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Verification of Virtual Climatic Data in MEPDG Using the LTPP Database

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Abstract: The Enhanced Integrated Climatic Model (EICM) integrated in the Mechanistic-Empirical Pavement Design Guide (MEPDG) allows users to select adjacent weather stations to generate a virtual weather station (VWS), whose data are further used to predict environmental impact on pavement performance. It is essential that the derived virtual data be accurate and representative of the actual climatic conditions. To evaluate the accuracy of the MEPDG generated VWS data, climatic data from corresponding automated weather stations (AWS) in the long-term pavement performance (LTPP) database are obtained to conduct the comparison analysis. It is observed that most VWS climatic data estimate the actual weather data reasonably well. However, in some cases, significant differences are observed. The potential factors resulting in the discrepancies are investigated. MEPDG analyses are conducted to quantify the climate data differences on predicted pavement performance. Finally, the paper presents recommendations when using the MEPDG software to generate VWS so as to help establish more accurate key climatic inputs.

Key words: *Enhanced integrated climatic model; Long-term pavement performance; Mechanistic-empirical pavement design guide.*

Introduction

Environmental conditions, such as temperature and moisture, can significantly affect the pavement layer and subgrade properties, and, hence, its pavement performance. The MEPDG approach fully considers the changes of temperature and moisture profiles in the pavement structure and subgrade over the design life through the incorporation of the EICM into the MEPDG software [1]. More than 800 weather stations from the National Climatic Data Center (NCDC) throughout the United States are identified for MEPDG software, which allows designers to select a given station or to generate a VWS for a project site under design.

The climate module is fully incorporated in the MEPDG software and, therefore, very limited research efforts have been devoted to verify the effectiveness of the VWS data generated using the MEPDG software. Using Canadian data from the LTPP program, Tighe et al. [2] adopted the MEPDG software to quantify the impacts of projected climatic changes on pavement performance of low volume roads at six sites located in southern Canada. Zaghloul et al. [3] found that using different weather stations to generate VWSs in MEPDG would result in significant differences in pavement performances, even though the two pavement sections under study were designed with the same structures and to be built about 15*mi* (24*km*) apart. The observation is against conventional engineering wisdom. In the NCHRP 1-37A report [1], it is suggested "the EICM has been validated only on a limited basis, and further comparison of outputs with actual field conditions has been recommended."

In this paper, the climate data obtained from the AWS in the LTPP database are used as the actual onsite climatic data to verify the accuracy of the MEPDG generated VWS data. The following tasks are conducted:

- Compare the MEPDG generated VWS data with the onsite LTPP AWS measurements by determining the accuracy of VWS data and identifying potential influencing factors.
- Investigate the impacts of MEPDG projected virtual climatic data on pavement performance.
- Present recommendations when using MEPDG software to generate VWS for a particular design.

Automated Weather Stations (AWS) in LTPP

AWS have been installed near almost all the LTPP SPS-1, SPS-2, and SPS-8 project sites to measure site-specific climatic information. Within the LTPP program, research efforts have been devoted to examine the reliability and accuracy of the LTPP climatic data [4, 5, and 6]. The AWS tables are structured to provide users with monthly, daily, and hourly climate statistics [7].

To ensure good quality of the measured AWS climate data, a two-step data quality control process including data scanning in the field and office data checks was developed and applied to the raw climate data collection [8]. Field data scanning was used to quickly examine collected data while the operator was still in the field to detect data anomalies that could be caused by malfunctions of AWS equipment or other unforeseen events. The office data quality checks adopted a computer program called AWSCheck [8] to automate the quality checks and to process collected AWS data. Only the data that passed the data check were stored in the LTPP database. Therefore, it is assumed that the climate data from AWS have good quality and can be served as actual onsite climate data to verify the accuracy of MEPDG generated VWS data. In total, 42 automated weather stations are derived from the LTPP Datapave online database [9].

