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A methodology for implementation of the mechanistic-empirical rigid pavement design in Turkey

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Abstract: The Mechanistic-Empirical Pavement Design Guide (MEPDG) was emerged and calibrated based on the North American conditions for analysis and designing of flexible and rigid pavements. Implementing this guide in elsewhere needs evaluation using local data, if need be, the local calibration should be conducted to improve the accuracy of the pavement distress prediction models. The state agencies in Unıted States of America (USA) and some developing countries have followed different implementation methodologies to apply the method. In this study, a detailed methodology was developed for the implementation of the ME Rigid Pavement Design Guide in Turkey. This methodology can serve as a guide for local calibration of the MEPDG in Turkey as well as the other countries.

Key words: Data collection, local calibration, mechanistic-empirical pavement design guide (MEPDG), rigid pavement

Türkiye'de mekanistk-ampirik rijit üstyapı tasarımının uygulanması için bir metodoloji

Öz: Mekanistik-Ampirik Üstyapı Tasarım Rehberi (MEPDG), esnek ve rijit üstyapıları analiz etmek ve tasarlamak için Kuzey Amerika koşullarına göre geliştirilmiş ve kalibre edilmiştir. Bu rehberin farklı koşullar altında gerçekleştirilmesi amacıyla, üstyapı yüzey bozuklukları tahmin modellerinin değerlendirilmesi ve kalibrasyonuna ihtiyaç duyulmaktadır. Amerika'daki eyaletler ve bazı gelişmekte olan ülkeler, MEPDG'yi uygulamak için farklı metodolojiler kullanmışlardır. Bu çalışmada, Türkiye'de ME Rijit Üstyapı Tasarım Rehberi uygulanması için ayrıntılı metodoloji geliştirilmiştir. Bu metodoloji, Türkiye'de ve diğer ülkelerde MEPDG'nin yerel kalibrasyonu için bir kılavuz olarak kullanabilecektir.

Anahtar kelimeler: Veri toplanması, yerel kalibrasyon, mekanistik-ampirik üstyapı tasarım rehberi, rijit üstyapı

1. Introduction

The MEPDG is an attempt to overcome various shortages and disadvantages of the empirical pavement design methods as well as to design both rigid and flexible pavements. It is a sophisticated pavement design method that analyses and designs Jointed Plain Concrete Pavement (JPCP) and Continuously Reinforced Concrete Pavement (CRCP) using the Finite Element Method. The MEPDG calculates pavement performance (stress and deflection) under the combination of traffic loading and environmental effects, computes incremental damages, and predicts pavement distresses such as joint faulting and transverse cracking (bottom-up and top-down cracking) in JPCP and Punch-out in CRCP as well as International Roughness Index (IRI) using various design parameters (material properties, traffic characteristics, and hourly climate data) [1, 2]. The MEPDG was developed and calibrated only for the North American conditions. To implement in other parts of the world, the MEPDG should be evaluated for local conditions to determine the accuracy level of pavement distress prediction models, and the local calibration should be conducted if it is needed. State agencies in the USA and some developing countries have made efforts to implement this guide. The implementation methodology which was persuaded by state agencies in the USA and other countries is different but has some similar activities (e.g., local data preparation, sensitivity analysis, establishing of design threshold values and reliability levels, evaluation, local calibration, validation, preparing design manual, and staff training) [3-7]. In the Ohio state, the MEPDG for JPCP was calibrated for local conditions. It was found that predicted distresses are close to the field observed distresses [8]. Won collected the data from 27 roadway segments in Texas USA to evaluate the MEPDG rigid pavement. He found that the MEPDG using nationally calibrated transfer functions highly over-estimates the amount of pavement distress (punch-out) [9]. In order to implement the MEPDG in Italy, the local data like vehicle classification, truck distribution factors, and truck axle load distribution, materials properties, and climate data were collected and prepared [10]. In Iran the fatigue cracking (alligator and longitudinal) model was calibrated for the local conditions. Forensic investigation

