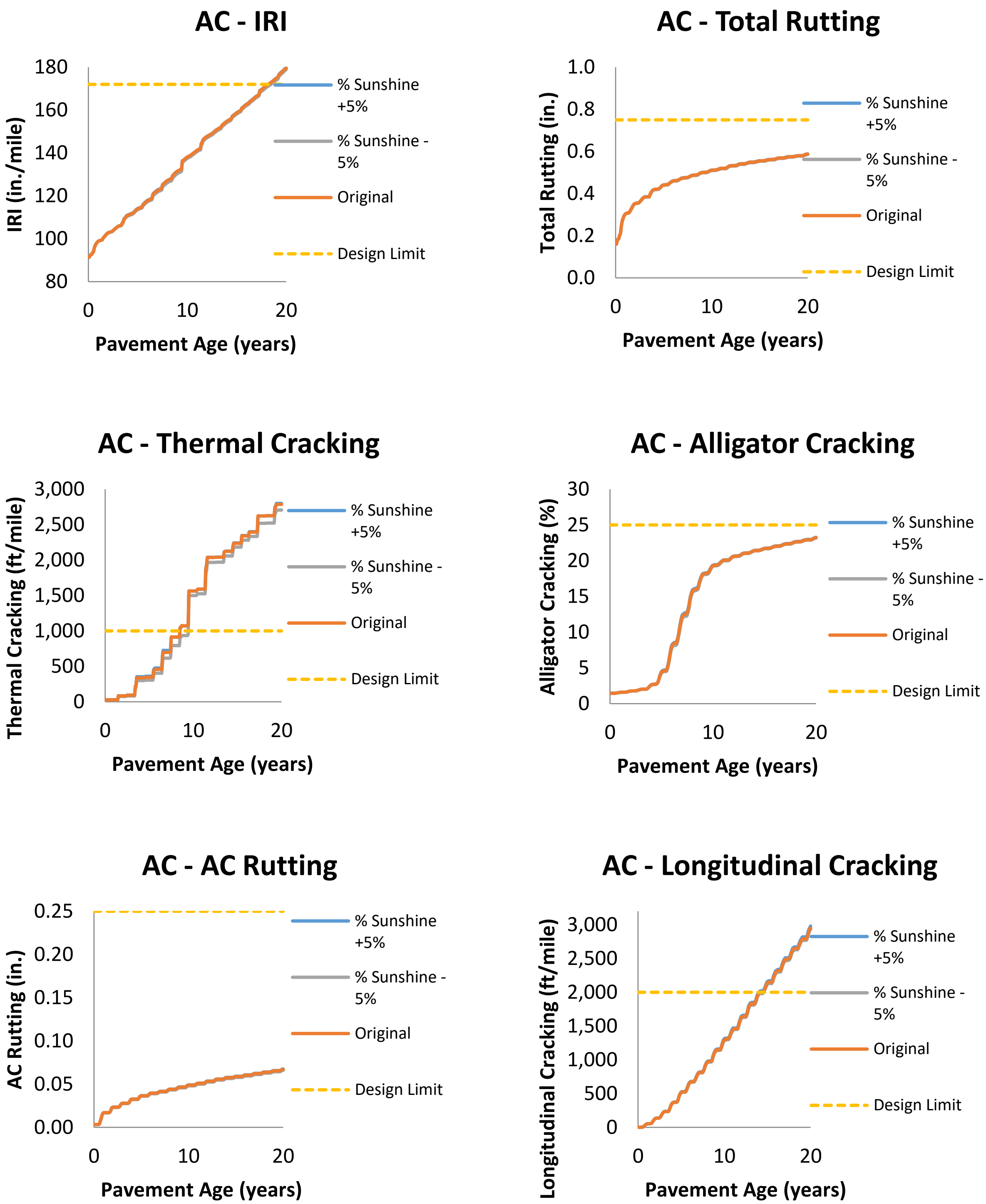


Figure D11. Asphalt Pavement, Varied Percent Sunshine for Sioux Falls

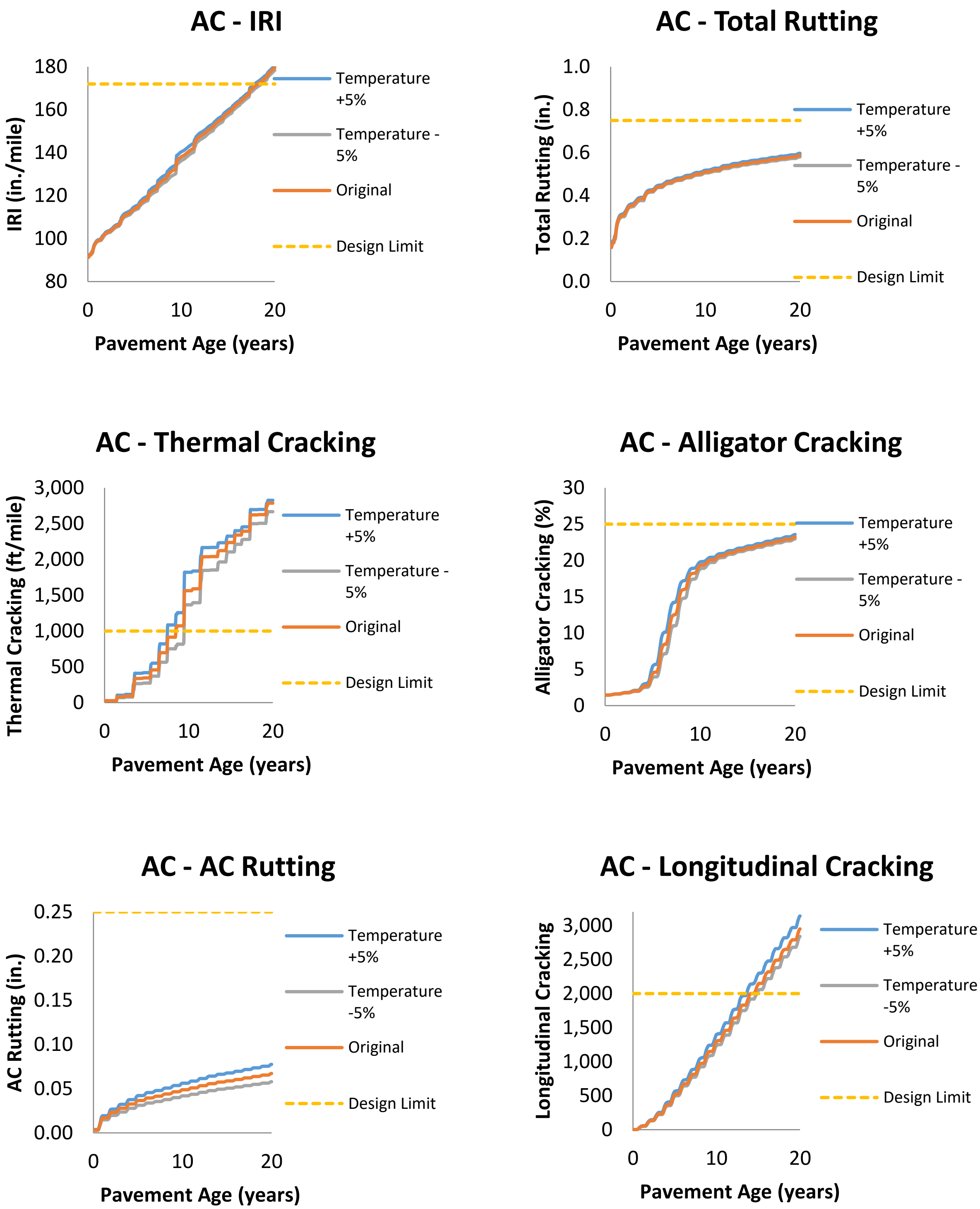


Figure D12. Asphalt Pavement, Varied Annual Air Temperature for Sioux Falls

