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Prediction of the MEPDG Asphalt Concrete Permanent Deformation Using Closed Form Solution

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Abstract: This research work focused upon the integration of the Mechanistic-Empirical Pavement Design Guide (MEPDG) methodology with the simple performance test to develop a rutting Closed Form Solution (CFS) for Asphalt Concrete (AC) layers to predict permanent deformation based on the Hot Mix Asphalt (HMA) dynamic modulus. The CFS would take only a few seconds to predict AC rutting instead of the significant MEPDG runtime. The rutting CFS can then be implemented in a probabilistic performance related specifications methodology for the Quality Assurance (QA) of HMA Construction. The main approach used to establish a rapid CFS for the AC MEPDG rutting distress module was to run the MEPDG for a large number of simulations using various combinations of inputs; and to develop an accurate CFS for the rutting distress prediction based on the dynamic modulus of HMA. To accomplish this work, two major studies have been completed: (a) development of a rutting database based for different structures, climatic locations, traffic and vehicle speed; and (b) development of an AC effective dynamic modulus model and its relationship with the rutting. The developed methodology accurately predicts the rutting distress in the HMA layer close to that from the MEPDG.

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Key words*: Asphalt pavement; Closed form solution; Hot mix asphalt; Permanent deformation; Quality assurance.*

Introduction

The Mechanistic-Empirical Pavement Design Guide (MEPDG), now also known as Pavement ME Design, is an advanced tool to improve the traditionally used pavement design methods [1, 2]. The MEPDG design approach is based on engineering principles, which will shift the design of the pavement structures to the Mechanistic-Empirical (ME) based design. The benefits of using ME-based design are more economical structure, better management of highway network, and better traveling conditions for the public.

The National Cooperative Highway and Research Program (NCHRP) project NCHRP 9-22 [3] for development of a performance based pay factor required the use of statistical analysis and simulations by using Monte-Carlo simulations. This project also required to use the MEPDG as a tool for the performance based pay factors. However, due to the complexity of the calculations to mechanistically predict distresses, the MEPDG demands a significant amount of time to finish the calculations and the Monte-Carlo simulations.

Accordingly, the research team in NCHRP 9-22 project decided to go for a Closed Form Solution (CFS) for the MEPDG to predict the Asphalt Concrete (AC) permanent deformation in few seconds in order for the Monte-Carlo simulations to be used in the stochastic solution implemented in NCHRP 9-22 [3].

The CFS would provide a quick and accurate HMA rut prediction. However, it is important to emphasize that the MEPDG will still give the most accurate prediction since it accounts for more design conditions such as:

- MEPDG uses Axle load Spectra while CFS uses Equivalent Single Axle Loads (ESALs).
- MEPDG uses monthly modifies layer modulus, while CFS uses a representative annual moduli.

Objective

The objective of this research work was to develop a CFS to predict AC permanent deformation using the MEPDG by integrating the MEPDG methodology (NCHRP 1-37A and NCHRP 1-40) [1, 2] with the Simple Performance Test (SPT) methodology (NCHRP 9-19) [4, 5] and to use that CFS to develop the performance based pay factors. In essence, this paper is one of a series of technical papers that was prepared to document the comprehensive NCHRP 9-22 study, which was aimed at developing a probabilistic approach to Quality Assurance (QA) based upon the MEPDG distress criteria.

Rutting Closed Form Solution

Background

The initial work, done on the development of the CFS for rutting, was developed by Sotil [6]. This initial work was finished in 2005; before the 1.0 version of the MEPDG developed under NCHRP 1-40D was published. The initial study used the MEPDG version 0.7 that was developed under NCHRP 1-37A. Under NCHRP 1-40D, some errors were corrected, the climatic model of the MEPDG was modified and calibration effort was done for adjustments to the new models. This work presented in this research paper was re-analyzed using the MEPDG version 1.0.

To develop a CFS for the prediction of rutting using the MEPDG,

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the following steps were followed:

A. Simulation runs of the MEPDG were conducted at different conditions to study the effect of each condition on the rutting predictions. Initially a fractional factorial was conducted to check on the significant factors that impact the HMA rutting prediction. Then an in-depth simulation runs were done using the selected factors to build a database for the rutting.

B. For a given structure, the rutting database will be interpolated to obtain the predicted rutting for that given structure at predefined dynamic modulus, climatic locations and traffic conditions.

C. For the same given structure, the dynamic modulus (|E*|) of the HMA layer is obtained for each of the predefined climatic location and traffic. |E*| is calculated based on the effective temperature concept.

D. A relationship between rutting and dynamic modulus is obtained, which can be used to predict the rutting for the given structure, climate, material property, speed and traffic level.

Rutting Database Formation

The first step of the rutting CFS development was to develop a rutting database. The database was formed on two steps: 1) an initial simulation to detect the significant factors; and 2) a full simulation using the selected significant variables. The following sections will cover these two simulations.