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was done to confirm the obtained data from Tehran municipality. The Tehran Climate data were obtained from Meteorological Organizations in their original formats and then converted to Enhanced Integrated Climatic Model (EICM) format to be used in the MEPDG software. The default traffic data were used. The local calibration results shown that default calibrated transfer functions extensively overestimate the fatigue cracking [11]. To conduct the local calibration of the MEPDG in New Mexico, the local data (e.g., traffic, climate, pavement structure, materials, and pavement distresses) were prepared. The local calibration successfully reduced the MEPDG prediction model error [12]. The Egyptian climate data were collected and converted to the MEPDG format and the environmental effects on flexible pavement performances was evaluated [13]. In the State of Qatar, the sensitivity analysis was done using local data (material properties which were extracted from the Qatar Highway Design Manual (QHDM)) and default data (equivalent climate data from Needles Airport in California and traffic data [14]. In China, the local calibration of the MEPDG were done for local material properties with using some default (Level Three) design inputs such as axle load distribution factors and climate data [15]. In India, material properties, traffic data and three years hourly climate data were prepared to conduct the local calibration of the MEPDG [16]. The local design data such as material properties, traffic data (vehicle class, vehicle class distribution factors, vehicle growth factors, axle load distribution, monthly adjustment factors, hourly distribution, axle per truck, axle configuration, and lateral traffic wander), climate data, and pavement performance were collected, analyzed and converted to the MEPDG format to be used in local calibration of MEPDG in Saudi Arabia [17]. The traffic data (e.g., vehicle classification, growth rate, and truck distribution factors) was collected and the sensitivity analysis was done for various climate condition in Lebanon [18]. Before conducting the evaluation and local calibration of the MEPDG, developing a procedure for local data preparation, evaluation, local calibration, and validation of the MEPDG are needed. It can assist to precisely carry out the data preparation, evaluation, local calibration, and evaluation efforts, improve the pavement distresses prediction models, and ultimately lead to the successful implementation of the MEPDG for local conditions. The objective of this study is to develop a methodology and procedure for local data collection, evaluation, local calibration, and validation of the ME Rigid Pavement Design in Turkey to be used as preliminary foundation for whoever wants to implement the MEPDG for local conditions.

2. Development of Methodology

To adopt the MEPDG for the local conditions, the evaluation and local calibration efforts are highly required. The local calibration can be carried out by following a realistic implementation methodology. In other words, developing a reliable and applicable methodology for data collection and preparation, evaluation, local calibration, and validation can lead to enhance the accuracy of the pavement distresses prediction models and finally successfully adopt the MEPDG for local conditions. Considering local material specifications, pavement structure, traffic characteristics, climate conditions, construction methodology as well as follow up the AASHTO guide for local calibration of the MEPDG [19], a methodology for the implementation of the MEPDG-Rigid Pavement for Turkey is developed. The implementation methodology consists of seven main stages and several sub-sections which are explained as follows. Also, for a better understanding, the methodology is illustrated in a flow chart as shown in Figure 1.

2.1. Select input level

The MEPDG requires design inputs in three levels which are based on availability of local data and capability of highway agencies. The Level 1 design inputs are provided through actual laboratory tests while the Level 3 is mostly default values, and design data in Level 2 is estimated based on previous laboratory works. To select the input level, a comprehensive sensitivity analysis should be done to find out the sensitivity level of local design inputs (materials, traffic, and climate). Highly sensitive inputs can be selected as Level 1 and low sensitive inputs can be selected in Level 3.

2.2. Select pavement segments

In this stage, the existing pavement segments with three conditions survey in 10 years are selected.