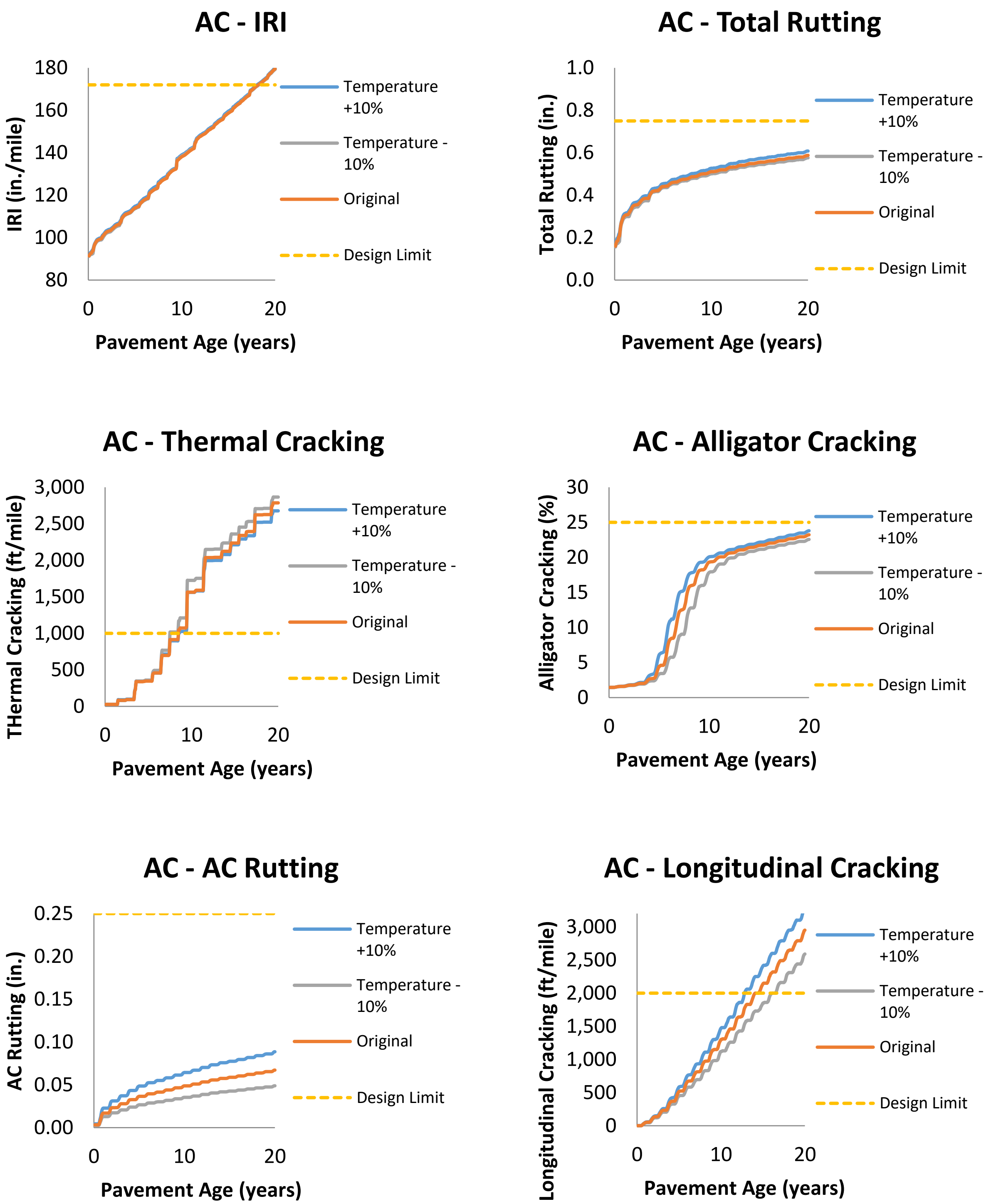


Figure D13. Asphalt Pavement, Varied Daily Air Temperature for Sioux Falls

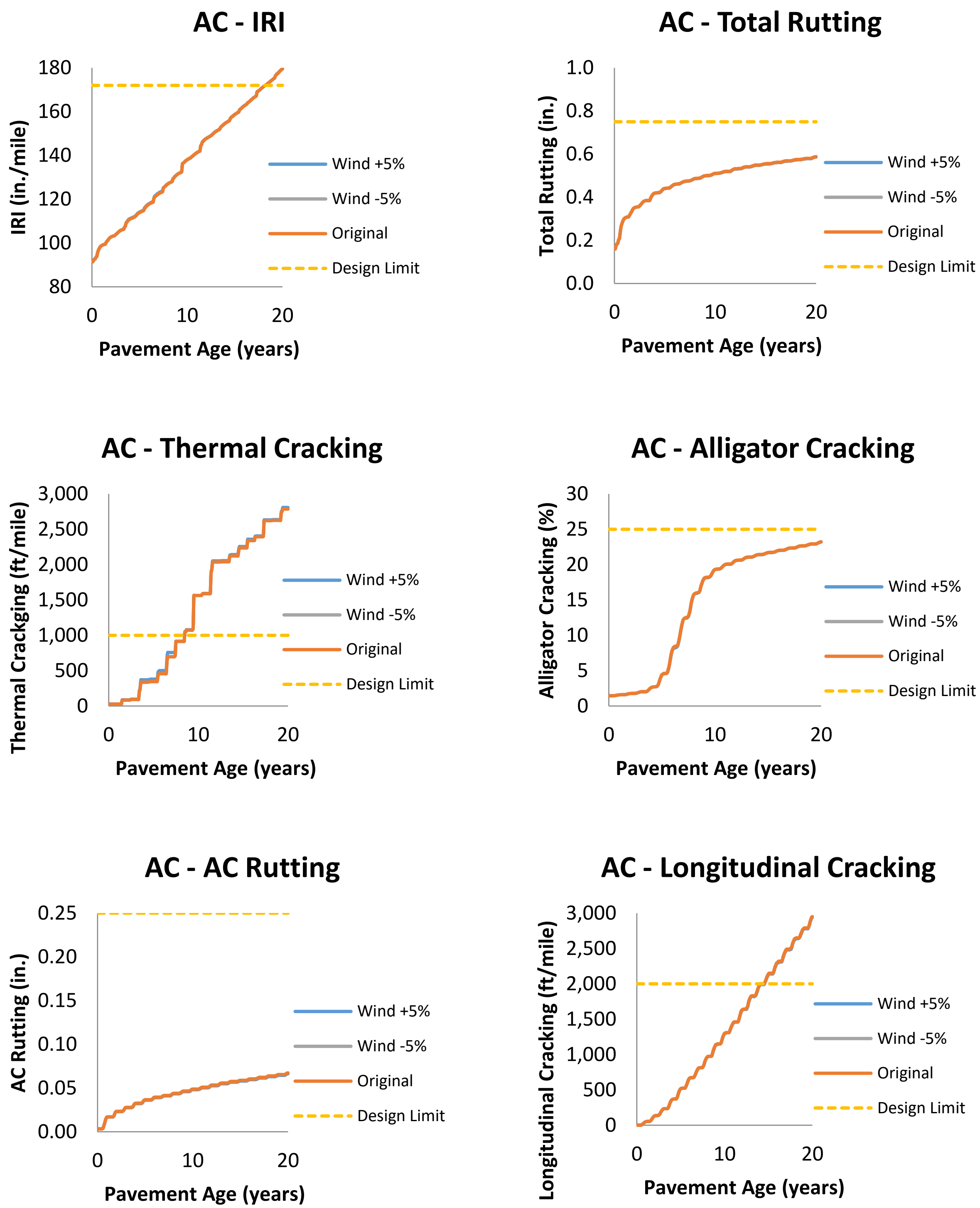
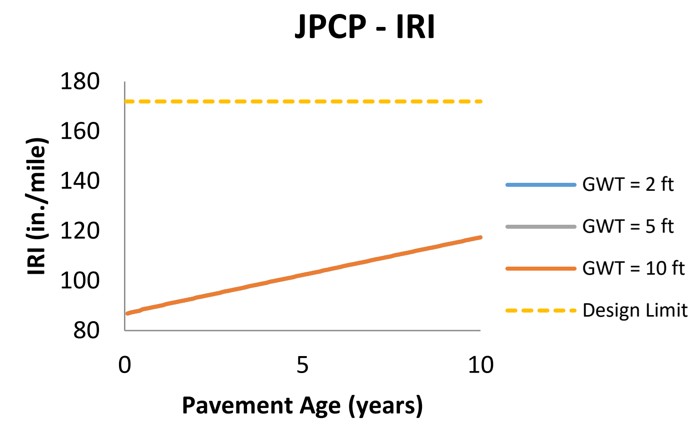
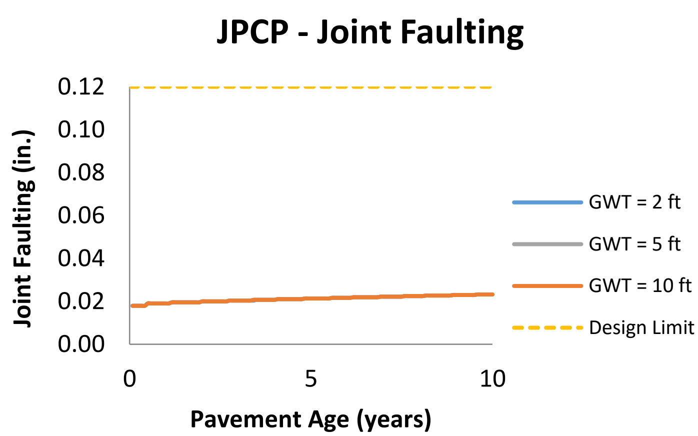


