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Modeling Pavement Performance Using LTPP Database for Flexible Pavements

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ABSTRACT

In many countries, incredible investments have been made in constructing roads that require conducting periodic evaluation and timely maintenance and rehabilitation (M&R) plan to keep the network operating under acceptable level of service. The timely M&R plan necessitates accurately predicting pavement performance, which is an essential element of road infrastructure asset management systems or Pavement Management Systems (PMS). Consequently, there is always a need to develop and to update performance prediction models embedded in PMS applications. This study focuses on developing distress prediction models for flexible pavements located in non-freeze climatic zone, which represent most of the Middle East countries using data extracted from the Long-Term Pavement Performance (LTPP) program. Six distress performance prediction models were developed in this study for both wet- and dry-non-freeze climatic zones, which are Fatigue (Alligator) cracking, longitudinal cracking, transverse cracking, raveling, bleeding, and rut depth models. These models can play an important role assisting decision makers in predicting pavement performance, identifying M&R needs, rational budget planning and resource allocation.

Keywords: Prediction models, distress models, ltp, statistical modeling, flexible pavement, non-freeze climatic zone.

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1. INTRODUCTION

Road network represents the powerful engine of economy to all countries, which requires conducting periodic evaluation and timely maintenance and rehabilitation (M&R) plan to keep the network operating under acceptable level of service [1, 2]. The timely M&R plan necessitates accurately predicting pavement performance, which is a key element of road Pavement Management Systems (PMS). The performance models calculate the future conditions of pavement based on which PMS optimizes several M&R treatments and estimates the consequences of maintenance operations on the future pavement condition during the life-span of the pavement [3, 4]. At the network level, pavement performance prediction is needed for programming M&R activities, while at the project level it is needed for determining the most appropriate M&R actions to be taken for a specific project, such as preventive maintenance, rehabilitation, or reconstruction [5, 6].

Consequently, there is always a need to develop and to update performance prediction models embedded in PMS applications. Early PMSs did not have pavement performance curves rather they evaluated only the current pavement condition. Later, the simplified pavement performance curves were introduced based on the engineering opinions on the expected design life of different M&R actions [7]. The only predictive variable of these performance curves was the pavement age. The development of pavement performance is explicitly complicated as the pavement performance is subjected to a large number of parameters of pavement performance. There are two streams of pavement performance modeling, which are deterministic and stochastic approaches. The major differences between deterministic and stochastic performance prediction models are model development concepts, modeling processor formulation, and output format of the models [8].

There are different types of deterministic models, such as mechanistic models, mechanistic-empirical models, and regression models. The mechanistic models draw the relationship between response parameters such as stress, strain, and deflection [8]. The mechanistic-empirical models are often developed in connection to design systems and therefore have not been widely applied in PMS but have the potential to be applied at a network level. On the other hand, the regression models draw the relationship between a performance parameter (e.g., pavement distresses) and the predictive parameters (e.g., pavement thickness, pavement material properties, traffic loading, and age) [8, 9].

This study focuses on developing regression models through deterministic approach to predict pavement performance. These prediction models allow highway authorities to predict the pavement performance and consequently identifying the M&R timely activities. Several performance prediction models have been introduced over the years, some of which are simple and others are quite complex. Many of these models are developed for application in a particular region or country under specific traffic and climatic conditions; hence, they cannot be directly applied in other countries or conditions. Therefore, this study comes to target specific climate condition. Table 1 shows selected published pavement distress models.

Hence, this study comes to develop pavement distress prediction models for roads located in wet- and dry-non-freeze climatic zones, which represent most of the Middle East countries using data extracted from the Long-Term Pavement Performance (LTPP) program. Therefore, the developed models can be utilized in the Middle East region experiencing the same climatic condition. This study is considered as a crucial attempt to develop such models

for the Middle East region due to lack of resources led to unavailability of such models in most of the Middle East countries. However, calibration of the developed models is recommended using local pavement performance data, whenever performance data is available.

Table 1 - Selected Pavement Distress Prediction Models

Model Formula	Abbreviations	Reference
$RD = \sum_{i=1}^{N_{sublayers}} \epsilon_p^i h_i$	RD = Rut Depth, mm ϵ_p^i = plastic strain h_i = layer thickness, mm	ARA, 2004 [10]
$\ln RD_{dry} = 0.681 + 0.114 (\ln KESAL) + 0.007 (D > 32 C^\circ)$	KESAL = Standard Traffic Axle loads, thousands $D > 32 C^\circ$ = Number of days maximum temperature $> 32 C^\circ$	Naiei, 2010 [6]
$\ln RD_{wet} = 0.9 + 0.19 (AC \%) - 0.077 (SN) + 0.063 (\ln KESAL)$	RD = Rut Depth, mm SN = Structural Number KESAL = No. of Standard Traffic Axle loads	Naiei, 2010 [6]
$N_{100}^{rut} = \frac{1}{0.9533 \times rut^{-0.0209}} \times \left(\frac{rut}{a}\right)^{\frac{1}{b}}$	N_{rut100} = the average annual ESALs per lane rut = the total rutting on the surface used to define failure, mm. a, b = parameters estimated from FWD test as the surface curvature index SCI300 in [μm] measured during the fall (autumn), first time after the pavement structure is built.	Göransson and Den Svenska, 2009 [11]
$N_f = 0.00432 \times \beta f_1 \times C \times \left(\frac{1}{\epsilon_t}\right)^{3.291 \times \beta f_2} \times \left(\frac{1}{E}\right)^{0.854 \times \beta f_3}$	N_f = the maximum allowable number of repetitions $\beta f_1, \beta f_2, \beta f_3$ = calibration factors C = laboratory to field adjustment factor ϵ_t = critical tensile strain E = the stiffness of the AC surface layer	AI, 1982 [12]
$\% \text{ Fatigue cracking} = \frac{0.021}{0.027 + e^{(-0.851 \times Df)}}$	FC = fatigue cracking in percent of entire lane area, (%). Df = cumulative fatigue damage	Ali and Tayabii, 1989 [13]
$(FC)_{wet} = \exp(-6.539 + 0.078 \times \text{age} + 0.00187 \times KESAL + 0.000673 \times \text{precip} + 0.0914 \times \text{temp} + 15097 \times \text{epsilon.t} + 0.0272 \times \text{ft})$	FC = fatigue cracking in percent of entire lane area, (%) age = pavement age, years. KESAL = the yearly ESALs, thousands. precip = mean annual precipitation, mm. temp = mean annual temperature, $^\circ C$ epsilon.t = the critical tensile strain. ft = yearly freeze-thaw cycle	Ker et al., 2007 [14]