Virtual Weather Station (VWS) Using MEPDG

The virtual climate stations are generated using the EICM software integrated in MEPDG. With the GPS coordinates and elevation of a

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design project, EICM calculates the distance between the site and each highlighted weather station and the amount of information (number of months) available for each station. After the appropriate representative weather stations are chosen, interpolation of climatic data from these stations is conducted, and the interpolated data are stored as a VWS. The VWS climatic data are estimated by averaging data from up to six nearby weather stations using a 1/R weighting scheme as follows [4].

$$V_m = \frac{\sum_{i=1}^{k} (V_{mi}/R_i)}{\sum_{i=1}^{k} (1/R_i)} \tag{1}$$

where, V_m = Calculated virtual weather data element for day m, k = Number of weather stations selected for VWS interpolation, V_{mi} = Value of a data element on day m for weather station i, and R_i = Distance of weather station i from the pavement project site.

Two virtual weather stations are generated using the MEPDG software at each location: (1) Case 1–interpolated based on the data from adjacent six closest weather stations and (2) Case 2–interpolated based on the data from the closest weather station only.

Comparison Analysis

The generated VWS data files include weather-related data on an hourly basis over the entire design life. Statistical summaries are obtained from the VWS hourly data.

Monthly Climate Summary Data

The absolute differences of the maximum temperatures, minimum temperatures, average temperatures, and precipitations between AWS and VWS climte data are computed respectively. The average value and standard deviation, maximum, and minimum values of the differences are then calculated for overall data sets. Table 1 presents the computed results for the LTPP AWSs, MEPDG Case 1, and Case 2 VWSs as well as the number of data points used in the analyses.

It can be observed that the average of the differences among all the three scenarios are relatively small, which indicates that the MEPDG VWS data generally are accurate enough to model onsite climate conditions. For example, the average of the differences of maximum temperature, minimum temperature, mean temperature, and precipitation between AWS and MEPDG Case 1 VWS are 2.15^{0}F, -1.47^{0}F, 0.031^{0}F, and -0.40*in.* (1.19^{0}C, -0.82^{0}C, 0.02^{0}C, and -10.16*mm*), respectively. However, when we examine the ranges of the absolute differences (maximum and minimum of the differences), wide variations are observed. The errors in maximum and minimum temperature may lead to the wrong selection of binder grade in a pavement design and, therefore, result in rutting and low temperature cracking issues.

The distributions of the absolute differences are plotted into histograms for the monthly climatic data. For illustration purposes, histograms of absolute differences between LTPP AWS and MEPDG Case 1 VWS data are shown on the left side of Fig. 1. It is observed that the distributions of the absolute differences are either positively or negatively skewed, which indicates that they do not follow normal distributions. Generally, normal distribution is assumed for most engineering data analysis to simulate systematic errors generated mostly from interior factors. Therefore, it is believed that prediction errors are stemmed from exterior factors rather than from the interior systematic statistical error. Scatter plots of LTPP AWS data and MEPDG Case 1 VWS data are shown on the right side of Fig. 1. Most of the data are relatively close to the line of equality. It is also noted that some data points are widely scattered from the line of equality, especially for the precipitation and minimum temperature data.

Standard deviations of the absolute differences may not be acceptable for some parameters. For example, the standard deviation of the absolute difference for minimum temperature is as high as 7.11^{0}F (3.95^{0}C). In general, the average of the differences for mean temperature shows the smallest variation, whereas that for minimum temperature data exhibits the biggest variation. The variation associated with maximum temperature is less than that with minimum temperature.

Annual Climate Summary Data

In addition to mean temperature and precipitation, number of freeze and thaw cycles is evaluated. The absolute differences and their associated standard deviations are computed annually for each test

Table 1. Comparisons of Monthly and Annual Climate Data.