Figure D14. Asphalt Pavement, Varied Wind Speed for Sioux Falls





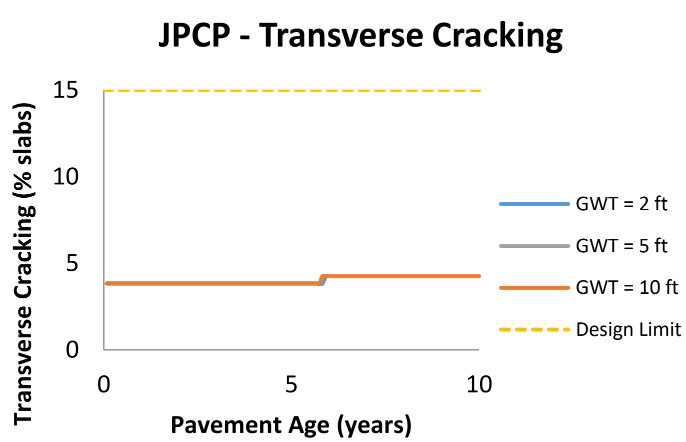
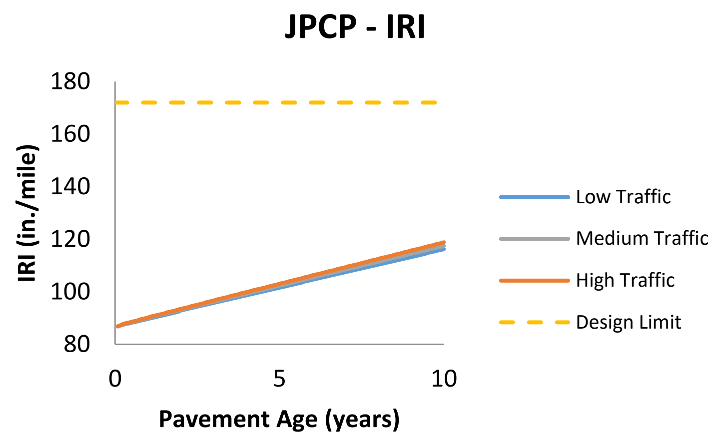
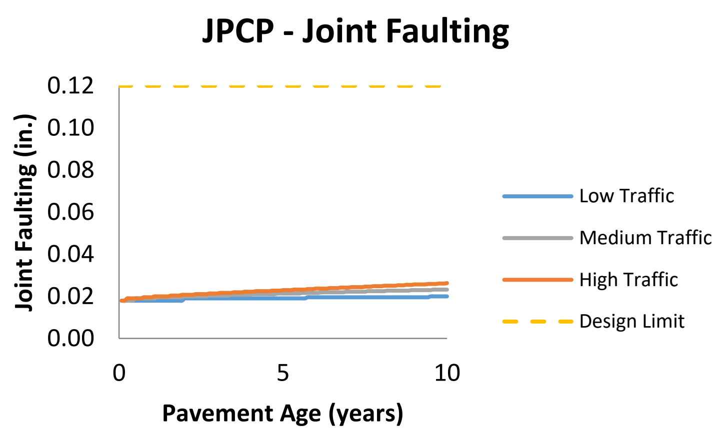


Figure D15. Concrete Pavement, Varied Groundwater Table for Rapid City





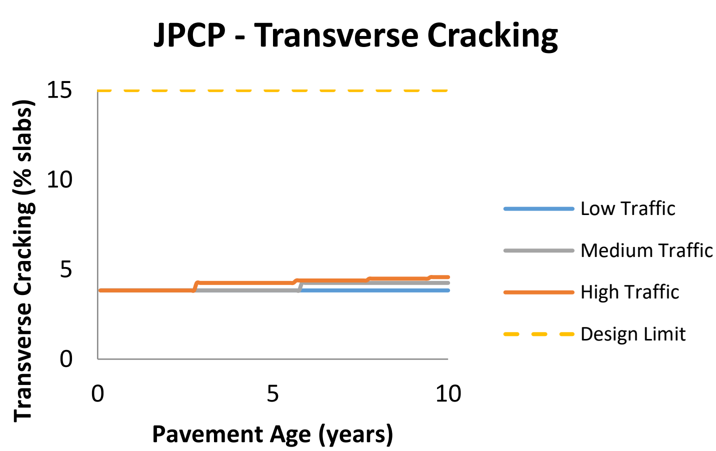
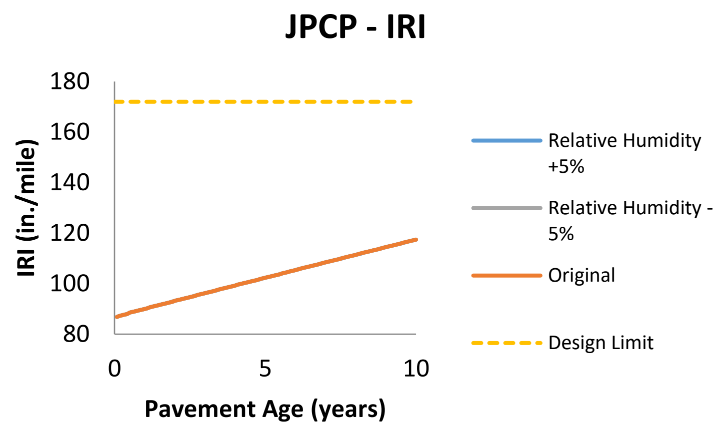
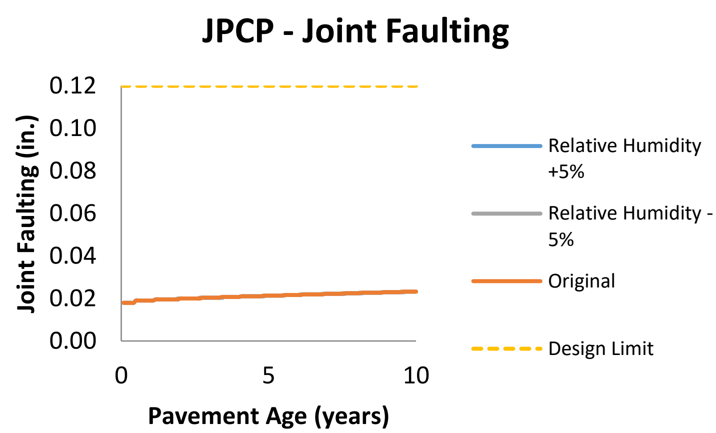