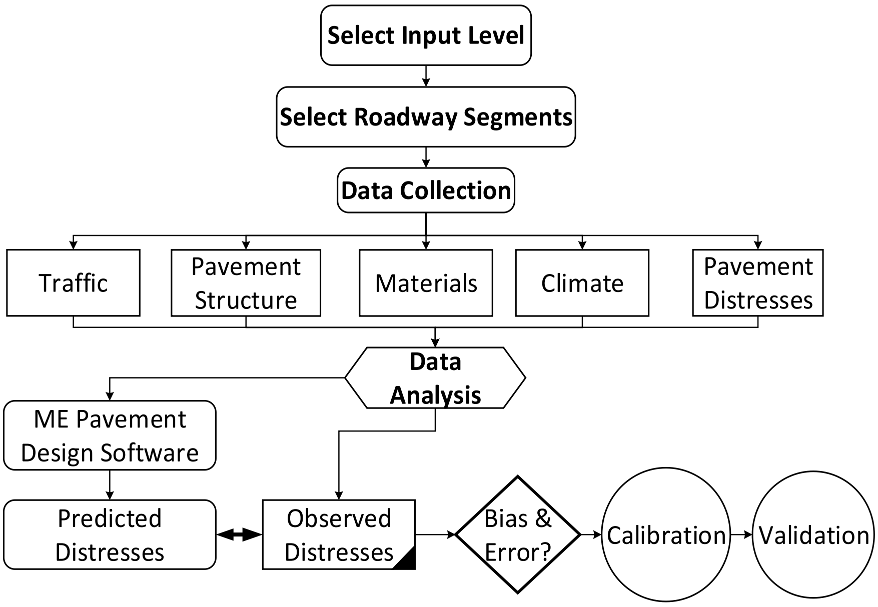

Figure 1. Methodology for local data collection and calibration of the MEPDG in Turkey

2.2.1. Data Collection

From the selected pavement segments, the local design parameters should be collected to start the evaluation and local calibration efforts. The local data which is required to be collected will be explained as follows.

2.2.2. Pavement structure

In this step, the rigid pavement type (JPCP or CRCP), pavement thickness, and the base thickness if any should be selected.

2.2.3. Pavement distresses

In this stage, the pavement distresses (Transvers cracking, Joint faulting, and International Roughness Index) should be collected. The pavement distress can be collected by two methods: 1). Distresses can be extracted from Turkish Directorate General of Highways database, if any. 2). Stablishing the Pavement Management System (PMS) to complete distress survey in accordance with the MEPDG requirements.

2.2.4. Materials properties

Various and detailed material properties for Plain Cement Concrete PCC, base and subgrade should be collected such as joint spacing, dowel diameter, steel percentage, PCC unite weight, PCC Elastic modulus, modulus of rapture, indirect tensile strength in 7, 14, 28, and 90 days, PCC poison's ratio, Air content, Coefficient of thermal expansion, water cement ratio, cement type, base and subgrade resilient modulus, and groundwater depth.

2.2.5. Traffic characteristics

The following traffic data should be collected for local calibration and sensitivity analysis efforts.

2.2.5.1. Base Year Traffic Information

- Design Life
- Opening Date
- Initial Two Way Annual Average Daily Truck Traffic (AADTT)

- Number of Lanes in Design Direction
- Percent Trucks in Design Direction
- Percent Trucks in Design Lane
- Operational Speed

2.2.5.2. Traffic Volume Adjustment Factors

- Monthly Adjustment Factors
- Vehicle Class Distribution
- Hourly Distribution
- Traffic Growth Factors

2.2.5.3. Axle Load Distribution Factors

The axle load distribution factors are required to be collected in four separate groups based on axle type and truck classification, such as single axle load distribution, tandem axle load distribution factors, tridem axle load distribution factors as well as quad axle load distribution factors if any.

2.2.5.4. General Traffic Inputs

- Lateral Traffic Wander
- Number of Axles per Truck
- Axle Configuration

2.2.6. Climate data

Climate data such as hourly temperature, wind speed, sunshine, precipitation, and relative humidity are required to be collected. It is recommended that the climate data should exist for the whole pavement design life. In Turkey, the hourly climate data can be obtained from Turkish State Meteorological Service (TC Meteoroloji Genel Müdürlüğü, MGM).