Initial Factorial Simulation Runs

The total number of variables, included in the MEPDG for flexible pavement design, was about 61 variables. However, not all of them were known to be significant for HMA rutting prediction. Only 10 variables were then used to determine which ones were "statistically" significant. Those variables were the following:

A. Environmental Condition (Hot: Phoenix, AZ and Cold: Grand Forks, ND)

B. Pavement Service Life (5 years and 15 years)

C. Traffic Number of Repetitions (10^5 and 10^6 18-kip ESALs during service life)

D. Average Traffic Speed (0.8 km/hr (0.5 mph) and 96.6 km/hr (60 mph))

E. Traffic Wander (10.2 cm (4 in.) and 25.4 cm (10 in.))

F. Asphalt Thickness (5.1 cm (2 in.) and 25.4 cm (10 in.))

G. Asphalt Layer Stiffness (Conventional Dense Graded Mix with PG 52-40 and PG 82-10 binder type)

H. Unbound Layer Thickness (10.2 cm (4 in.) and 30.5 cm (12 in.))

I. Unbound Layer Stiffness (34.5 MPa (5 ksi) and 206.8 MPa (30 ksi))

J. Groundwater Table (1.5 meters (5 ft) and 4.6 meters (15 ft))

A fractional factorial of runs using these 10 variables at 2 levels was used, which yielded only 32 runs. From the 2^{10-5} fractional factorial design, it was concluded that the main factors affecting rutting, as shown in Fig. 1, were the following:

- Environmental conditions
- Number of Traffic Repetitions
- Average Traffic Speed

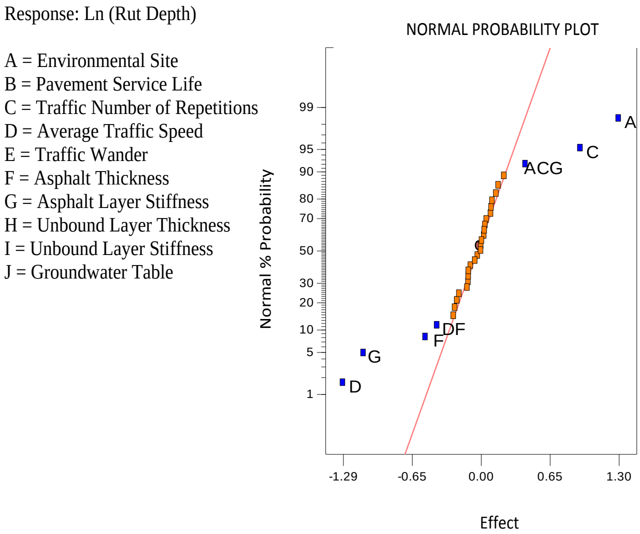

Fig. 1. Significance of Variables Affecting Rutting Predictions Results from 2^{10-5} Fractional Factorial Design of Experiments [6].

- Asphalt Layer Stiffness
- Asphalt Layer Thickness

It is very important to note that rutting within the AC layer is not a function of any of the other pavement layers in the structure. In essence, AC rutting is a function of the mix quality, AC layer thickness, traffic and the design location environment.

Simulation Runs to Build Database

After the initial study was finished, a more detailed simulation was conducted to build the rutting database. These runs used only the variables listed earlier that were significant in the rutting prediction. The matrix of runs was conducted to create the database. All runs had the same base, subbase and subgrade layer thickness and properties and a design life of 20 years. The matrix of runs was then based on the following levels of the salient variables previously defined.

1. 8 different HMA layer thickness, 2.5, 5.2, 7.6, 10.3, 15.2, 20.3, 30.5 and 50.8 cm (1, 2, 3, 4, 6, 8, 12, and 20 inches)
2. 12 climatic locations, (as shown in Table 1).
3. 8 asphalt mixture properties.
4. 4 different traffic speeds, 0.8, 24.2, 72.5, and 96.6 km/hour (0.5, 15, 45, and 60 mph)
5. 4 different traffic levels 10^5, 10^6, 10^7 and 10^8 ESALs.

This matrix of runs yielded a total of 8*12*8*4*4 = 12,288 MEPDG runs. Knowing that each run would take 20 minutes, the complete simulation would have taken about 6 months of only computational runs. Accordingly, mini-studies were conducted to reduce the number of runs. The following sections provide more details of each one of the 5 variables used in the simulation.

HMA Layer Thickness

The study performed by El-Basyouny [7, 8] concluded that the maximum AC rutting was likely to happen when the pavement structure had an AC thickness between 5.08 to 12.7 cm (2 in. and 5 in.). In general, the AC rutting decreased when the AC layer depths

Table 1. Summary of 12 Selected Environmental Sites.