Table 1 - Selected Pavement Distress Prediction Models (continue)

Model Formula	Abbreviations	Reference
(FC)dry= $\exp(-48.411 + 0.119 \text{ age} + 0.025 \text{ x precip} + 1.774 \text{ x temp} + 2729 \text{ x epsilon.t} + 0.0272 \text{ x ft})$	FC = fatigue cracking in percent of entire lane area, (%) epsilon.t = the critical tensile strain. ft = yearly freeze-thaw cycle	Ker et al., 2007 [14]
(FC)freeze = $\exp(-5.944 + 0.00583 \text{ x precip} + 41.768 \text{ x epsilon.t} - 0.002 \text{ x visco} + 0.4 \text{ x trange})$	Visco = viscosity of the AC layer, p. trange = the difference of maximum and minimum mean annual temperature, °C	Ker et al., 2007 [14]
(FC)nonfreeze = $\exp(-7.87 + 0.102 \text{ x age} + 0.00219 \text{ x KESAL} + 0.00102 \text{ x precip} + 0.0472 \text{ x temp} + 15172 \text{ x epsilon.t} + 0.0476 \text{ x ft})$	FC = fatigue cracking in percent of entire lane area, (%) epsilon.t = the critical tensile strain. ft = yearly freeze-thaw cycle	Ker et al., 2007 [14]

Such models would help highway authorities, located in non-freeze climatic zones, to precisely predict pavement performance and hence using these predictions in identifying the M&R activities. Based on the data available in the LTPP, six distress prediction models were developed in this study, for both wet- and dry-non-freeze climatic zones, as follows:

- Fatigue Cracking model
- Longitudinal Cracking model
- Transverse Cracking model
- Raveling model
- Bleeding model
- Rut depth model

The precision and accuracy of the distress prediction models are affected by the type of the mathematical model. Therefore, a comprehensive statistical analysis should be performed to get a model with high accuracy. A stepwise regression analysis was conducted to come up with the most effective factors that could affect such models. Consequently, a Statistical Package for Social Science (SPSS) program was used to develop such models. To check the reliability of the model, some measures of the statistical accuracy are used as follows [15, 16]:

- The Standard Error (SE), which is a measure of the statistical accuracy of an estimate,
- The coefficient of determination (R^2), which is defined as the proportion of the variance in the dependent variable that is predictable from the independent variable(s).

In statistics, normality tests are used to determine if a data set is well-modeled by a normal distribution and to compute how likely it is for a random variable underlying the data set to be normally distributed. If the data is normally distributed, analysis of variance (ANOVA) test is used. However, Kruskal-Wallis or Mann-Whitney tests is used for non-normal data.

2. BACKGROUND OF LTPP

The Long-Term Pavement Performance program (LTPP) is the largest pavement performance research program ever undertaken, gathering data from more than 2,000 pavement test sections over a 20-year test period. The single most significant product of the LTPP program is the pavement database - the largest and most comprehensive collection of research-quality performance data on in-service highway pavements ever assembled.

The Long-Term Pavement Performance program is one of the significant research regions of the Strategic Highway Research Program (SHRP). The initial five years of the LTPP program were finished under the subsidizing and course of SHRP. Since 1991, the Federal Highway Administration (FHWA) has proceeded with the administration and subsidizing of the program. The LTPP program is overseen by the LTPP Team under the Office of Infrastructure Research and Development [17, 18, 19].

The LTPP program has two complementary experiments to meet the objectives. First, the General Pavement Studies (GPS) use existing pavements as originally constructed or after the first overlay and focus on the most commonly used structural designs for pavement. The second set of LTPP experiments is the Specific Pavement Studies (SPS) whose test sections allow critical design factors to be controlled and performance to be monitored from the initial date of construction. The results will provide a better understanding of how selected maintenance, rehabilitation, and design factors affect pavement performance. The consolidated GPS and SPS programs comprise of more than 2,500 test segments situated on all through North America built in four climate zones: wet-non-freeze, dry-non-freeze, wet-freeze, and dry-freeze. The LTPP program screens and gathers asphalt execution information on every single dynamic site. The gathered information incorporates data on seven modules: Inventory, Maintenance, Monitoring (Deflection, Distress, and Profile), Rehabilitation, Materials Testing, Traffic, and Climatic. The LTPP Information Management System (IMS) is the focal database where every one of the information gathered under the LTPP program are put away. This database is persistently being produced as more information is gathered and handled [17, 18].