Figure D16. Concrete Pavement, Varied Traffic for Rapid City





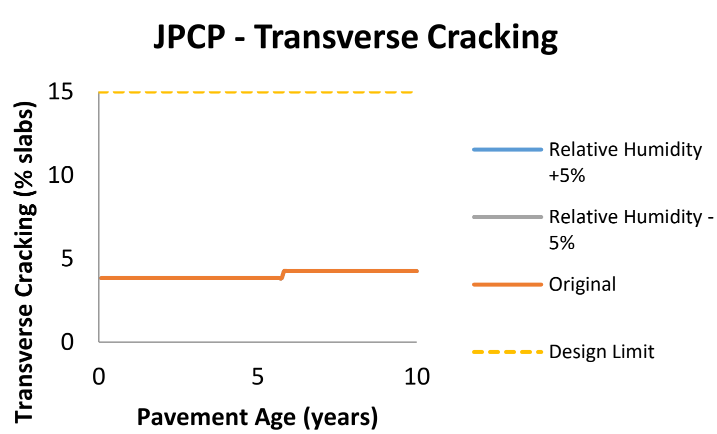
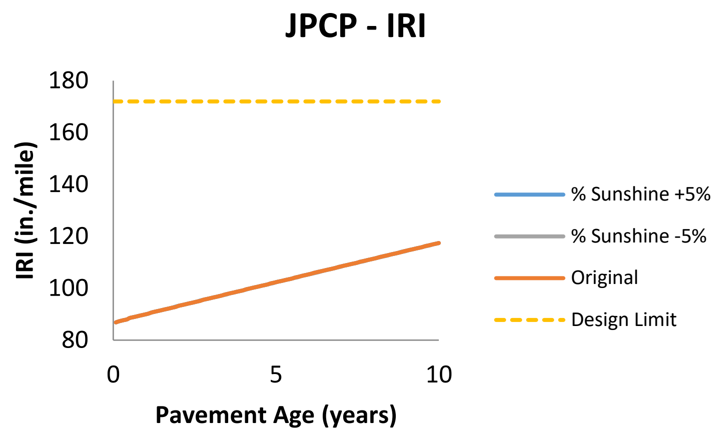
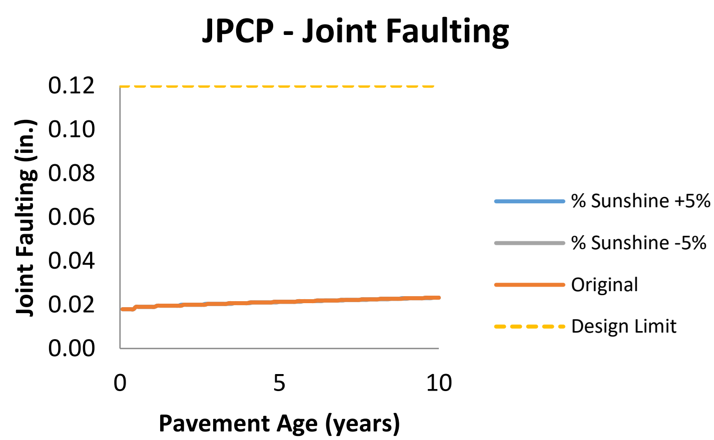