Location	MAAT (°C)	Wind Speed (km/hour)	Sunshine (%)	Rainfall (cm)	σ_{MMAT} (°C)
Kotzebue, Alaska	-5.6	15.5	40.6	22.61	-5.0
Homer, Alaska	3.6	8.9	30.0	60.71	-10.4
Grand Forks, ND	5.4	14.3	53.4	50.04	-4.5
Great Falls, Montana	7.7	15.8	58.4	28.19	-6.5
Chicago, Illinois	10.8	13.0	36.6	78.23	-7.6
Hartford, Connecticut	10.8	11.0	52.6	106.68	-6.7
Indianapolis, Indiana	12.3	13.4	38.8	97.28	-7.1
Oklahoma City, OK	16.2	15.6	49.9	85.09	-7.2
Jackson, Mississippi	18.3	7.4	68.8	127.25	-8.7
Houston, Texas	20.6	8.9	39.4	131.57	-9.6
Phoenix, Arizona	23.8	8.1	62.3	17.02	-8.1
Key West, Florida	25.5	12.9	72.7	102.36	-14.0

were either lower than 5.08 cm (2 in.), or higher than 12.7 cm (5 in.). Because of this bell shape relationship between rutting occurrence and AC layer thickness (depth), it was decided to study as many depth values as possible.

The MEPDG subdivides each layer into multiple sublayers [1]. The AC layer is subdivided into sublayer thicknesses of 1.3, 1.3, 2.5, 2.5, 2.5, 5.1, 5.1, 10.2 cm (0.5, 0.5, 1, 1, 1, 2, 2, 4 in.) and the remaining thickness. For example, the 50.8 cm structure is subdivided into 1.3, 1.3, 2.5, 2.5, 2.5, 5.1, 5.1, 10.2 and 20.3 cm (0.5, 0.5, 1, 1, 1, 2, 2, 4, and 8 in.). The simulation runs were done in a way to capture rutting in each one of these sublayers to provide a more accurate comparison between the rutting CFS and the MEPDG prediction.

During the simulation runs, it was discovered that there was a discontinuity problem in the prediction when structures of 5.1 and 7.6 cm (2 and 3 in.) AC layer thicknesses were used. This discontinuity was overcome by using an additional thickness of 7.0 cm (2.75 in.) in the matrix. This gave 9 different structures.

Climatic Locations

The environmental condition was the factor that most affected the MEPDG rutting prediction. It was therefore decided to cover a wide range of climatic conditions. Twelve environmental sites were randomly selected, with regions in the United States as cold as Kotzebue, Alaska with a Mean Annual Air Temperature (MAAT) of -5.6 °C to regions as hot as Phoenix, Arizona and Key West, Florida with MAAT equal to 23.8 and 25.5 °C, respectively. Table 1 shows a summary of the 12 environmental sites selected with their respective MAAT value, Mean Annual Average Wind speed (Wind Speed), Mean Annual Sunshine Percentage (Sunshine), Cumulative Annual Precipitation (Rainfall), and Mean Monthly Air Temperature Standard Deviation (σ_{MMAT}).

The climatic variables are essential to calculate the effective temperature (T_{eff}) for each site. The effective temperature concept is explained, in more detail, in a publication by El-Basyouny and Jeong [9]. The effective temperature negates the necessity to conduct cumulative incremental damage throughout a change in annual environmental conditions. Thus T_{eff} saves a significant amount of computational time. The effective temperature equation for rutting is shown in Eq. (1). Note that the equation was developed in the English unit system.

$$T_{eff} = 14.62 - 3.361\ln(Freq) - 10.940(z) + 1.121(MAAT) + 1.718(\sigma_{MMAT}) - 0.431(Wind) + 0.333(Sunshine) + 0.08(Rain) \quad (1)$$

where:
T_{eff} = Modified Witczak T_{eff}, °F
z = Critical Depth, inch
$Freq$ = Loading Frequency, Hz
$MAAT$ = Mean Annual Air Temperature, °F
σ_{MMAT} = Standard Deviation of the Mean Monthly Air Temperature
$Rain$ = Annual Cumulative Rainfall Depth, inches
$Sunshine$ = Mean Annual Percentage Sunshine (%)
$Wind$ = Mean Annual Wind Speed (mph)

HMA Mixture Properties

Eight different mixtures were initially thought to be used in the simulation runs. The different types of mixtures evaluated, were based on a conventional dense graded mix of 7% air voids (AV), 10% binder content (V_{beff}), and 1.9mm Nominal Aggregate (NMA) Size. The stiffness values were calculated from the Witczak Predictive Equation (WPE) given in Eq. (2). The following eight PG binders were also used in this analysis:

- PG52-34 - PG52-40 - PG58-22
- PG58-34 - PG64-22 - PG70-10
- PG76-16 - PG82-10

$$\log E^* = -1.249937 + 0.029232 \cdot p_{200} - 0.001767 \cdot (p_{200})^2 - 0.002841 \cdot p_4 - 0.058097 \cdot Va - 0.8022 \cdot \frac{Vb_{eff}}{(Vb_{eff} + Va)} + \frac{3.87197 - 0.0021 \cdot p_4 + 0.003958 \cdot p_{38} - 0.000017 \cdot (p_{38})^2 + 0.00547 \cdot p_{34}}{1 + e^{(-0.603313 - 0.313351\log(f) - 0.393532\log(\eta))}} \quad (2)$$

where,
E^* = Asphalt Mix Dynamic Modulus, in 10^5 psi
η = Bitumen viscosity in 10^6 poise (at any temperature)
f = Loading frequency in Hz
Va = Air voids in the mix, by volume, %
Vb_{eff} = Effective bitumen content, by volume, %
p_{34} = % retained on the 3/4 inch sieve
p_{38} = % retained on the 3/8-inch sieve
p_4 = % retained on the No. 4 sieve

p_{200} = % passing the No. 200 sieve

The WPE requires the frequency of the applied load. The frequency is calculated using Eq. (3) as a function of the vehicle speed and the effective length (L_{EFF}) at the mid depth of an AC layer [1, 7]. It should be recognized that several recent papers have suggested the MEPDG methodology for computing frequency is erroneous because it doesn't take into account the delayed response of the moving wheel load. However, critics need to recognize that the MEPDG methodology is totally based upon linear elasticity and the current methods of computing "frequency" are completely correct and consistent with the pavement response utilized in the design guide.

$$Freq = 17.6 * (Speed / L_{EFF}) \tag{3}$$

where:
Speed = Average Traffic Speed, mph
L_{EFF} = Effective Length, inches

Using the effective temperature and frequency values corresponding to the project, $|E^*|$ values were calculated and then related to the predicted MEPDG rutting. A highly correlated power function was found to very accurately define the relationship between $|E^*|$ and the MEPDG predicted rutting. The format of the relationship (power function) was found to exist for a wide range of condition changes. Fig. 2 shows an example of the $|E^*|$-rut relationship. The equation format is as follows:

$$R_D = a\,E^{*\,b} \tag{4}$$

where:
R_D = Rut Depth
$|E^*|$ = Effective Dynamic Modulus

It is clear from Fig. 2 that all of the mixtures lie on the same power model. Because of this, it was concluded that only 2 mixtures could be used instead of 8. Accordingly, only a stiff binder (PG82-10) and a soft binder (PG52-40) were used to form the power model between the rutting and $|E^*|$.

Traffic Speed

Since traffic speed (time of loading) is another important factor affecting rutting, it was necessary to develop an approach that was applicable to a wide range of traffic speeds. It was the scope and goal of another mini-study to develop a relationship between traffic speed and rutting that would simplify the $|E^*|$-SPT Criteria development even further. Four traffic speeds were used in order to cover many types of roads:

- 0.8 km/hr (0.5 mph): intersections, parking lots, traffic jams
- 24.2 km/hr (15 mph): local roads, school zones
- 72.5 km/hr (45 mph): collector and arterial city roads.
- 96.6 km/hr (60 mph): city freeways and interstate highways

As expected, it was found that rutting and speed also have a very strong power relationship. This is observed in the typical example shown in Fig. 3. It can be observed that rutting is significantly increased at creep speed conditions (0.8 km/hr). This relationship is very conceptually identical to that found for the AASHO Road Test in the late 1950's and early 1960's [10].

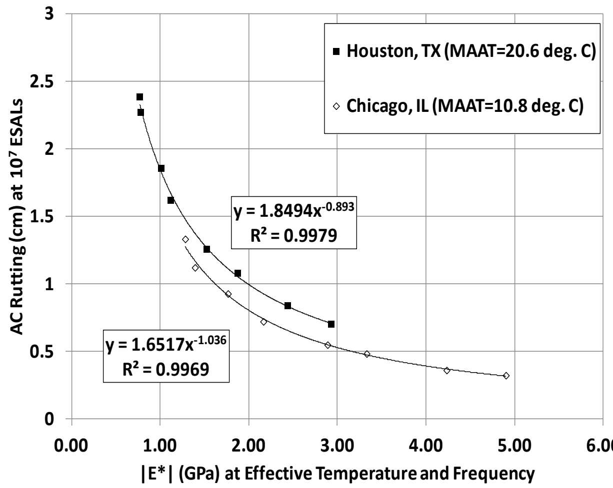

Fig. 2. Typical Relationships of $|E^*|$ and Rutting Relationships at Effective Temperature, Frequency and Selected Layer Depth.