			AWS vs. VWS Case 1				AWS vs. VWS Case 2				VWS Case 1 vs. VWS Case 2			
	Criterion	n[a]	$\overline{X}$[b]	Max[c]	Min[d]	STD[e]	$\overline{X}$	Max	Min	STD	$\overline{X}$	Max	Min	STD
	Max Temp. (^{0}F)	2952	2.2	18.1	-17.0	2.6	1.5	14.7	-37.5	3.5	-0.6	9.3	-24.9	2.2
	Min Temp.(^{0}F)	2952	-1.5	53.6	-19.6	5.4	-0.5	102.1	-16.5	7.1	1.0	106.2	-51.9	4.5
	Mean Temp(^{0}F)	2952	0.03	11.8	-7.9	1.6	0.02	13.9	-7.7	2.6	-0.01	7.9	-6.6	1.6
	Precip. (*in.*)	2851	-0.4	94.3	-19.1	2.5	-0.3	94.5	-19.2	2.5	0.09	5.9	-3.8	0.6
Annual	Mean Temp.(^{0}F)	42	-0.4	3.1	-4.3	1.4	-0.5	7.9	-5.8	2.7	-0.06	6.8	-5.4	2.0
	Precip. (*in.*)	42	-5.3	4.5	-34.3	8.9	-4.1	7.2	-32.5	9.1	-1.2	2.3	-9.8	2.1
	Freeze/Thaw Cycles	42	15.3	64.0	-20.1	18.8	9.6	51	-37.5	21.9	-4.1	42	-48	17.3

Notes: [a] n = Number of data points, [b] $\overline{X}$ = Average of absolute difference, [c] Max = Maximum of absolute difference, [d] Min = Minimum of absolute difference, [e] STD = Standard deviation of absolute difference.