3. OBJECTIVE AND METHODOLOGY

The main objective of this study is to develop pavement distress prediction models for flexible pavements located in wet- and dry-non-freeze climatic zones, which represent most of the Middle East countries using LTPP database. This study focuses on developing such models for the Middle East countries experiencing wet- and dry-non-freeze climatic zones, to be used in their PMS; while calibration of the developed models is recommended based on local condition of a country whenever the pavement performance data is available.

Therefore, four main steps were conducted to achieve the objective of this study. Data collection and preparation using LTPP database was the first main step. The second step was statistical analysis that came to play the role of judgment on all possible factors that could affect developing such models as well as their significance. Developing and optimizing the pavement distress prediction models using SPSS software were the third step. The validation process was the last essential step.

4. DATA COLLECTION AND PREPARATION

The LTPP dataset was the main source of data in this study, which includes data until year 2016. Therefore, LTPP sites, located in wet- and dry-non-freeze climatic zones, were selected to obtain the required data according to specific criteria as follows:

- Sites located in wet- and dry-non-freeze climatic zones.
- Only overlaid sections were chosen to simulate newly constructed pavement.
- Rural sections were selected to represent main roads.
- Design period or data range was selected for 25 years, starting from 1991.

Accordingly, 43 and 57 LTPP sites were selected for wet- and dry-non-freeze climatic zones, respectively. Data collection step was then started. There are numerous factors related to the occurrence of the pavement problems. However, this study selected some factors that are considered as the most important factors related to pavement problems especially for fatigue cracking, longitudinal cracking, transverse cracking, raveling distress, bleeding distress, and rutting distress. These factors are summarized as follows:

- Air temperature (T_a), °C
- Pavement age since overlay (PA), years
- Traffic loading represented by Equivalent Single Axle Load (ESAL), No. of Axles
- Annual Precipitation, mm
- Available pavement distresses, area (sq.m.) or length (m)
- Asphalt pavement thickness (T), mm
- Material characteristics:
 - Resilient modulus of subgrade soil (M_r), MPa
 - % Passing the #200 sieve (0.075 mm) of subgrade soil (P_{200}),
 - % Air voids of asphalt mix (V_a),
 - % Asphalt content in the mix (P_b)
 - % Moisture content of base/subbase courses (MC_b),
 - % Moisture content of subgrade soil (MC_s), and
 - Plasticity index of subgrade soil (PI)

All data were collected on different dates during the 25-year data range. The collected data have been filtered through a screening process to come up with feasible data that could be used to develop the required models. The criteria for screening process are selected as follows:

1. Unavailability and/or insufficient of some distresses data
2. Absence of material characteristics data
3. Abnormal data patterns, e.g. distress density should be increased with time not decreased.

Table 2 - Selected Non-Freeze LTPP Sites

Site ID	State	Site ID	State
Wet-Non-Freeze Climatic Zone			
12-3997	Florida (FL)	28-2807	Mississippi (MS)
12-3996	Florida (FL)	28-3081	Mississippi (MS)
12-4106	Florida (FL)	37-1024	North Carolina (NC)
12-4107	Florida (FL)	37-1030	North Carolina (NC)
12-4108	Florida (FL)	37-1802	North Carolina (NC)
12-4097	Florida (FL)	40-1017	Oklahoma (OK)
12-9054	Florida (FL)	40-4163	Oklahoma (OK)
13-4096	Georgia (GA)	40-4087	Oklahoma (OK)
13-4112	Georgia (GA)	40-4161	Oklahoma (OK)
13-4113	Georgia (GA)	40-4165	Oklahoma (OK)
13-4111	Georgia (GA)	45-1025	South Carolina (SC)
13-4420	Georgia (GA)	5-3048	Arkansas
1-1021	Alabama (AL)	48-3729	Texas (TX)
1-4126	Alabama (AL)	48-1113	Texas (TX)
1-4129	Alabama (AL)	48-1116	Texas (TX)
1-1001	Alabama (AL)	48-1093	Texas (TX)
1-1019	Alabama (AL)	48-1068	Texas (TX)
24-1632	Maryland (MD)	48-1060	Texas (TX)
28-1001	Mississippi (MS)	48-3609	Texas (TX)
28-3028	Mississippi (MS)	51-1023	Virginia (VA)
28-3091	Mississippi (MS)	51-2021	Virginia (VA)
Dry-Non-Freeze Climatic Zone			
4-1002	Arizona (AZ)	35-0108	New Mexico (NM)
4-1003	Arizona (AZ)	35-0103	New Mexico (NM)
4-1006	Arizona (AZ)	35-0104	New Mexico (NM)
4-1007	Arizona (AZ)	35-0106	New Mexico (NM)
4-1015	Arizona (AZ)	35-0105	New Mexico (NM)
4-1017	Arizona (AZ)	35-1112	New Mexico (NM)
4-1021	Arizona (AZ)	35-0107	New Mexico (NM)
4-1024	Arizona (AZ)	35-0109	New Mexico (NM)
4-1025	Arizona (AZ)	35-0110	New Mexico (NM)
4-0113	Arizona (AZ)	35-0112	New Mexico (NM)
4-1062	Arizona (AZ)	35-0101	New Mexico (NM)
4-0160	Arizona (AZ)	48-1111	Texas (TX)
4-1065	Arizona (AZ)	48-1061	Texas (TX)
4-6055	Arizona (AZ)	48-1076	Texas (TX)
6-8151	California (CA)	48-3769	Texas (TX)
6-2004	California (CA)	48-6060	Texas (TX)
35-0101	New Mexico (NM)	48-1048	Texas (TX)
Sites to be selected for validation process			

Consequently, 42 LTPP sites out of 43 were selected for wet-non-freeze climatic zone; and 34 LTPP sites out of 57 were selected for dry-non-freeze climatic zone, as shown in Table 2. Furthermore, fatigue cracking, longitudinal cracking, transverse cracking, raveling distress, bleeding distress, and rutting distress were selected for model development. The unit of distress data recorded in the LTPP database is based on the distress types. The unit of area is accounted for fatigue, raveling, and bleeding; on the other hand, the unit of length or depth is accounted for longitudinal, transverse, and rutting distress. In addition to the collected distress data, distress density was calculated by dividing the length or area of distress by the area of examined section based on the PAVER system [20].

