Development of Pavement Performance Models for Riyadh Street Network

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Pavement performance models are the main element in any Pavement Maintenance Management System (PMMS). The objectives of this paper are to investigate the factors that affect the pavement condition of the Riyadh street network, to develop pavement performance models, and to validate the developed models. The urban distress index (UDI) was used as a measure of pavement condition. The factors included in the models were pavement age, traffic level, availability of drainage system, and maintenance type. A separate model was developed for pavement sections with utility cut patching. All the developed models were found statistically significant in predicting pavement condition at the 95 percent confidence level.

The city of Riyadh has passed through an extremely rapid rate of development during the past two decades. The city area has expanded from a mere 75 km² to more than 1600 km², and the total street length of the city is more than 9000 km (*1*). The Riyadh Municipality, represented by the General Administration of Operation and Maintenance (GAOM), is the agency responsible for maintaining the city street network. The main challenge at this time is to preserve and improve the condition of the existing network. In recognition of the difficulty of maintaining a street network of this length with traditional maintenance practices, Riyadh City is in the final stages of developing a Pavement Maintenance Management System (PMMS) for the city street network.

An essential element of any PMMS is a reliable and accurate prediction of pavement performance. Pavement performance models can be used to determine future maintenance needs and the required maintenance budget and to set maintenance priorities based on the available budget. Pavement performance is a measure of the adequacy of a pavement's structural and functional service over a specified design period. The public assesses pavement performance in subjective ways. As users, they are concerned with ride quality, safety, appearance, and convenience. The highway agency expects pavements to last long enough to justify the cost of their construction.

Most of the highway agencies that incorporate the PMMS have developed performance models using either a theoretical approach or actual pavement data to predict current and future pavement condition. In the cases where actual pavement data were used, the performance models predict pavement rate of deterioration as a function of the factors that affect pavement condition. Many of the existing performance models are simple and include only some illustrative variables. These models generally do not include the effect of type and level of maintenance on pavement performance. The more complex models that include many variables in addition to the maintenance effect were found to be practical but have proved to fit the data poorly. A series of models that can provide a proper balance between realism and proper fit of in-service data is the key for an effective maintenance management system (*2*).

STUDY OBJECTIVE

The specific objectives of this study are as follows:

1. To identify the major factors affecting the condition of Riyadh's pavements,
2. To experiment with various pavement performance model forms and identify the most appropriate for Riyadh's pavement data, and
3. To verify the accuracy of the developed models.

PAVEMENT CONDITION INDICATOR

The Riyadh PMMS developed a combined index of local pavement distresses. The index is called the urban distress index (UDI) and ranges from 0 to 100, where 100 represents excellent pavement condition. The UDI is calculated on the basis of pavement distress type, severity, and density (*3*).

Studies were carried out to determine common types of distresses in the Riyadh street network (*4,5*). It was found that there are 11 types of basic construction distresses and 4 types of distresses, particularly in areas of patching, that form the major cause of street deterioration in the Riyadh street network. The common distresses were then grouped according to type into five groups: cracking, patching and potholes, surface deformation, surface defects, and utility cut patching distresses.

Once the common types of distresses had been identified, three grades of distress, according to severity level, were proposed: low, medium, and high. A local deduct point for each distress severity level combination was established based on local professional judgment. The deduct points range from 0 to 5, where 5 means that the distress severity level combination has the greatest effect on pavement condition. Distress density was represented by dividing the distress representative area by the sample unit area. The value of the UDI is calculated as follows (*3*):

$$UDI = 100 - 20\sum\left(\frac{T_{ij} * D_i}{100}\right) \quad (1)$$

where

UDI = urban distress index,
T_{ij} = deduct points for distress severity combination, and
D_i = distress density.

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DATABASE DEVELOPMENT

In order to achieve the objectives of this research, a database was developed that included information on pavement characteristics, pavement condition, and pavement maintenance. The selected pavement sections were based on the network identification and coding system developed through the Riyadh PMMS project (*5*). The main sources of the collected data were the Riyadh PMMS project, the Ministry of Communications (MOC), and a special survey and inspection of some selected pavement sections.