Figure D17. Concrete Pavement, Varied Relative Humidity for Rapid City





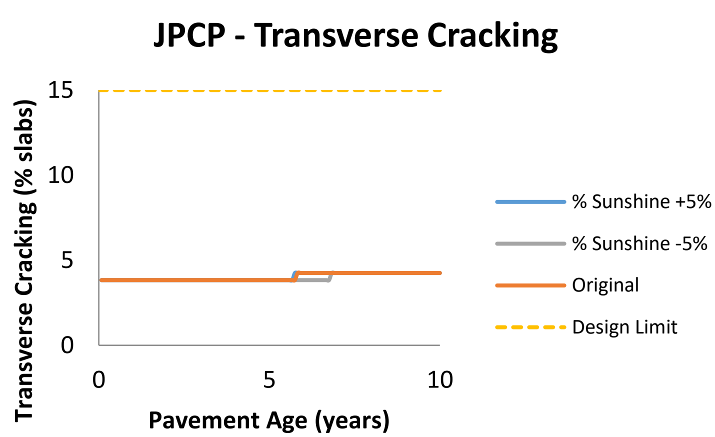


Figure D18. Concrete Pavement, Varied Percent Sunshine for Rapid City

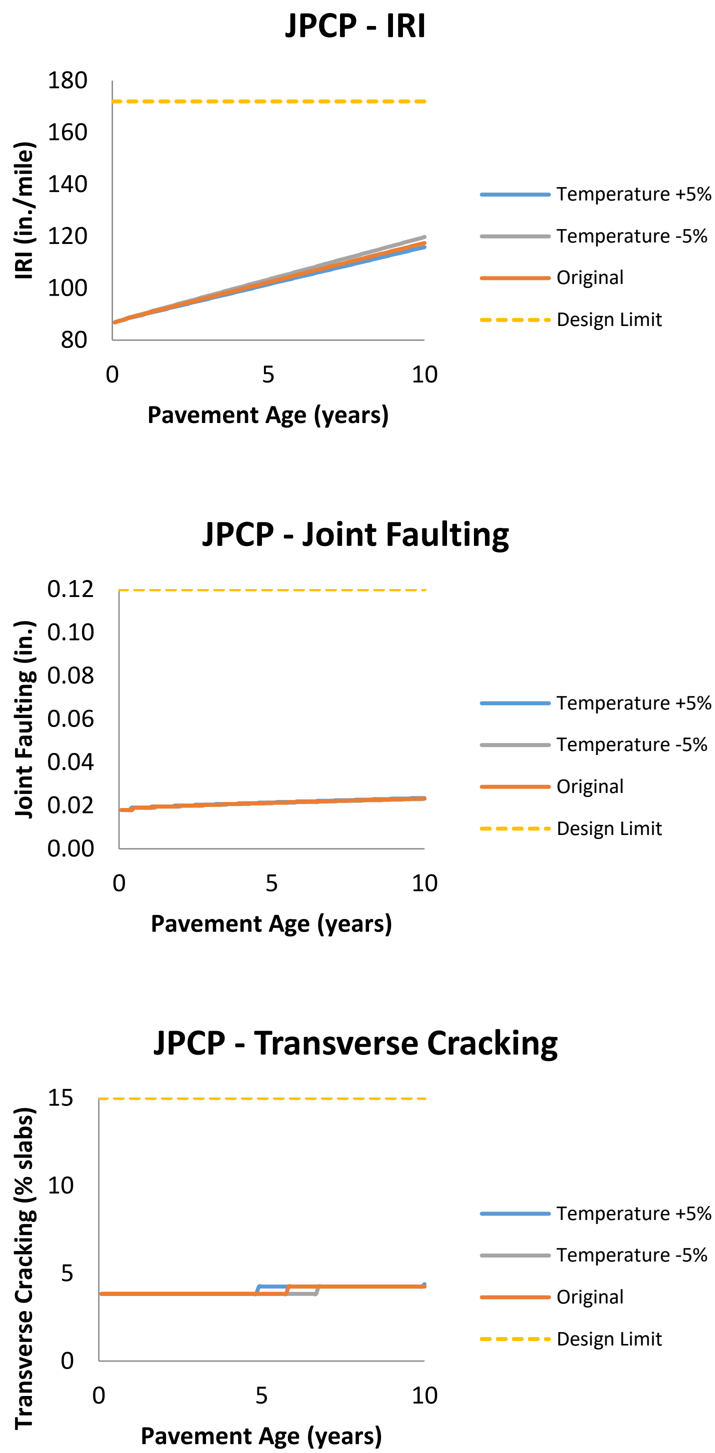
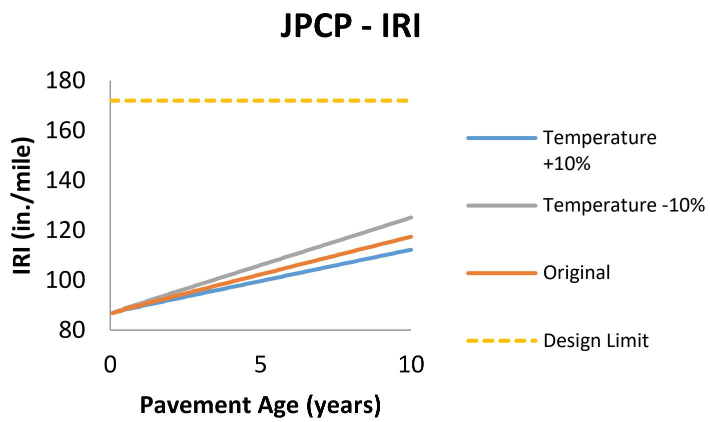
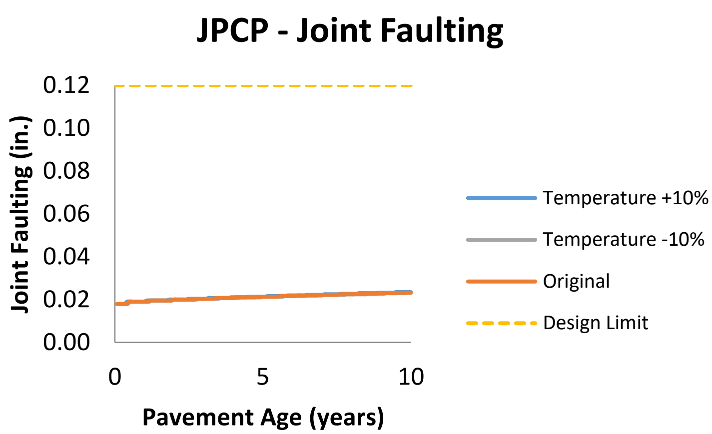


Figure D19. Concrete Pavement, Varied Annual Air Temperature for Rapid City





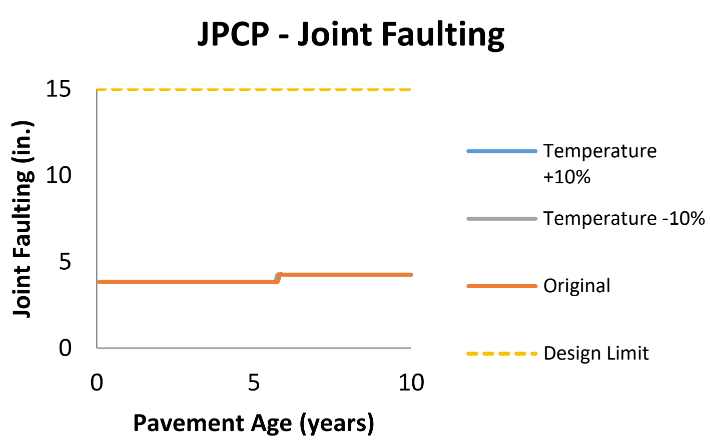


Figure D20. Concrete Pavement, Varied Daily Air Temperature for Rapid City

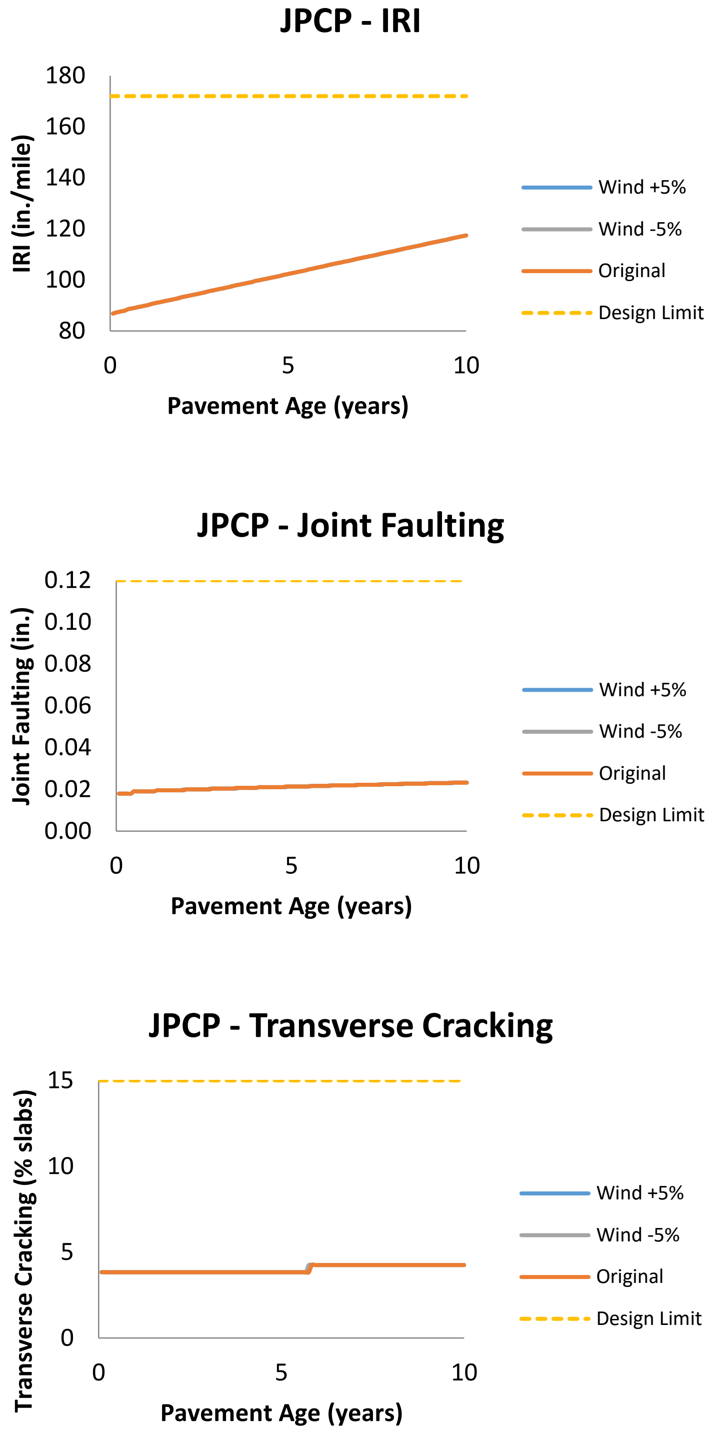
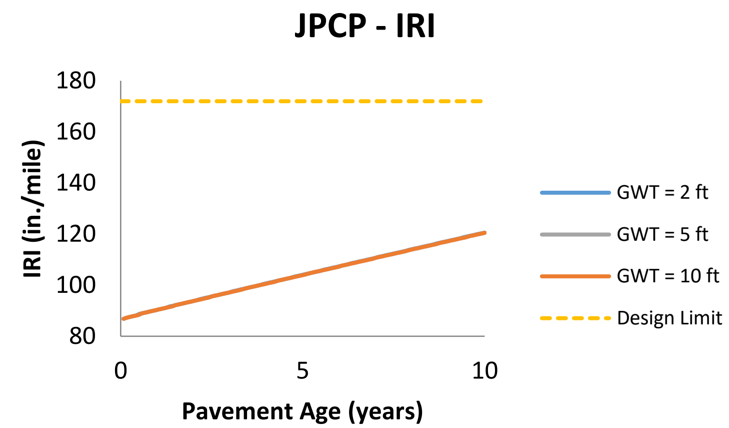
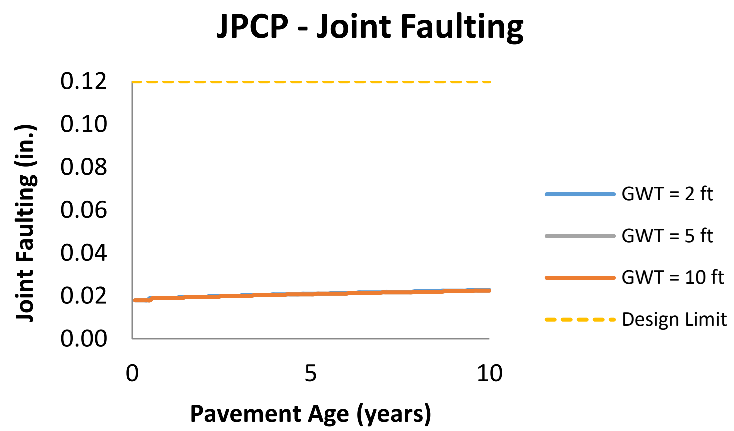