Comprehensive database was then created to be used for model development and validation process. The database was split into two categories of dataset. The first category is for model development, which represents 79% of all databases, and the second category is for validation process, which represents 21% of all database, as shown in Table 2. The validation data of 21% is considered reasonable statistically and the validation sites were selected to represent most of the original data and most of the sites. It is noteworthy that the developed models should not be exposed to the validation dataset while developing the models.

5. DEVELOPMENT OF PAVEMENT DISTRESS PREDICTION MODELS

This part deals with the process of developing fatigue cracking, longitudinal cracking, transverse cracking, raveling distress, bleeding distress, and rutting distress models. Since ESAL is a function of time or age, either ESAL or age would be selected as independent variable in the developed models. Sample of collected data is shown in Table 3 and Table 4 for wet- and dry-non-freeze climatic zones, respectively, for different LTPP sites shown in Table 2.

Table 3 - Sample of Collected Data using Wet-Non-Freeze LTPP Sites for Different LTPP Sites

%Density	Ta, C°	PA, Years	Mr, MPa	P ₂₀₀ (%)	%Va	%MC _b	%MC _s	PI
<u>Fatigue Cracking Model</u>								
0	24.30	4	114	-	-	4	7	-
6.67	19.40	14	73	3.50	-	4	7	2
16.67	21.90	16.16	65	9.40	-	3	15	-
<u>Longitudinal Cracking Model</u>								
0	24.29	4	114	-	-	4	7	-
0.05	19.29	5.83	124	30.7	-	9	10	-
17.0	18	6.42	95	-	-	-	-	-
<u>Transverse Cracking Model</u>								
0	20.00	0.18	-	-	-	15	-	8
0.7624	16.40	4.52	-	83.00	-	15	4	6
7.8756	20.30	7.02	25	15.60	-	14	-	-

Table 3 - Sample of Collected Data using Wet-Non-Freeze LTPP Sites for Different LTPP Sites (continue)

%Density	Ta, C°	PA, Years	Mr, MPa	P ₂₀₀ (%)	%Va	%MC _b	%MC _s	PI
<u>Raveling Model</u>								
0	13.50	0.12	20	25.40	4.593	4	18	12
12.5041	19.40	4.7	73	3.50	6.993	4	7	2
36.9383	24.30	13	-	-	-	-	5	-
<u>Rutting Model</u>								
Rut Depth mm	Ta, C°	PA, Years	ESAL	Annual Precipitation, mm	%Va			
6	15.89	5.92	711	1778.5	7.091			
8	16.89	15.3	59	1679.30	5.823			
10	15.60	12	40	1290.30	7.09			
15	19.79	9.66	106	1418.59	3.993			

Table 4 - Sample of Collected Data using Dry-Non-Freeze LTPP Sites for Different LTPP Sites

%Density	Ta, C°	PA, Years	Mr, MPa	P ₂₀₀ (%)	%Va	T, mm	%MC _b	%MC _s	PI
<u>Fatigue Cracking Model</u>									
11.8	17.6	15.5	87	-	-	221	5	11	30
36.67	19.1	15.58	37	-	-	53.3	3	7	0
37.7	18.5	17.41	114	-	-	63.5	2	9	9
<u>Longitudinal Cracking Model</u>									
2.84	-	15.5	88.6	29.5	-	-	5	-	30
6.45	-	16	72.3	23.6	-	-	2	-	0
8.17	-	17.1	64.4	22.8	-	-	-	-	-
<u>Transverse Cracking Model</u>									
0	-	0	5794	51	-	-	2	-	0
2.84	-	15.5	88.6	29.5	-	-	5	-	30
4.18	-	18.09	101.8	28.5	-	-	5	-	0
<u>Bleeding Model</u>									
0	-	1.2	45	24.9	1.87	-	3	-	6
7.21	-	8.21	105.5	28.5	3.62	-	2	-	0
27.37	-	12.58	75	9.6	12	-	1	-	-

Table 4 - Sample of Collected Data using Dry-Non-Freeze LTPP Sites for Different LTPP Sites (continue)

Rutting Model					
Rut Depth mm	Ta, C°	PA, Years	ESAL	Annual Precipitation, mm	%Va
4	16.10	8.416	12	294.6	6.12
5	17.70	15.5	4	343.4	6.12
7	23.10	16.58	768	41	16.3
11	22.70	18.25	925	121.9	16.3

5.1. Stepwise Regression Test

Stepwise regression test was performed within 95% confidence interval to come up with the most effective factors that could affect fatigue cracking, longitudinal cracking, transverse cracking, raveling distress, bleeding distress, and rutting distress. The decision would be made based on p-value for all considered factors. A small p-value (typically ≤ 0.05) indicates strong evidence against the null hypothesis, so the null hypothesis is rejected. A large p-value (> 0.05) indicates weak evidence against the null hypothesis, so fail to reject the null hypothesis [21]. Table 5 and Table 6 depict the results of p-value of the considered factors for wet- and dry-non-freeze climatic zones, respectively.