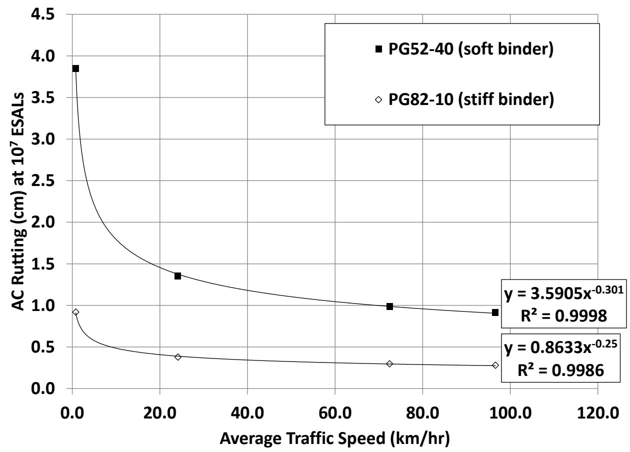

Fig. 3. Typical Rutting vs. Traffic Speed Power Relationship.

The correlation of these power functions is quite high at any combination of environmental site, binder type, and layer within a specific structure condition. Table 2 shows an example of the data for locations 1 and 2 for a 50.8 cm (20 in.) AC structure. Thus, it was concluded that the rutting at any given speed could be calculated using the following equation:

$$RUT_{X\text{-}SP} = M{*}Speed^{N} \tag{5}$$

where:
Speed = Average Traffic Speed, km/hr
$RUT_{X\text{-}Speed}$ = Desired Rutting Prediction at "X" number of traffic repetitions and "Speed" average traffic speed
M, *N* = Regression Coefficient dependent on the environmental site, binder type, and AC layer thickness within given pavement structure.

Even though the finding on the traffic speed did not reduce the number of simulation runs, it did reduce the size of the database to be saved. It also provided a general model to calculate rutting at different speeds other than the ones used in the simulations.

Table 2. Summary of Rutting Data in Centimeter Used for the Calculation of Eq. (5). Total AC Thickness = 50.8 cm (20 in.)

Location ID***	PG Binder Type	Traffic Speed (km/hr)	Layer Thick 2.5 cm (1 in.)	Layer Thick 2.5 cm (1 in.)	Layer Thick 2.5 cm (1 in.)	Layer Thick 2.5 cm (1 in.)	Layer Thick 5.1 cm (2 in.)	Layer Thick 5.1 cm (2 in.)	Layer Thick 30.5 cm (12 in.)
1	52-40	0.8	0.0500	0.1532	0.0978	0.0417	0.0178	0.0020	0
1	52-40	24.2	0.0188	0.0612	0.0396	0.0170	0.0074	0.0008	0
1	52-40	72.5	0.0142	0.0470	0.0305	0.0132	0.0056	0.0005	0
1	52-40	96.6	0.0132	0.0439	0.0287	0.0122	0.0053	0.0005	0
		M	-0.2793	-0.262	-0.2578	-0.2564	-0.2543	-0.2971	0
		N	0.0500	0.1532	0.0978	0.0417	0.0178	0.0020	0
		R^2	0.9994	0.9994	0.9993	0.9995	0.9994	0.9965	N/A
1	82-10	0.8	0.0114	0.0338	0.0213	0.0091	0.0038	0.0005	0
1	82-10	24.2	0.0058	0.0185	0.0119	0.0051	0.0020	0.0003	0
1	82-10	72.5	0.0048	0.0157	0.0102	0.0043	0.0018	0.0003	0
1	82-10	96.6	0.0046	0.0152	0.0099	0.0041	0.0018	0.0003	0
		M	-0.1918	-0.1682	-0.1627	-0.1685	-0.1648	-0.1518	0
		N	0.0109	0.0323	0.0205	0.0088	0.0036	0.0050	0
		R^2	0.9994	0.9982	0.9979	0.9994	0.9879	0.9261	N/A
2	52-40	0.8	0.0521	0.1915	0.1356	0.0620	0.0290	0.0036	0
2	52-40	24.2	0.0201	0.0772	0.0551	0.0251	0.0117	0.0015	0
2	52-40	72.5	0.0155	0.0597	0.0427	0.0193	0.0091	0.0010	0
2	52-40	96.6	0.0145	0.0559	0.0399	0.0183	0.0084	0.0010	0
		M	-0.2689	-0.2586	-0.2567	-0.2573	-0.2582	-0.2679	0
		N	0.0486	0.1797	0.1274	0.0582	0.0272	0.0034	0
		R^2	0.9988	0.9993	0.9993	0.9992	0.9992	0.9936	N/A
2	82-10	0.8	0.0173	0.0574	0.0381	0.0168	0.0076	0.0010	0
2	82-10	24.2	0.0086	0.0302	0.0201	0.0089	0.0041	0.0005	0
2	82-10	72.5	0.0071	0.0254	0.0170	0.0074	0.0033	0.0005	0
2	82-10	96.6	0.0069	0.0244	0.0163	0.0071	0.0033	0.0005	0
		M	-0.1953	-0.1803	-0.179	-0.181	-0.1798	-0.1518	0
		N	0.0164	0.0548	0.0364	0.0160	0.0073	0.0009	0
		R^2	0.9984	0.9985	0.9981	0.9991	0.9967	0.9261	N/A