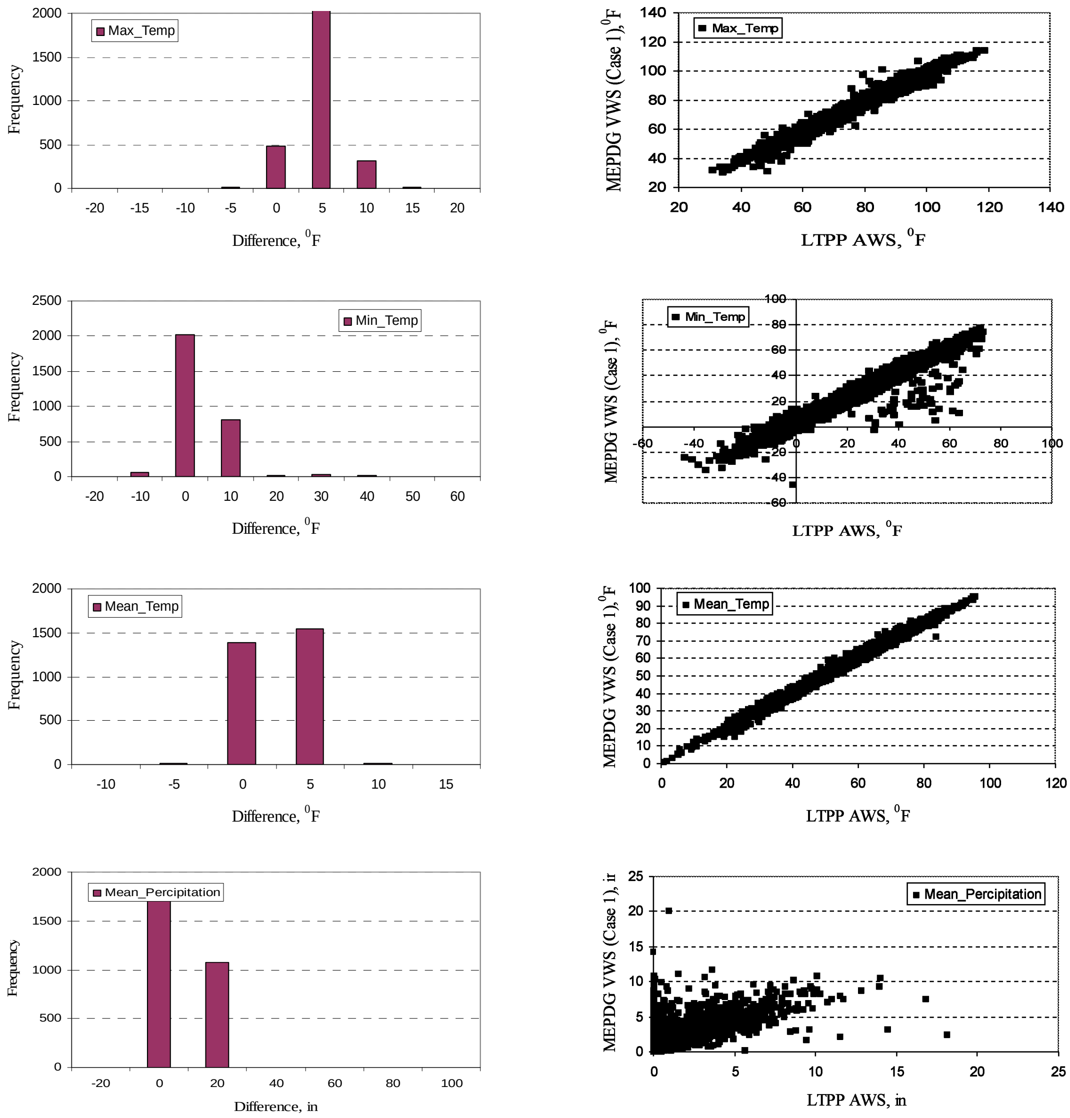

Fig. 1. Comparisons of Monthly Average Climate Data.

site. The results are presented in Table 1. Similar observations are found to those for monthly data. The VWS mean temperature data are observed to represent the onsite condition reasonably well. However, wide dispersions are found for annual precipitation and number of freeze and thaw cycles data between AWS and VWS. Again the distributions of the absolute climatic difference are not subjected to normal. The precipitation VWS data are under-predicted and the histogram is negative skewed, which has a long tail in the negative direction. By contrast, the number of freeze and thaw cycles data from VWS is over-predicted and the histogram is positively skewed.

Average Monthly Summary Data

The average monthly summary data are presented to show the average monthly absolute differences between VWS data and onsite AWS data around the year from January to December. It is observed that the 12 months VWS temperature and rainfall data are approximately identical to those monitored in LTPP AWS.

MEPDG Case 1 and Case 2 Data

In order to identify the influence of the number of weather stations used for VWS interpolation on the accuracy of climate data, comparisons between MEPDG Case 1 and Case 2 VWS data are analyzed. Similarly, the average of the absolute differences for each climate parameter is found to be very small. Comparing with Case 2, the ranges of the absolute difference are far decreased than those in MEPDG Case 1, which demonstrates that the adoption of more applicable weather stations in the virtual weather station generation process does smooth the erroneous data or fill in the missing information. It is recommended using as many applicable weather stations as possible for a particular design.

Distance and Elevation Influence

As abovementioned, the skewed distribution of the histograms for the absolute differences should be caused by exterior factors. When

Table 2. ANOVA Analysis for Air Temperature.

Influencing Parameter	Absolute Temperature Difference between					
	AWS & VWS Case 1			AWS & VWS Case 2		
	F-ratio	p-value	Sample #	F-ratio	p-value	Sample #
Distance	0.60	0.44	42	0.35	0.56	42
Elevation Diffe.rence	2.97	0.09	42	2.59	0.12	42

Table 3. Inputs of the Baseline Pavement Structure for the MEPDG Software.

Description			Input
General Information		Reliability	90%
		Design Life	20 years
Traffic		Two-way AADTT	10,000
		Lanes in Design Direction	2
		Traffic Growth (%)	3
		Other Factors	MEPDG Default
Climate		Fayetteville, AR	
Flexible	AC	Thickness	11*in.* (30*cm*)
		Mix	12.5*mm* and PG 70-22
		Retained on #3/4 (%)	0.1
		Retained on #3/8 (%)	12.6
		Retained on #4 (%)	37.4
		Passing #200 (%)	6.3
		Effective Binder Content (%)	6.0
		Air Voids (%)	4.2
	Granular Base	Thickness	14*in.* (35*cm*) Crushed Stone
		Modulus	40,000*psi* (275*MPa*)
Rigid	Concrete Layer	Thickness	12*in.* (30*cm*)
	Granular Base	Thickness	8*in.* (20*cm*) Crushed Stone
		Modulus	40,000*psi* (275*MPa*)
Subgrade		Classification	A-7-6
		Modulus	5,000*psi* (34.5*MPa*)