Table 5 - P-value using Wet-Non-Freeze LTPP Sites

	Fatigue Cracking	Longitudinal Cracking	Transverse Cracking	Raveling Distress	Rut Depth
Ta	0.54337	0.42071	0.97183	0.27308	0.46982
PA	<u>0.01447</u>	0.89778	0.52564	<u>0.03860</u>	nil
ESA					<u>0.02762</u>
L	nil	nil	nil	nil	
Mr	0.66094	<u>0.03473</u>	0.49485	0.88260	0.79112
P ₂₀₀	0.66620	0.14896	0.95062	0.30984	-
Va	0.87726	0.14831	nil	<u>0.01427</u>	<u>0.05558</u>
T	0.98640	0.28561	nil	nil	0.90004
MC _b	0.79172	<u>0.00194</u>	<u>0.03165</u>	0.66059	nil
MC _s	<u>0.00960</u>	0.61107	0.10406	0.24776	nil
PI	0.57023	0.26024	<u>0.04055</u>	0.12184	nil
P _b	nil	nil	nil	nil	nil

nil means that this factor is not considered in testing

As shown in Table 5, fatigue cracking model is affected by pavement age and moisture content of subgrade soil for wet-non-freeze climatic zone. On the other hand, pavement age, air temperature, and plasticity index of subgrade soil are the factors that affect fatigue cracking model for dry-non-freeze climatic zone, as shown in Table 6. It could be concluded that moisture condition-related factors of subgrade soil affect the occurrence of fatigue cracking.

On the other hand, longitudinal cracking model is affected by resilient modulus of subgrade soil and moisture content of base/subbase courses for wet-non-freeze climatic zone while pavement age and % passing the #200 sieve (0.075 mm) of subgrade soil are the factors affecting longitudinal cracking model for dry-non-freeze climatic zone. It could be concluded that too much fine aggregate experiences this type of crack.

Table 6 - *p*-value using Dry-Non-Freeze LTPP Sites

	Fatigue Cracking	Longitudinal Cracking	Transverse Cracking	Bleeding Distress	Rut Depth
Ta	<u>0.00740</u>	nil	nil	nil	<u>0.00111</u>
PA	<u>0.01515</u>	<u>0.00000</u>	<u>0.00351</u>	<u>0.00003</u>	nil
ESA	nil		nil	nil	
L		nil			<u>0.00010</u>
Mr	0.43891	0.93581	0.14276	0.93685	0.14071
P ₂₀₀	nil	<u>0.01896</u>	0.12448	0.54376	-
Va	nil	nil	nil	<u>0.01832</u>	<u>0.00000</u>
T	0.38696	nil	nil	nil	nil
MC _b	0.28823	0.66000	0.82018	0.17165	nil
MC _s	0.17819	nil	nil	nil	nil
PI	<u>0.01646</u>	0.75348	0.26137	0.22060	nil
P _b	nil	nil	nil	nil	0.53185

nil means that this factor is not considered in testing

For transverse cracking model, it is affected by moisture content of base/subbase courses and plasticity index of subgrade soil for wet-non-freeze climatic zone while pavement age is the only factor affecting transverse cracking model for dry-non-freeze climatic zone.

Raveling and bleeding distress models are affected by pavement age and % air voids of asphalt mix for wet- and dry-non-freeze climatic zones, respectively. Finally, rut depth is affected by ESAL and Va for wet-non-freeze climatic zone. On the other hand, ESAL, Ta and V_a are the factors that affect rut depth for dry-non-freeze climatic zone.

5.2. Regression Analysis

Multiple regression analysis technique was applied to develop fatigue cracking, longitudinal cracking, transverse cracking, raveling distress, bleeding distress and rut depth prediction models for wet- and dry-non-freeze climatic zones using SPSS software. Several trials were made to develop the required models that best represent the relation between the distresses with related factors. Table 7 shows regression analysis for developed models using non-freeze LTPP sites.

Table 7 - Regression Analysis for Developed Models using Non-Freeze LTPP Sites

Distress Model	Climate	Estimate	Parameters				R ²	df	Mean Squares
			A	B	C	D			
Fatigue Cracking	Wet	Value	-10.356	1.936	1.422	-	0.884	3	488.633
		SE	2.263	0.359	0.251	-			
	Dry	Value	-45.281	9.260	2.101	6.135	0.465	4	482.729
		SE	120.087	20.856	8.318	4.457			
Longitudinal Cracking	Wet	Value	14.201	-5.320	0.365	-	0.318	3	7.152
		SE	116.202	38.766	0.698	-			
	Dry	Value	24.258	22.118	-	0.078	0.478	4	31.956
		SE	7.389	0.109	7.385	-			
Transverse Cracking	Wet	Value	-10.725	1.146	-	9.164	0.980	3	0.072
		SE	1.851	0.188	1.873	-			
	Dry	Value	0.048	0.203	-	-	0.755	1	420.013
		SE	0.147	0.11	-	-			
Reveling Distress	Wet	Value	-2.075	-0.902	0.823	-	0.323	3	19.273
		SE	1.924	1.037	0.468	-			
Bleeding Distress	Dry	Value	4.708	1.042	1.203	-	0.820	3	1588.807
		SE	8.933	0.283	0.299	-			
Rut Depth	Wet	Value	10.097	-0.987	0.478	-	0.233	3	693.294
		SE	2.664	0.474	0.229	-			
	Dry	Value	21.338	0.009	-	0.255	0.479	5	411.999
		SE	0.317	0.210	1.055	0.002			