Traffic Levels

The traffic used had to be converted in ESALs to simplify the analysis. However, a new calibration factor, other than the national calibration factor obtained using general traffic, was obtained to correct for this conversion. The traffic repetition effect was studied in more detail and it was found that rutting can be mathematically related to traffic repetitions by the following equation:

$$RUT_X = RUT_{ST} * 10^{0.479244(\log X - \log ST)} \tag{6}$$

where:
RUT_X = Desired Rutting Prediction at "X" number of traffic repetitions, inches
RUT_{ST} = Rutting Prediction at Standard "ST" number of traffic repetitions, inches

This relationship implied that the simulation didn't need to be run at different traffic levels as one traffic volume will be adequate to represent other traffic levels. As a consequence, one traffic level of $N=10^7$ ESALs was used in the study to represent all traffic levels.

Conclusion of Simulation Runs

From the previous discussion, it was therefore concluded that 12 climatic locations, 9 structures, 4 speeds, 1 traffic level and 2 AC mixtures were sufficient to form the rutting database. This combination yielded a total of 12*9*4*1*2 = 864 runs which was done in 12 days instead of 6 months.

A sample of the database is given in Table 2. For a complete database, refer to the NCHRP 9-22 final report publications [3]. The NCHRP 9-22 project has Fugro, Inc. as the prime contractor and ASU as the subcontractor.

Rutting Interpolation

The second step of the rutting CFS development was to estimate the rutting for a given structure using the predefined 12 climatic locations, 2 AC mixtures, 4 speeds and 1 traffic level. If the thickness of the AC layer was similar to that in the database, no interpolation is required. This interpolation is done for each sublayer in the pavement structure. The database is first reduced to two structures: one thinner than the given structure and one thicker. For example, if the required structure is 11.4 cm (4.5 in.), then 10.2 cm and 15.2 cm (4 in. and 6 in.) structures are used. Then, the rutting database is calculated for the given traffic speed using Eq. (5). Similarly, using Eq. (6), the rutting from the database is obtained for

Table 3. Sample Database Interpolation for Cumulative Rutting Prediction.

Traffic Repetitions (ESALs)	Climatic Site	PG Binder	Traffic Speed (km/hr)	Database Pavement Thickness	Cumulative Rutting					
					2.5cm	5.1cm	7.0cm	7.6cm	10.2cm	15.2cm
1,000,000	Chicago, IL	52-40	56.4	10.2 cm (4 in.)	0.0086	0.1615	0.3139	0.3647	0.5245	
				15.2 cm (6 in.)	0.0262	0.1687	0.2634	0.2951	0.3660	0.4181
User-Specified Total AC Thickness				11.4 cm (4.5 in.)	Final Interpolation Results					
				Cumulative	0.0132	0.1633	0.3012	0.3475	0.4849	0.4978

the given traffic level.

The next step is to interpolate between the different structures to obtain the rutting prediction for the given structure. Linear interpolation is used for this process. Table 3 shows a sample of the calculation sheet for the rutting interpolation. The last point, corresponding to the total AC rutting for the 11.4 cm (4.5 in.), is interpolated between the total AC rutting values of the 10.2 cm and 15.2 cm (4 in. and 6 in.) structures. Hence, the 9 structure database is reduced to only 1 structure at one speed and traffic level, which will reduce the database from 864 to only 24 points (12 climatic locations and 2 AC mixtures). The rutting database is 24 points for each sublayer of the pavement structure.

Dynamic Modulus, Effective Temperature and Frequency Calculations

The first two steps of the process focused mainly on the estimation of the rutting. The third step of the rutting CFS development requires the computation of the $|E^*|$, at the effective temperature (T_{eff}) and frequency (*Freq*), associated with the rutting predictions. The database is obtained using two AC mixtures with a soft and stiff binder, for the 12 environmental sites, given in Table 1. The database is also formulated using the traffic speed for the specific project to calculate the loading frequency at the mid-depth of each sublayer.

To compute the effective load frequency, the $|E^*|$ from Eq. (2) and frequency from Eq. (3) are used in an iteration process to calculate the $|E^*|$ values. The output of this iteration process will yield the $|E^*|$, T_{eff} and *Freq* values for each sublayer, binder type and climatic location. Similar to the reduced rutting database the total number of $|E^*|$ values will be 12*2=24 for each sublayer. The same iteration process is used to obtain the $|E^*|$, T_{eff} and *Freq* of the specific structure using the actual material properties.