Pavement characteristics data included information on pavement type, pavement age, traffic level, and availability of a drainage system. Most of the pavements in the city were flexible. Therefore, only flexible pavements were included in the analysis. Pavement age was defined as the number of years since construction or last resurfacing. Traffic data were characterized by two levels: high and low. The average daily traffic (ADT) was used as a measure of the traffic level. Information on the availability of a drainage system was collected for each pavement section.

To enable the collection of appropriate street distress data, a team of inspectors from the General Directorate for Maintenance and Operation, Riyadh Municipality, was given an extensive short course on the newly developed index. Each inspector was then sent to a particular section of the network to record the existing distress types, quantities, and severity for each sample unit within that section. An engineer to ensure work quality regularly supervised the inspector's work. Two pavement condition surveys were conducted: one in 1995 and the other in 1997.

Three types of maintenance strategies were included in the analysis: no maintenance, basic routine maintenance (BRM), and overlay. Maintenance data recorded include section number, maintenance type, code, date, quantity, contractor, and supervisor engineer.

A total of about 3,849 pavement sections were included in the pavement condition analysis, about 90 percent of the total main street pavement sections in the city. However, because of incomplete records, only 1,480 observations were used in pavement condition evaluation and 724 for pavement performance model development.

MODELING APPROACH FORMULATION

The first step in developing pavement performance models was to identify a suitable classification scheme that would yield categories with homogenous pavement sections and adequate data points.

On the basis of the available data, the sectioning scheme adopted was as follows. Pavement sections were first classified into main street pavements and secondary street pavements. This classification accounts for the variation in pavement design and construction standards. However, only main street pavements were included in the analysis because of a lack of information for secondary street pavements. Main street pavement sections were then grouped on the basis of the availability of a drainage system into those with and those without a drainage system. Each group was then divided on the basis of traffic level into pavement sections with high traffic and pavement sections with low traffic. The average ADT value was used as the cutoff point between high and low traffic levels. Pavement sections within each group were again subdivided on the basis of type of maintenance they receive during their service lives: pavement with no maintenance, pavement with BRM, pavement with slurry seal, and pavement with overlay. The layout of the experimental design along with the data included in the model development are presented in Table 1.

SIGNIFICANT FACTORS AFFECTING DETERIORATION

Various factors can affect flexible pavement condition. These factors include pavement age, traffic level, availability of a drainage system, type of maintenance, and existence of utility cut patching. A brief discussion of the effect of these factors is presented in this section.

It is known that pavement age is one of the most important variables that affect pavement condition. Pavement age is measured from the date of construction or from the date of the last resurfacing. Pavement sections were grouped into three categories as follows: young (1 to 5 years), moderate (6 to 10 years), and old (>10 years). The average UDI values of pavement sections within each age group are shown in Figure 1(*a*).

A number of techniques are used to measure traffic volume. ADT was used in this analysis. ADT is the average number of vehicles per lane per day (vplpd). It was classified in two levels, low and high. A low traffic level is less than 3,000 vplpd and a high level is more than or equal to 3,000 vplpd. The average UDI value for low traffic pavement sections was found to be 89 and that for high traffic level sections was 83 [Figure 1(*b*)]. As expected, pavement sections tend to deteriorate more with high traffic level. However, this deterioration rate is relatively low, mainly because most of the vehicles using the city street network are passenger cars.

The availability of a drainage system can affect the condition of pavement. Therefore, pavement sections were grouped into those sections with a drainage system and those sections without a drainage system. It was expected that pavement sections with a

TABLE 1 Experimental Design of Performance Models

Maintenance Type	Number of Main Street Sections			
	With Drainage System [a]		Without Drainage System	
	Low Traffic [b]	High Traffic [c]	Low Traffic	High Traffic
No Maintenance	0	0	65	0
Basic Routine Maintenance [d]	53	118	49	34
Overlay	66	37	289	13

a. Drainage includes surface and sewer system
b. Low traffic level < 3000 vpdpl
c. High traffic level ≥ 3000 vpdpl
d. Basic Routine Maintenance includes potholes repair and/or crack sealing