2.3. Data analysis

Some of the local data are not suitable to be used directly as design inputs in the MEPDG software; therefore, data analysis is required to be made to improve the local data and convert them to a suitable format. Right now, in Turkey, vehicles are classified in five groups as per vehicle types such as Cars, Medium Goods Vehicles, Bus, Trucks, and Trailers while, in the MEPDG the vehicles are classified based on axle types, number, and spacing as well as vehicle types in ten groups. Therefore, a comprehensive study is required to classify the observed vehicles in Turkey as per the MEPDG standard. The observed vehicles in Turkey which are shown in Figure 2 are classified based on axle type (single, tandem, and tridem axles), axle number (two, three, four, five and six), and tire configurations (single and dual). For example: “1” represents single axle and single tire, “2” represents single axle and dual tire, “11” shows single tire and tandem axle, “111” represent super-single tire and tridem axle as well as “222” represents dual tire and tridem axle. Another important design parameter that should be considered is the axle load distribution factors. In Turkey, the axle load distribution is collected in interval of 1000 Kg using weighbridge measurement system which is shown in Table 1. But the MEPDG requires different axle load intervals as follows [1, 20-21].

- Single Axle Load Distribution Factors (1000 kg to 20000 kg) at interval of 500 kg.
- Tandem Axle Load Distribution Factors (2000 kg to 40000 kg) at interval of 1000 kg.
- Tridam and Quad Axle Load Distribution Factors (4500 kg to 49500 kg) at interval of 1500 kg.

Therefore, the local axle load distribution should be converted as per the MEPDG standard that can be used as design inputs in the MEPDG software. The bus axle load is not measured in Turkey. Thus, the default bus axle load distribution factors can be used until further measurement.

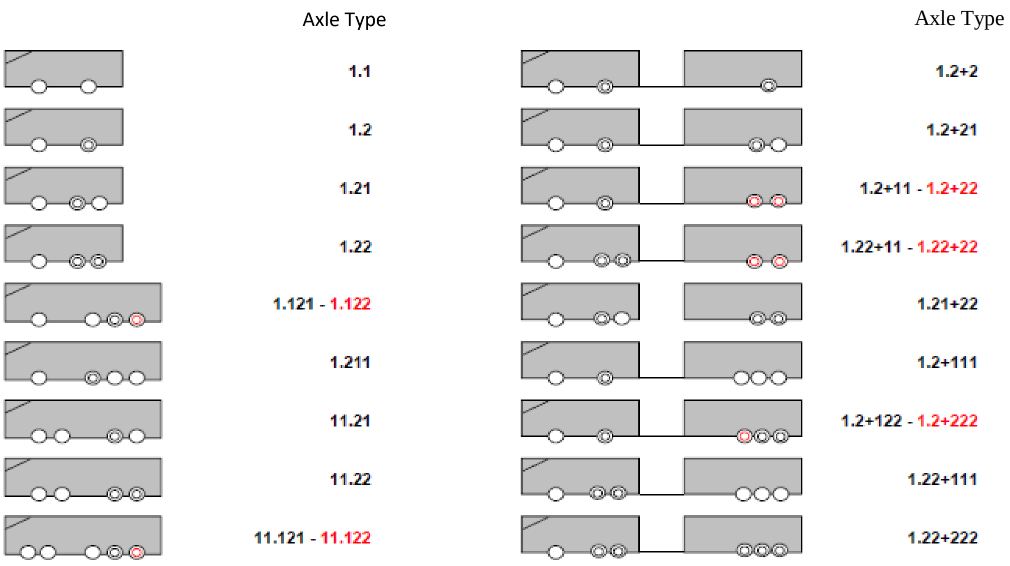

Figure 2. Measured axle load distribution [9]

Table 1. Measured axle load distribution [9]