$|E^*|$ and AC Rut Relationship

The last step required is to find the final relationship between the $|E^*|$ and AC rutting. This process consists of two steps: 1) to reduce the database into only one climate (actual climate of the specific project) and 2) to find rutting for the actual mixture for each sublayer.

The database reduction, from the 24 database to two database sets for each sublayer, is performed by creating relationships for each binder type and sublayer, between the 12 effective temperatures and the 12 corresponding rutting predictions. The resulting relationships follow a power function trend, as shown in Fig. 4. If the project effective temperature is known, then the corresponding rutting prediction at the given binder type and sublayer may be easily found. As explained in the previous step, the T_{eff} for the give structure is obtained using the iteration process. Finally, the rutting database is reduced to two rutting values and two $|E^*|$ values for each of the two binders for each sublayer. Using these two points, a power relationship is obtained between $|E^*|$ and the AC rut depth for each sublayer as shown in Fig. 5. It should be recalled from previous discussions that these two points are accurate enough to create the $|E^*|$ - AC rut relationship.

From $|E^*|$ - AC rut power model, and using the actual $|E^*|$ for each sublayer, the sublayer rut depth can be obtained. The summation of the sublayer run depth will give an estimation of the total AC rut depth in a given pavement structure.

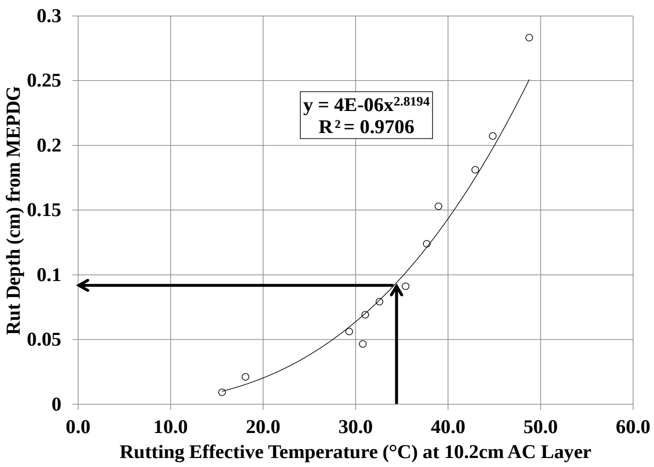

Fig. 4. Typical Rut Depth versus Effective Temperature Relationship.

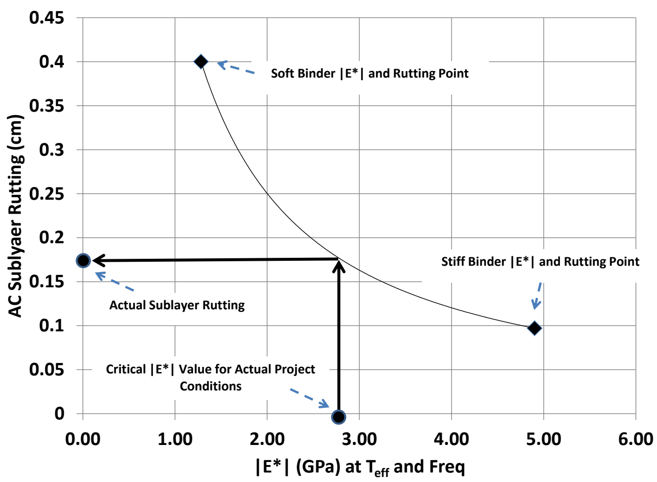

Fig. 5. Typical AC Sub-layer E^* vs. Rut Depth Universal Relationship at Environmental, Traffic and Structural Design Conditions.

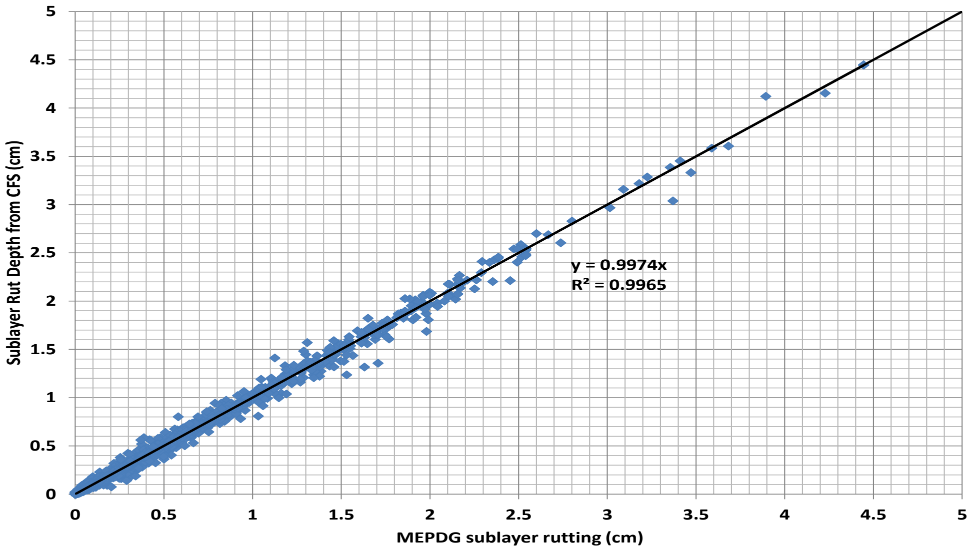

Fig. 6. Comparison Between Rutting CFS and MEPDG 1.0 AC Rut Depth.