Figure D21. Concrete Pavement, Varied Wind Speed for Rapid City





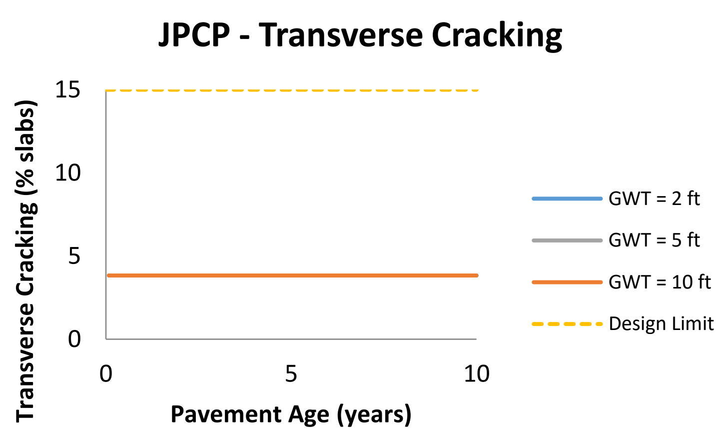
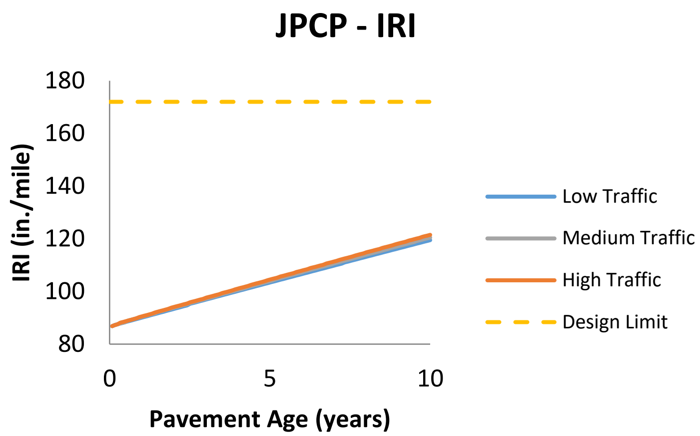
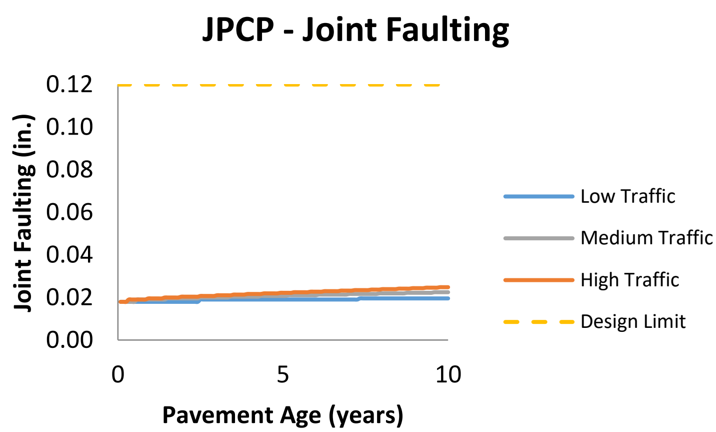