Load class (ton)	Single axle		Tandem axle		Tridem axle	
	Axle Number	%	Axle Number	%	Axle Number	%
0-1	200	0.203273	9	0.032619	6	0.016634
1-2	3155	3.206627	11	0.039868	8	0.022178
2-3	6748	6.858421	74	0.268203	155	0.429708
3-4	10353	10.52241	522	1.891921	386	1.070112
4-5	16137	16.40106	1156	4.189772	2088	5.788584
5-6	20190	20.52038	1838	6.661593	3221	8.929611
6-7	17104	17.38388	2773	10.05038	1974	5.47254
7-8	8250	8.384998	2528	9.162408	1828	5.067783
8-9	3614	3.673138	2233	8.093219	1587	4.399656
9-10	3360	3.414981	1849	6.701461	1162	3.221424
10-11,5	5539	5.629637	2350	8.51727	1293	3.584597
11,5-12	1264	1.284683	781	2.830633	363	1.006349
12-13	1598	1.624149	1633	5.918597	793	2.198442
13-14	640	0.650473	1557	5.643145	806	2.234482
14-15	158	0.160585	1410	5.110362	797	2.209531
15-16	46	0.046753	1085	3.932442	899	2.492307
16-17	13	0.013213	1040	3.769345	1009	2.797261
17-18	11	0.01118	955	3.461274	1114	3.088354
18-19	6	0.006098	950	3.443152	1374	3.809154
19-20	4	0.004065	875	3.171324	1586	4.396884
20-21			669	2.424704	1876	5.200854
21-22			369	1.337393	2268	6.287599
22-23			288	1.043819	2355	6.52879
23-24			192	0.695879	2081	5.769177
24-25			140	0.507412	1621	4.493915

25-26			82	0.297198	1067	2.958055
26-27			48	0.17397	830	2.301017
27-28			35	0.126853	535	1.483186
28-29			31	0.112355	311	0.862188
29-30			17	0.061614	191	0.529511
30-31			27	0.097858	127	0.352083
31-32			19	0.068863	87	0.241191
32-33			17	0.061614	60	0.166339
33-34			7	0.025371	49	0.135843
34-35			11	0.039868	39	0.10812
35-36			7	0.025371	22	0.060991
36-37			3	0.010873	13	0.03604
37-38					16	0.044357
38-39					11	0.030495
39-40					6	0.016634
40-41					12	0.033268
41-42					6	0.016634
42-43					7	0.019406
43-44					10	0.027723
>44					22	0.060991
Total	98390	100	27591	100	36071	100

The MGM measures the cloud cover in the 8-Okta unit but sunshine is used in the MEPDG in percent. In okta measurement unit the sky is divided in eight parts (0-8), which 0 shows a sunny day and 8 represents 100% cloud cover [17]. Therefore, the okta unit should be converted into percent and the cloud percentage cover should be changed to sunshine percentage. And finally, the collected local climate data should be converted to the MEPDG format (text file in ".hcd" extension) because the climate data has not been yet developed in the MEPDG format for all parts of Turkey [22]. Each climatic file consists of date (YYYY/mm/dd/hr), air temperature (°C), precipitation (mm), wind speed (m/hr), cloud cover (%), and humidity (%) which is shown in Figure. 3. Due to several reasons (maintenance, extreme weather or malfunction) the weather stations are not able to record continuously; therefore, the missed data should be completed using interpolation method or adoption from another stations [13][23].