5.2.1. Fatigue Cracking Model

Table 7 indicates that the model has R^2 value of 0.884 and 0.465 based on the obtained data from LTPP for wet- and dry-non-freeze climatic zones, respectively. Therefore, the proposed distress model of fatigue cracking could be written as follows:

Wet-non-freeze zone:

$$\%Fatigue\ Cracking = e^{(-10.356+1.936\sqrt{PA}+1.422\sqrt{MC_S})} \quad (1)$$

Dry-non-freeze zone:

$$\%Fatigue\ Cracking = e^{(-45.28+9.26\sqrt{PA}+2.1\sqrt{PI})} + 6.14 \cos Ta \quad (2)$$

5.2.2. Longitudinal Cracking Model

Table 7 indicates that the model has R^2 value of 0.318 and 0.478 based on the obtained data from LTPP for wet- and dry-non-freeze climatic zones, respectively. Therefore, the proposed distress model of longitudinal cracking could be written as follows:

Wet no-freeze zone:

$$\%Longitudinal\ Cracking = e^{(-22.896-0.185 \log MC_b-28.073\sqrt{Mr})} \quad (3)$$

Dry no-freeze zone:

$$\%Longitudinal\ Cracking = 24.258 + 22.118 \sin \sqrt{PA} - 0.078P_{200} \quad (4)$$

5.2.3. Transverse Cracking Model

Table 7 indicates that the model has R^2 value of 0.980 and 0.755 based on the obtained data from LTPP for wet- and dry-non-freeze climatic zones, respectively. Therefore, the proposed distress model of transverse cracking could be written as follows:

Wet no-freeze zone:

$$\%Transerve\ Cracking = e^{(-10+1.146 \sin PI-9.164 \cos MC_b)} \quad (5)$$

Dry no-freeze zone:

$$\%Transverse\ Cracking = 0.048 + 0.203 PA \quad (6)$$

5.2.4. Raveling Distress Model

Table 7 indicates that the model has R^2 value of 0.323 based on the obtained data from LTPP for wet-non-freeze climatic zones. Therefore, the proposed distress model of raveling distress could be written as follows:

Wet no-freeze zone:

$$\%Raveling = -2.075 - 0.902 \sin PA + 0.823Va \quad (7)$$

5.2.5. Bleeding Distress Model

Table 7 indicates that the model has R^2 value of 0.820 based on the obtained data from LTPP for dry-non-freeze climatic zones. Therefore, the proposed distress model of bleeding distress could be written as follows:

Dry no-freeze zone:

$$\%Bleeding = 4.708 + 1.043 PA + 1.203 V_a \quad (8)$$

5.2.6. Rut Depth Model

Table 7 indicates that the model has R^2 value of 0.233 and 0.479 based on the obtained data from LTPP for wet- and dry-non-freeze climatic zones, respectively. Therefore, the proposed rut depth model could be written as follows:

Wet no-freeze zone:

$$Rut\ Depth = 10.097 - 0.987 \ln(ESAL) + 0.478V_a \quad (9)$$

Dry no-freeze zone:

$$Rut\ depth = 21.39 + 0.009ESAL - 1.05Ta + 0.255V_a \quad (10)$$

6. VALIDATION PROCESS

Once the models were developed, validation process should start using LTPP data sets different from the database used in the development process. The second category of dataset was used for validation process, which represents 21% of entire database.

Predicted values were calculated using the developed models; however, the actual or measured values were obtained from the selected LTPP sites. Table 8 and Table 9 show the results of measured and predicted values of fatigue, longitudinal, transversal, raveling, bleeding and rutting for wet- and dry-non-freeze climatic zones, respectively. The results indicate that the predicted values are fairly close to the measured values at the corresponding LTPP sites.

Table 8 - Measured and Predicted Distress Density for Wet-Non-Freeze LTPP Sites

%Fatigue Cracking		%Longitudinal Cracking		%Transverse Cracking		%Raveling		Rut Depth, mm	
M	P	M	P	M	P	M	P	M	P
0.00	0.01	0.00	0.23	0.10	0.0531	0.14	0.74	4	4.77
0.59	0.39	0.00	0.00	0.00	0.3756	0.00	0.63	12	12.09
7.46	8.29	0.00	0.00	0.00	0.00	9.83	6.81	6	8.56
0.00	0.04	2.18	1.27	0.00	0.00	0.35	0.59	7	9.43
0.00	0.05	0.00	0.00	0.00	0.10	0.00	0.00	17	13.71

Table 8 - Measured and Predicted Distress Density for Wet-Non-Freeze LTPP Sites
(continue)

%Fatigue Cracking		%Longitudinal Cracking		%Transverse Cracking		%Raveling		Rut Depth, mm	
2.23	1.64	0.00	0.00	0.00	0.02	0.00	0.00	12	10.54
1.79	2.48	0.00	0.005	3.34	0.06	0.00	0.00	9	8.01
20.56	24.35	0.00	0.00	6.82	0.01	0.00	0.00	6	5.29
0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	5	4.19
13.32	9.54	13.52	1.03	0.41	0.40	0.00	2.4	6	5.06
0.00	4.12	0.134	.006	0.30	0.40	2.45	3.17	12	13.71