generating VWS in MEPDG, GPS coordinates and elevation of a project site are the only controllable parameters for designers. The GPS coordinates are used to calculate the distances between the design project and the adjacent MEPDG weather station(s) selected for interpolation. Distance and elevation differences are therefore identified as the primary suspects for the cause of wide variations.

To examine the significance of these two factors on the accuracy of MEPDG generated virtual data, ANOVA statistical analysis is conducted. Table 2 shows the F-ratio and P-value statistics from the ANOVA analysis. The F-ratio is a variance measure that also indicates whether a variable is contributing to the model. The P-value indicates whether a variable is a significant contributor to the model at a certain confidence level. A P-value greater than 0.1, for example, indicates that a variable is not significant at a 90% confidence level. It is discovered that the distance from the project site to its closest weather station doesn't have a significant influence on the accuracy of the climate data for both Case 1 and Case 2 VWS stations. Elevation difference does affect the accuracy of the climate data with a p-value of 0.09 and 0.12 for Case 1 and Case 2 VWS data, respectively. This observation shows that the topography around the weather station used for interpolation should be similar to that of the project site under design. If a weather station is relatively closer to the design site but has a significant difference in elevation of terrain, it is recommended to not use the station in the MEPDG interpolation process, but selecting a farther one with similar climate condition instead.

Comparing to the Case 2 VWS data, the influence of distance and elevation difference on generated Case 1climatic data accuracy is minimized, which indicates again that more applicable stations involved in the interpolation process can smooth the abnormal data sets, therefore improving the virtual climate data quality. However, the effectiveness is very limited based on the statistical data shown in Table 2.

Impact of Generated Climatic Data on Pavement Performance

The baseline pavement structures for a new flexible and a rigid pavement shown in Table 3 are designed using the 1993 AASHTO guide. The project is in Fayetteville Arkansas with an AADTT of 10,000 and a 20-year design life. Six closest weather stations are identified by the MEPDG software. The related information of these stations is presented in Table 4.

Analyses are performed using the MEPDG software to quantify the influence of predicted pavement performance by varying the temperature data and monthly total precipitation in the climate data. The average temperatures are set to be 3^0F (1.67^0C) above and below the baseline data, while the monthly total precipitation 7.2*in.* (18.28*mm*)

Table 4. Weather Stations Identified by MEPDG.

No.	Station Location	Latitude	Longitude	Elevation (feet)	Distance to the Design Location (mile)	Data Source	Months of Data
1	Northwest Arkansas Regional Airport	36.01	-94.10	1247(380*m*)	0(0*mi*)	NCDC	105
2	Drake Field Airport	36.17	-94.19	1272(388*m*)	20.2(32.5*mi*)	NCDC	82
3	Joplin Regional Airport	35.20	-94.22	480(146*m*)	48.5(70.1*mi*)	NCDC	116
4	Boone County Airport	36.16	-93.10	1380(421*m*)	58.4(94.0*mi*)	NCDC	66
5	Fort Smith Regional Airport	35.40	-95.22	610(186*m*)	71.4(114.9*mi*)	NCDC	115
6	Davis Field Airport	35.16	-93.05	382(116*m*)	79.9(128.6*mi*)	NCDC	86

Table 5. Pavement Performance (% of Change) for Different Climate Scenarios.