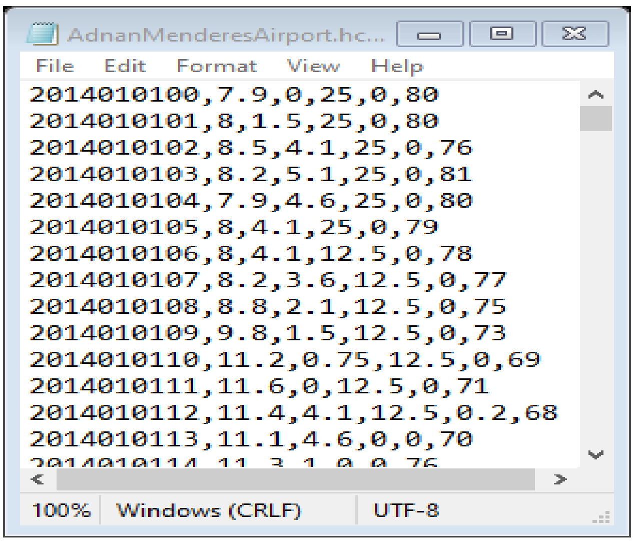

Figure 3. Climate data in MEPDG required format

2.4. Evaluation

In this step the prepared local design data are used as design inputs in the MEPDG software and the pavement distresses (transvers cracking, joint faulting, punch-outs, and IRI) are predicted for each selected pavement segments. The predicted and observed pavement distresses are compared together to verify the accuracy level of pavement distress prediction models. If significant bias and standard error exist between predicted and observed distresses, the local calibration step is required to be carried out. In this purpose, the Null hypothesis which is shown by Equation. 1 is used.

$$H^0: \sum_{i=1}^{n} (Y_{measured} - X_{predicted}) = 0 \tag{1}$$

Where;
$Y_{measured}$ = Measured value and $X_{Predicted}$ = Predicted value

2.5. Local calibration

In the case of the existence of significant bias and standard error between measured and predicted pavement distresses, the local calibration is conducted to remove the bias and decrease the standard error to an acceptable level. In this stage, the local calibration factors should be adjusted to eliminate the bias and reduce the standard error. The following activity can be done.

2.5.1. Local calibration of transvers cracking

To remove the bias and decrease the standard error from the cracking model the calibration factors (C_1, C_2, C_3, C_4, C_5) in Equation 2 and Equation 4 should be adjusted.

$$CRK = \frac{100}{1 + C_4 (DI_F)^{C_5}} \tag{2}$$

Where;
CRK = predicted amount of bottom-up or top-down cracking;
DI_F = fatigue damage calculated using the equation 3.
C_4 and C_5 = calibration coefficients

$$DI_F = \sum \frac{n_{i,j,k,l,m,n,o}}{N_{i,j,k,l,m,n,o}} \tag{3}$$

Where;
$n_{i,j,k,m,n,o}$ = applied number of load applications at condition i, j, k, l, m, n,o.
$N_{i,j,k,m,n,o}$ = allowable number of load applications at condition i, j, k, l, m, n,o.

$$Log\left(N_{i,j,k,l,m,n,o}\right) = C_1 \left(\frac{MR_i}{\sigma_{i,j,k,l,m,n,o}}\right)^{C_2} \tag{4}$$

Where:
$N_{i,j,k,m,n,o}$ = allowable number of load applications at condition *i*, *j*, *k*, *l*, *m*, *n*,
MR_i = PCC modulus of rupture at age *i*, Mpa,
$\sigma_{i,j,k,m,n,o}$ = applied stress at condition i, j, k, l, m, n,o.
C_1 and C_2 = calibration factors

2.5.2. Local calibration of joint faulting

The local calibration coefficients (C_1, C_2, C_3, C_4, C_5, C_6, C_7, and C_8) from joint faulting predicted model (Equation 5 and 6) should be adjusted to eliminate the bias and reduce the standard error.

$$Fault_m = \sum_{i=1}^{m} \Delta Fault_i \quad (5)$$

Where;
$Fault_m$ =mean joint faulting at the end of month *m*;
$\Delta ault_i$=incremental change in mean transverse joint faulting during month, *i*.

$$\Delta Fault_i = C_{34} * \left(FAULTMAX_{i-1} - Fault_{i-1}\right)^2 * DE_i \quad (6)$$

$$FAULTMAX_i = FAULTMAX_0 + C_7 * \sum_{i=1}^{m} DE_j * Log\left(1 + C_5 * 5.0^{EROD}\right)^{c_6} \quad (7)$$