M: Measured values

P: Predicted values

Table 9 - Measured and Predicted Distress Density for Dry-Non-Freeze LTPP Sites

%Fatigue Cracking		%Longitudinal Cracking		%Transverse Cracking		%Bleeding		Rut Depth, mm	
M	P	M	P	M	P	M	P	M	P
4.18	4.35	2.69	2.54	2.55	4.31	13.54	10.11	8	7.45
3.60	4.11	8.17	8.01	3.14	5.41	2.21	2.01	3	5.16
5.78	4.99	11.31	10.52	2.34	3.92	5.32	6.15	7	6.42
5.08	5.24	3.34	3.10	4.01	5.68	0.14	0.17	6	6.06
4.58	5.94	4.48	3.75	3.65	6.08	24.63	28.61	7	7.30
4.18	5.06	7.66	7.02	3.78	5.48	2.25	2.58	8	5.91
4.32	4.89	6.45	6.44	6.89	9.28	4.31	4.92	7	5.93
4.87	3.38	11.02	11.46	4.52	6.61	13.14	11.46	6	5.95
5.44	4.85	3.64	3.21	8.44	9.98	0.15	.16	5	5.31
3.88	3.76	6.87	6.21	4.85	6.73	15.41	15.64	6	6.64
4.02	4.92	8.99	8.36	1.48	3.5	6.54	6.27	7	6.73
4.87	7.51	4.01	4.56	3.12	5.31	30.41	30.08	6	6.15
2.73	2.61	5.08	6.75	6.51	8.17	44.17	48.73	6	5.37
1.50	2.02	6.57	6.03	0.51	2.68	50.15	54.65	3	6.63
1.56	0.99	3.22	4.25	9.99	12.17	39.71	35.69	6	7.65
3.48	4.35	13.67	13.42	8.64	10.59	22.42	19.99	7	5.11
1.78	1.42	10.51	10.22	3.93	5.88	7.00	7.09	7	6.37
1.30	1.21	11.41	10.68	5.12	7.59	15.24	15.29	5	5.41
1.35	1.76	6.12	5.88	4.61	6.51	0.46	0.56	6	6.79

M: Measured values

P: Predicted values

7. COMPARISON WITH AVAILABLE PUBLISHED MODELS

The developed models of fatigue and rutting, which are considered the most important structural pavement failure, were compared with the available published models as follows and as shown in Figure 1, Figure 2, Figure 3 and Figure 4:

- **Fatigue wet-non-freeze zone:** model developed by Ker et al., 2007 [14] as shown in Table 1 versus the developed model of Equation (1). The comparison is shown in Figure 1.
- **Fatigue dry-non-freeze zone:** model developed by Ker et al., 2007 [14] as shown in Table 1 versus the developed model of Equation (2). The comparison is shown in Figure 2.
- **Rut depth wet-non-freeze zone:** model developed by Naiel, 2010 [6] as shown in Table 1 versus the developed model of Equation (9). The comparison is shown in Figure 3.
- **Rut depth dry-non-freeze zone:** model developed by Naiel, 2010 [6] as shown in Table 1 versus the developed model of Equation (10). The comparison is shown in Figure 4.

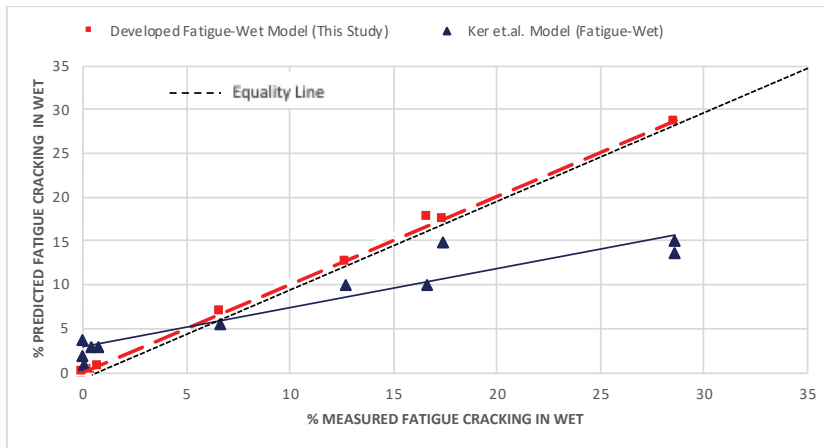


Figure 1 - Measured vs. Predicted Values using Different Fatigue-Wet Models

It can be clearly noticed that the developed models of fatigue and rutting in this study predict better than the available published models. The developed model of fatigue-wet generally overestimated the values; however, the Ker et al. model overestimated in case of %fatigue less than 7% and underestimated when %fatigue is more than 7%. On the other hand, the developed model of fatigue-dry overestimated the values when %fatigue is less than 2% and underestimated over 2%. However, the Ker et al. model overestimated when %fatigue is less than 3.5% and underestimated over 3.5%.

For rut-wet model, the developed model in this study overestimated the rut depth when the depth is less than 11.5 mm and underestimated over this value. However, the model

developed by Naiel overestimated the rut depth when the depth is less than 7.5 mm. On the other hand, the developed model of rut-dry overestimated the rut depth in case of rut depth less than 6.5 mm. However, the model by Naiel generally underestimated the values.

In conclusion, the average % error of fatigue and rutting models developed in this study is 4 times less than the average % error obtained from the available published models.