Scenario	Flexible Pavement				Rigid Pavement	
	Alligator Cracking	AC Rutting	Total Rutting	IRI^a	Faulting	IRI*
Temp (+3^{0}F)	-9.66	-16.07	-6.79	-1.8	3.85	4.4
Temp (-3^{0}F)	7.59	12.79	5.60	1.3	-2.88	-3.5
Precip (-7.2*in.*)	17.93	-1.97	1.19	3.5	3.37	3.7
Precip (+7.2*in.*)	2.07	3.93	1.67	-1.1	-1.44	-1.9
Temp (+3^{0}F) & Precip (-7.2*in.*)	13.79	-18.36	-5.48	1.8	7.21	8.3
Temp (+3^{0}F) & Precip (+7.2*in.*)	-9.66	-16.07	-6.79	-3.1	3.85	4.4
Temp (-3^{0}F) & Precip (-7.2*in.*)	22.07	11.15	6.55	4.7	0.48	0.4
Temp (-3^{0}F) & Precip (+7.2*in.*)	7.59	12.79	5.60	-0.1	-2.88	-3.5

Note: ^{a} The change of IRI is the absolute IRI values in *in/m*i.

difference with the baseline precipitation data. In total there are eight climate scenarios (shown in Table 5) for each pavement type. Eighteen runs of MEPDG are completed in the analysis.

The comparisons are based on the percentage of change in the terminal pavement performance at the end of design life for various climate scenarios. The percentage of change is calculated as follows:

$$PC = \frac{\left| x_{baseline} - x_{changed} \right|}{x_{baseline}} \times 100 \qquad (2)$$

where, PC = percentage of change, $x_{baseline}$ = predicted terminal performance for the baseline inputs,; and $x_{changed}$ = predicted terminal performance for changed climate scenario.

No longitudinal cracking and transverse cracking are observed in the flexible structure, and very few slabs are cracked in rigid pavement. As a result, only alligator cracking, AC rutting, total rutting, and IRI for flexible pavement, faulting, and rigid pavement are studied. The comparison results are presented in Table 5. Significant differences are observed for the asphalt concrete (AC) rutting prediction. AC rutting increases 16.07% when the average temperature increases 3^{0}F. On the contrary, if the average temperature decreases 3^{0}F, the AC rutting will be 12.79% less. Much less change is observed for the total rutting parameter, which suggests that permanent deformation in the lower layers are reduced thus compensated for the AC surface rutting. Changes in total rutting ranges from a reduction of 6.55% for the "Temp (-3^{0}F) & Precip (-7.2*in.*)" scenario to an increase of about 6.79% for "Temp (+3^{0}F)" and "Temp (+3^{0}F) & Precip (+7.2*in.*)" scenario. In addition, it seems that the change of precipitation contributes little influence on AC rutting and total rutting.

The change of alligator cracking has the most significant differences between baseline condition and changed climate scenarios, ranging from a 22.07% decrease to a 9.66% increase. However, the trend is inconsistent with the change of temperature and precipitation for these eight scenarios. The least amount of change between baseline and varied climate scenarios for both flexible and rigid pavement is observed for the IRI parameter, which is generally less than 3.5% in terminal IRI. Modest changes are observed for the faulting parameters in rigid pavement.

Conclusions

In this paper, virtual climate data generated using the MEPDG software are compared with LTPP AWS data. Factors affecting the precision and bias of the climatic estimates are investigated. The changes in climate data on terminal pavement deterioration and performance are studied. The major findings are summarized as follows:

- Comparing to the data from LTPP AWS data, the virtual climatic data generated by the MEPDG software are reasonably accurate to model the onsite climate condition.
- The differences between LTPP AWS and MEPDG VWS climatic data do not follow normal distributions, either positively or negatively skewed.
- Using as many applicable nearby weather stations as possible for estimating the climatic parameters provides more accurate results than using the closest weather station.
- Elevation differences (between the project site and the nearby weather stations) significantly affect the accuracy of the MEPDG generated virtual climatic data.
- The distance between the project site and the contributing weather stations does not significantly influence the MEPDG generated virtual climatic parameters.

In the example pavement design, variations of climate data are observed to have significant influence on AC rutting, while much less influence is observed for the total rutting. IRI is the least influenced parameter for both flexible and rigid pavement.

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