Overall Prediction Accuracy

To validate the rutting prediction process, a completely new set of 3457 MEPDG AC rutting data points were conducted and compared to the rutting database predictions. These 3457 runs composed of different structures, climatic location, AC mixtures, traffic levels, traffic speeds and design life.

Fig. 6 shows the comparison between the MEPDG predicted rut depth and the rutting CFS predictions. The comparison clearly shows that the prediction is excellent and very relevant to the MEPDG prediction. The regression coefficient (R^2) is 0.996 which is an excellent correlation with very little scatter.

Summary and Conclusions

This paper discusses the methodology to obtain a CFS to predict rutting in the AC layers of a flexible pavement without the need to run the MEPDG. The comparative accuracy between the CFS developed and the results from the MEPDG is exceptionally excellent. This CFS will reduce the tremendous efforts to run a large number of MEPDG simulations in order to find stochastic solutions for a probabilistic Performance Related Specifications methodology for the Quality Assurance of Hot Mix Asphalt Construction established in the NCHRP 9-22 project.

The methodology to predict rutting is based on a rutting database obtained from running 864 MEPDG simulations. These scenarios included 12 environmental sites, 4 average traffic speeds, 2 mix types, and 9 structural designs (AC layer thickness values). Correlations were obtained to relate general traffic volume to a standard traffic volume used in creating the database. Another correlation was obtained between the predicted AC rut depth and the vehicle speed.

To develop this methodology a couple of assumptions were used. The first assumption was that, to represent traffic volume, ESALs will be used instead of the general traffic characterization to simplify the database. The second assumption was that the AC rut depth prediction would be one value at the end of the design life specified for the project. These assumptions did work well for the purpose of this research: performance related specification for quality assurance of HMA construction. The comparison between the rutting predicted from the developed CFS methodology and that obtained from MEPDG shows an excellent correlation.

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References

1. Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures (2004). *NCHRP 1-37A Final Report*, Transportation Research Board, National Research Council, Washington, DC, USA.
2. Darter, M.I., Mallela, J., Titus-Glover, L., Rao, C., Larson, G., Gotlig, A., Von Quintus, H., Khazanovich, L., Witczak, M., El-Basyouny, M., El-Badawy, S., Zborowski, A., and Zapata, C. (2006). Changes to the Mechanistic-Empirical Pavement Design Guide Software through Version 0.900, *Research Results Digest 308*, National Cooperative Highway Research Program, Transportation Research Board, Washington, DC, USA.
3. Moulthrop, J., and Witczak, M.W. (2011). A Performance-Related Specification for Hot Mixed Asphalt. *NCHRP Report 704*, Transportation Research Board, Washington, DC, USA.
4. Witczak, M.W. (2007) Specification Criteria for Simple Performance Tests for Rutting, Vol 1: Dynamic Modulus (E*), *NCHRP Report 580*, National Cooperative Highway Research Program, Transportation Research Board, Washington, DC, USA.

5. Witczak, M.W., Kaloush, K.E., Pellinen, T., El-Basyouny, M., and Von Quintus, H. (2002) Simple Performance Test for Superpave Mix Design. *NCHRP Report 465*. Transportation Research Board. Washington, DC, USA.
6. Sotil, A. (2005). Use of the Dynamic Modulus E* Test as Permanent Deformation performance Criteria for Asphalt Pavement Systems. Ph.D. Dissertation, Arizona State University, Tempe, AZ, USA.
7. El-Basyouny, M. (2004). Calibration and Validation of Asphalt Concrete Pavements Distress Models for 2002 Design Guide, Ph.D. Dissertation. Arizona State University, Tempe, AZ, USA.
8. El-Basyouny, M., Witczak, M.W., and El-Badawy, S. (2005). Verification of the Calibrated Permanent Deformation Models for the 2002 Design Guide, *Journal of the Association of Asphalt Paving Technologists*, 74, pp. 601-652.
9. El-Basyouny, M. and Jeong, M. (2009). Effective Temperature for Permanent Deformation and Fatigue Distress Analysis of Asphalt Mixtures. *Transportation Research Record*, No. 2127, pp. 155-163.
10. Highway Research Board (1962). The AASHO Road Test, Report 5, Pavement Research, Highway Research Board Special Report 61E, National Research Council, Washington, DC, USA.