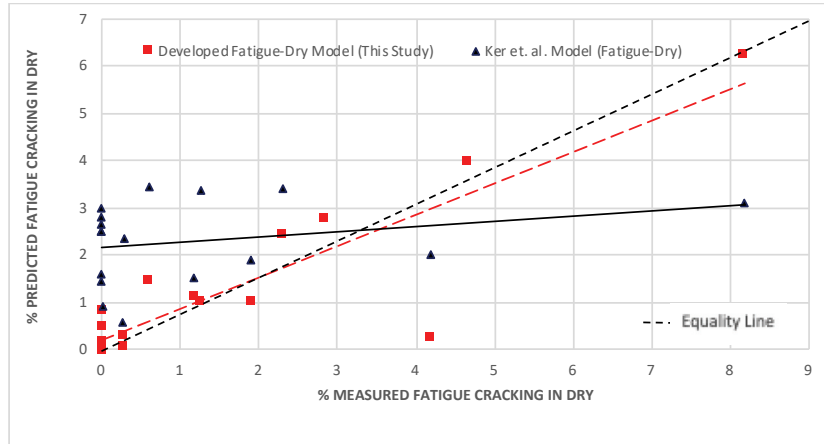


Figure 2 - Measured vs. Predicted Values using Different Fatigue-Dry Models

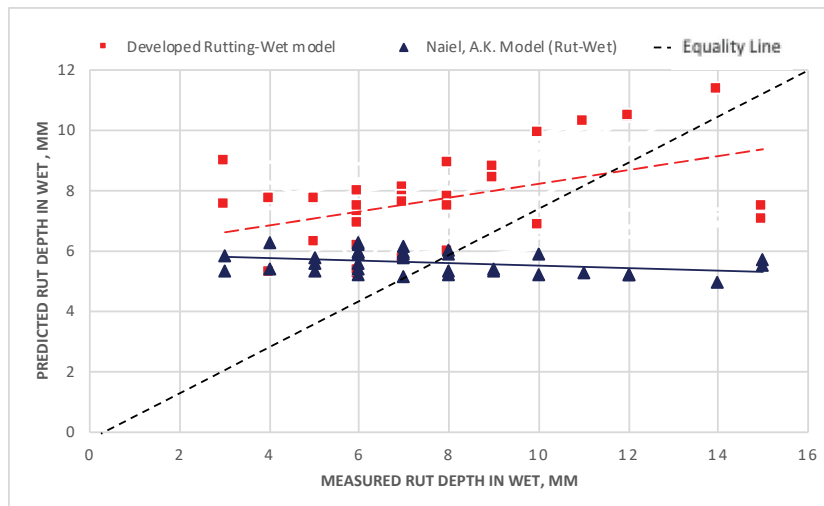


Figure 3 - Measured vs. Predicted Values using Different Rut-Wet Models

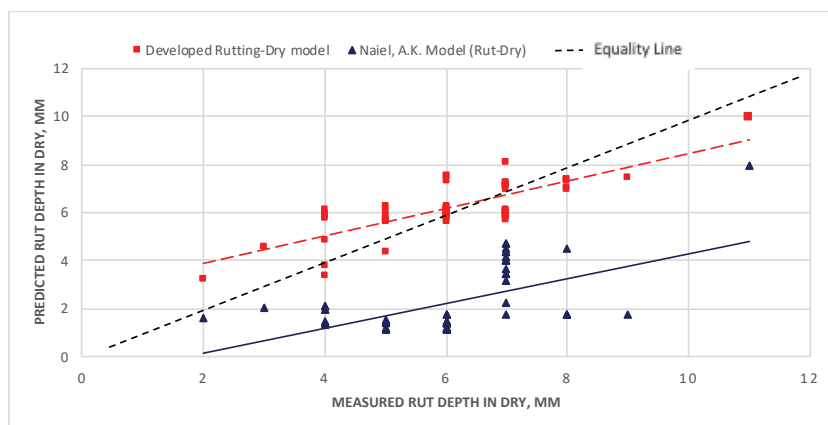


Figure 4 - Measured vs. Predicted Values using Different Rut-Dry Models

8. CONCLUSIONS

The main objective of this study is to develop pavement distress prediction models for main roads located in non-freeze climatic zones, which represent most of the Middle East countries, to be used in pavement management system. Six pavement distress prediction models were developed for fatigue cracking, longitudinal cracking, transverse cracking, raveling distress, bleeding distress and rut depth using data extracted from the Long-Term Pavement Performance (LTPP) program. It was found that pavement age factor is sensitive to most of the developed models while plasticity index and air temperature are very sensitive to fatigue cracking. Additionally, %passing the #200 sieve (0.075 mm) of subgrade soil is sensitive to longitudinal cracking, which indicates that too much fine aggregates in the mix could result longitudinal cracking. On the other hand, %air void of asphalt layer is sensitive to bleeding distress. Validation process was performed using Long-Term Pavement Performance data sets different from the database used in the model development process. The results indicate that the predicted values are fairly close to the measured values at the corresponding LTPP sites. A comparison is also made between the developed models and the available published models for fatigue and rutting models, which are assumed the most important pavement distresses. This study is considered as a crucial attempt to develop such models for the Middle East region due to lack of resources led to unavailability of such models in most of the Middle East countries. However, calibration of the developed models is recommended based on local conditions of a country whenever the pavement performance data is available.

9. FUTURE WORKS AND RECOMMENDATIONS

The results of this study are very important to the Middle East countries experiencing similar climatic conditions. However, calibration of the developed models is recommended based on local conditions, whenever pavement performance data is available. Furthermore, elastic modulus of AC layer shall be considered as possible factor that could affect the developed

models especially for fatigue, longitudinal, and transverse cracking. On the other hand, layer thickness and % voids in mineral aggregate should also be considered as possible factors that could affect rut depth models.

List of Abbreviations

ESAL : Traffic loading represented by Equivalent Single Axle Load

MCb : Moisture content of base/subbase courses

Mr : Resilient modulus of subgrade soil

MCS : Moisture content of subgrade soil

P200 : % Passing the #200 sieve (0.075 mm) of subgrade soil

PA : Pavement age since overlay

Pb : % asphalt content in the mix

PI : Plasticity index of subgrade soil

T : Asphalt pavement thickness

Ta : Air temperature

Va : % Air voids of asphalt mix

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