And,

$$FAULTMAX_0 = C_{12} * \delta_{\text{curling}} * \left[\sum_{i=1}^{m} Log\left(1 + C_5 * 5.0^{EROD}\right) * Log\left(\frac{P_{200} * WetDays}{p_s}\right)\right]^{c_6} \quad (8)$$

Where;
$FAULTMAX_i$=maximum mean transverse joint faulting for month *i*, m.,
FAULTMAX0 $FAULTMAX_0$=initial maximum mean transverse joint faulting, m.,
EROD = base and subbase erodibility confections
DE_i = differential density of energy of subgrade deformation accumulated during month, *i*.
$\delta_{curling}$ = maximum mean monthly slab corner upward deflection PCC due to temperature curling and moisture warping,
PS = overburden on subgrade, kg,
*P*200 = percent subgrade material passing #200 sieve,
WetDays =average annual number of wet days
C_1, C_2, C_3, C_4, C_5, C_6, C_7, and C_8 are calibration constants.

$$C_{12} = C_1 + C_2 * FR^{0.25} \quad (9)$$

$$C_{34} = C_3 + C_4 * FR^{0.25} \quad (10)$$

Where;
FR = base freezing index defined as percentage of time the top base temperature is below 0°C temperature.

2.5.3. Local calibration of smoothness

In order to conduct the local calibration for the International Roughness Index (IRI) prediction model, the C_1, C_2, C_3, C_4 factors should be adjusted to eliminate the bias and reduce the standard error from the model which are shown in Equation. 11.

$$IRI = IRI_1 + C_1 * CRK + C_2 * SPALL + C_3 * TFAULT + C_4 SF \quad (11)$$

Where:
IRI = Predicted IRI, in./mi,
IRI_I = Initial smoothness measured as IRI, in./mi,
CRK = Percent slabs with transverse cracks (all severities),

SPALL = Percentage of joints with spalling (medium and high severities),
TFAULT = Total joint faulting cumulated per mi, in., and
SF = Site factor

2.6. Validation

In this step the prepared local design data are used as design inputs in the MEPDG software and the pavement distresses (transvers cracking, joint faulting, punch-outs, and IRI) are predicted for each selected pavement segments. The predicted and observed pavement distresses are compared together to verify the accuracy level of pavement distress prediction models. If significant bias and standard error exist between predicted and observed distresses, the local calibration step is required to be carried out. In this purpose, the Null hypothesis (Equation 1) is used.

2.7. Conclusion and summary

The MEPDG was developed and calibrated based on the USA conditions. Therefore, to implement it in countries, the MEPDG has to be evaluated for local conditions and the local calibration and validation should be conducted if required. The local calibration is done to improve the accuracy level of the MEPDG distress prediction models. Developing a methodology is required to carry out such efforts. The summary of local calibration efforts and local data collection are summarized as follows.

- State agencies and countries followed different methodologies for data collection and local calibration. But they still have some similar activities (e.g., data collection, sensitivity analysis, evaluation, local calibration, and validation).
- Some of the collected data may not be directly used as design input in the MEPDG. Therefore, they should be analysed and converted to the suitable format that is required by the MEPDG.
- In Turkey, vehicles are classified based on their types in five groups (e.g., cars, medium goods vehicles, buses, trucks, and trailers) which is different from truck classification in the MEPDG. Therefore, a new vehicle classification is required to be developed.
- In Turkey, vehicles axles load (single, tandem, and tridem) are measured in the interval of 1000kg using weighbridge system, which is not based on the MEPDG standard. The measured axle load should be analysed and converted to the MEPDG required format.
- The extracted hourly climate data from automatic weather stations may have missing data and gaps (hours, days, months, and years), which can be provided and completed using data from the closest weather stations or by using interpolation. Climate data (temperature, wind speed, sunshine, precipitation, and humidity) should be converted to the text file format with ".hcd" extension.
- The cloud cover is measured in 8-Okta units in Turkey, while the sunshine is used by MEPDG in percentage. Therefore, the 8-Okta unit should be converted to percent and then the cloud cover percentage should be changed to sunshine percentage.

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