Figure D22. Concrete Pavement, Varied Groundwater Table for Sioux Falls





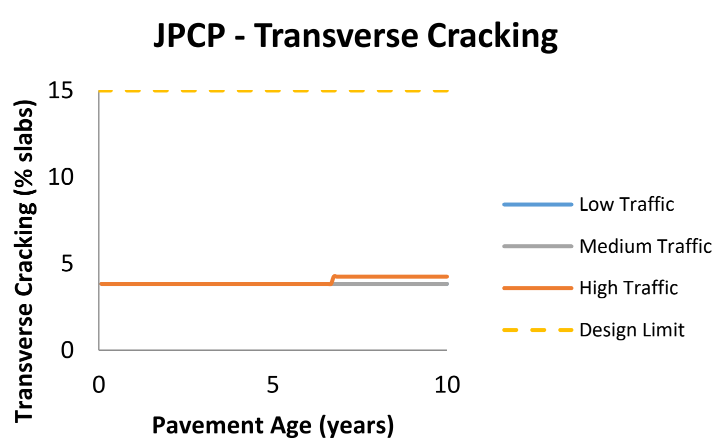


Figure D23. Concrete Pavement, Varied Traffic for Sioux Falls

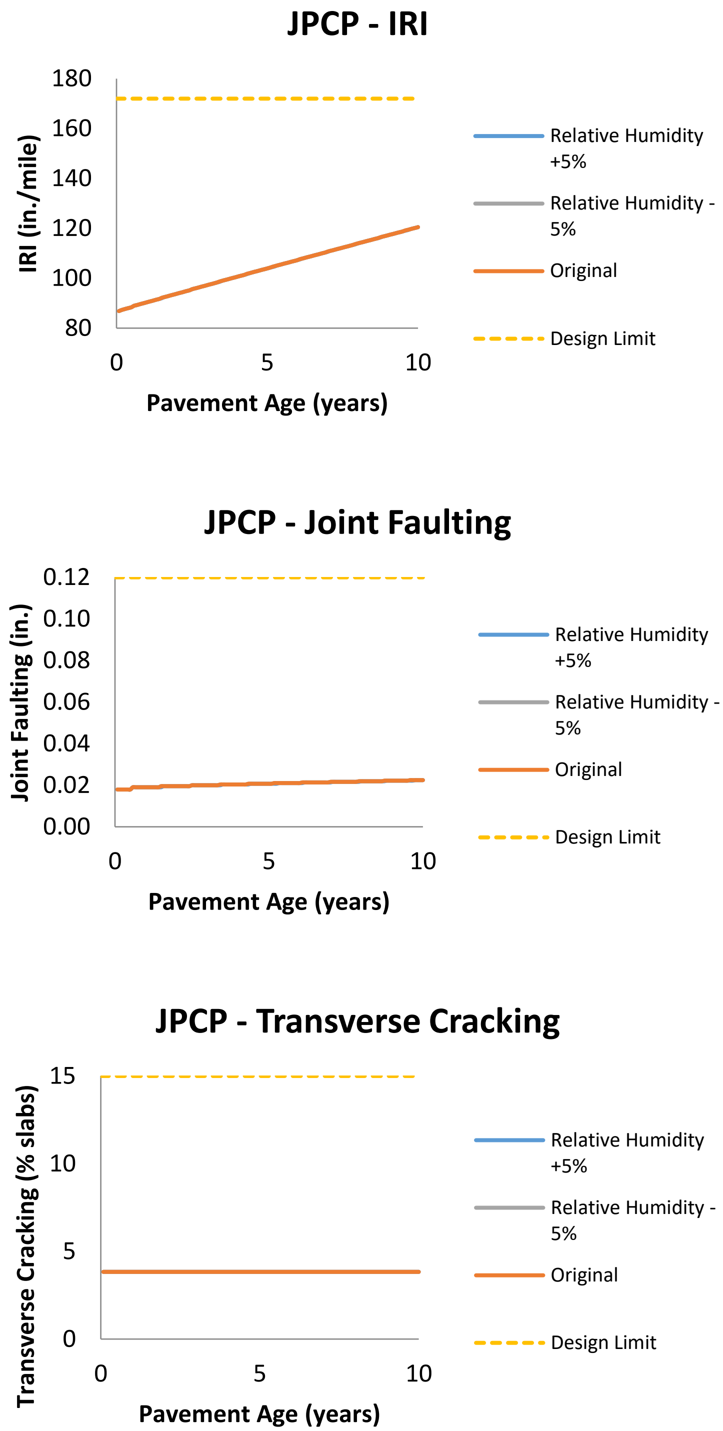
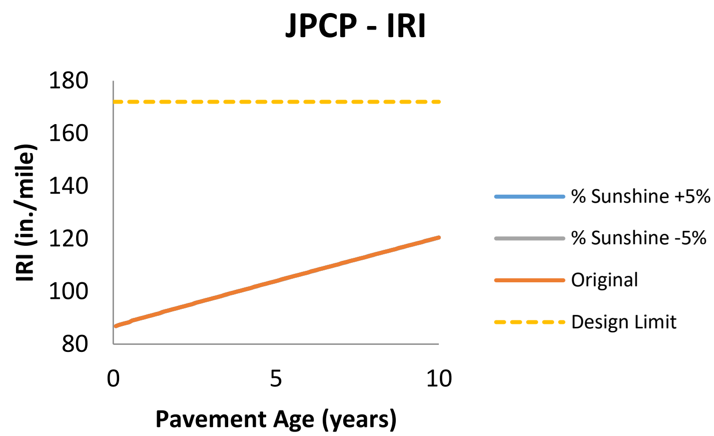
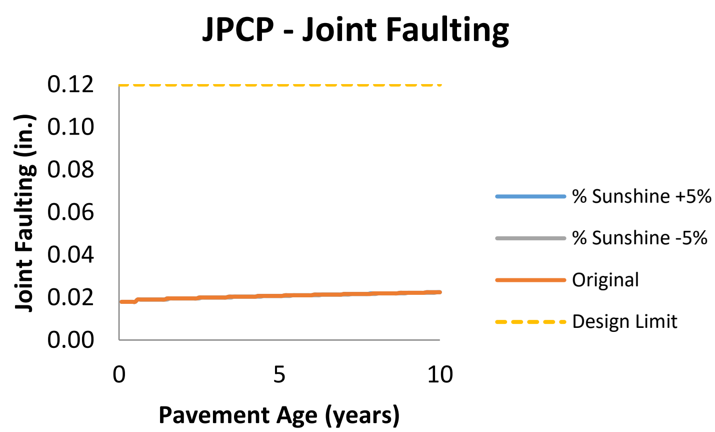


Figure D24. Concrete Pavement, Varied Relative Humidity for Sioux Falls





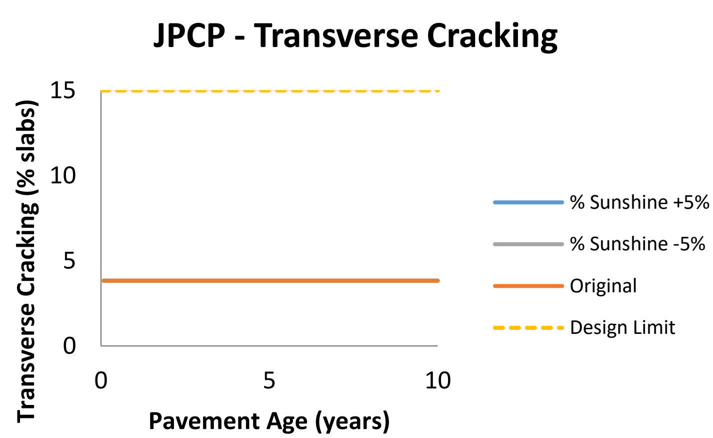
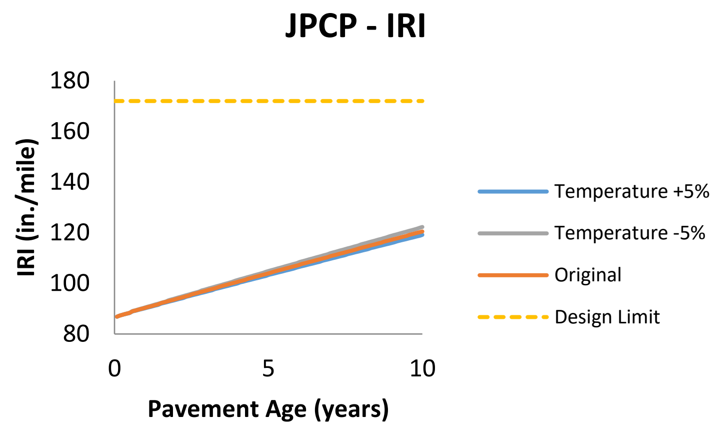
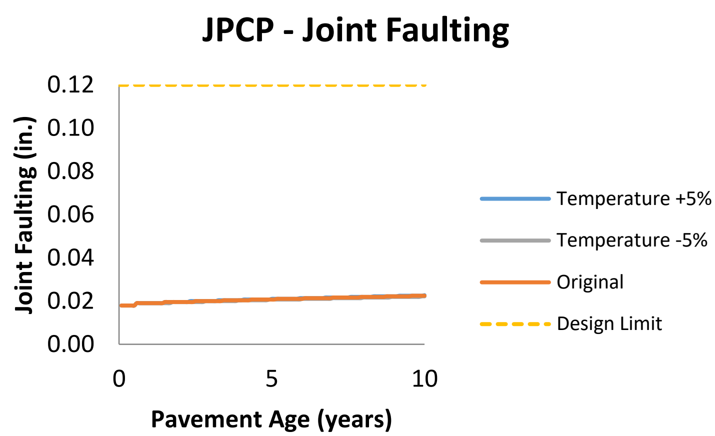


Figure D25. Concrete Pavement, Varied Percent Sunshine for Sioux Falls





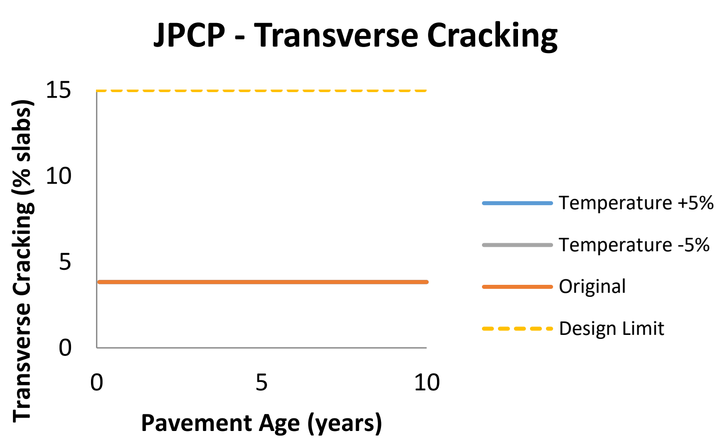
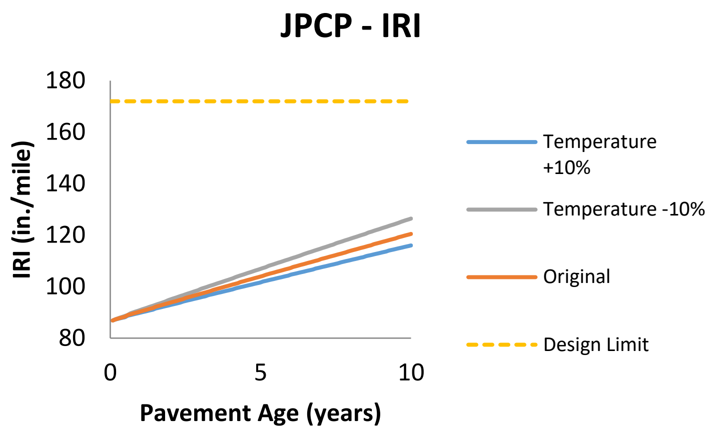
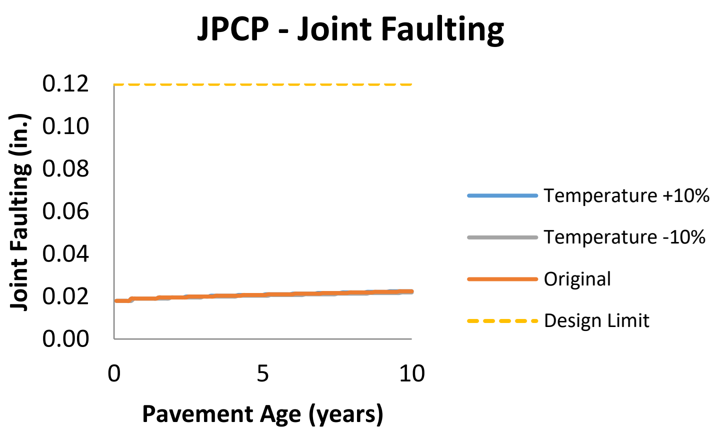


Figure D26. Concrete Pavement, Varied Annual Air Temperature for Sioux Falls





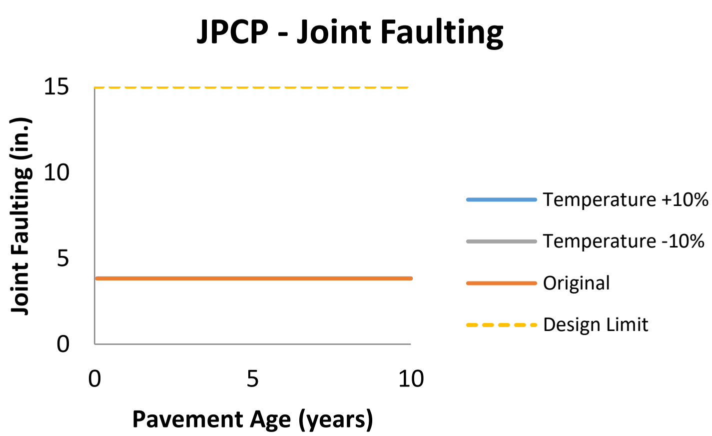


Figure D27. Concrete Pavement, Varied Daily Air Temperature for Sioux Falls

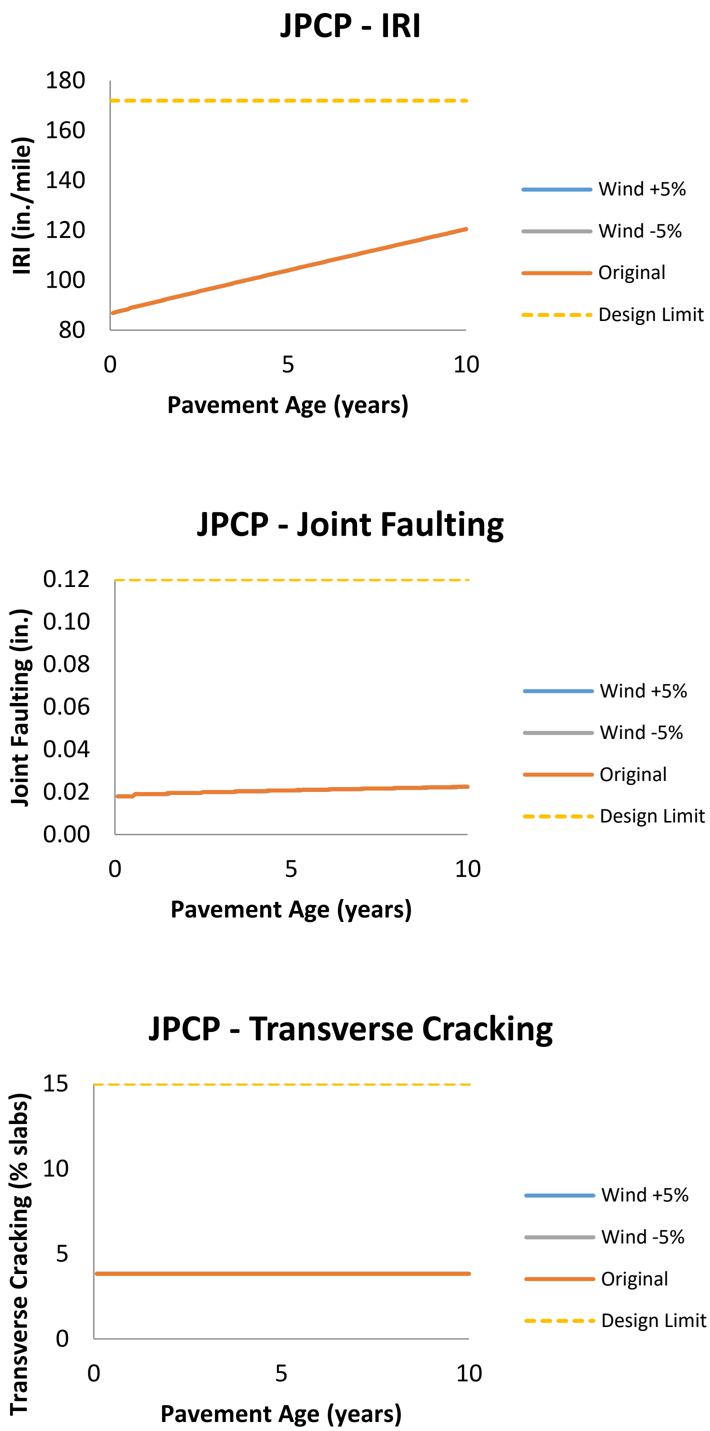


Figure D28. Concrete Pavement, Varied Wind Speed for Sioux Falls