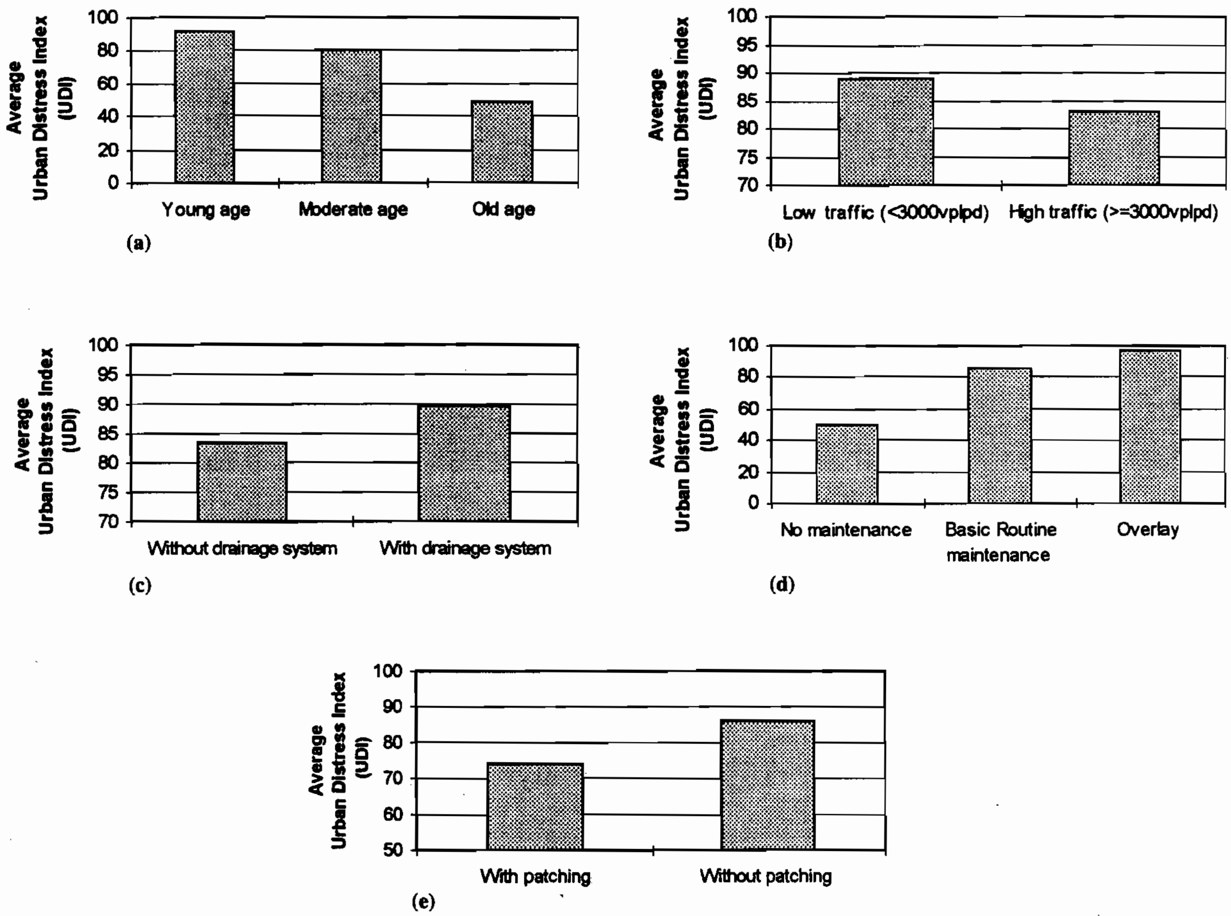

FIGURE 1 Effect on UDI of (*a*) age, (*b*) traffic level, (*c*) drainage, (*d*) maintenance type, and (*e*) patching.

drainage system would be in better condition than those without a drainage system. Figure 1(*c*) shows the average UDI value for pavement sections with and without a drainage system.

Pavement deterioration is highly affected by the type of maintenance received. Therefore, pavement sections were categorized into three groups on the basis of different pavement maintenance types: ηo maintenance, BRM, and overlay. As expected, the condition of .vement sections in the overlay group was excellent (UDI = 97). On the other hand, the condition of the BRM and no-maintenance groups was good (UDI = 86) and fair (UDI = 50), respectively, as shown in Figure 1(*d*).

Utility cut patching is the main cause of fast deterioration of pavement surface and structure in urban areas. A total of 2,804 pavement lanes were included in the evaluation. A comparison of pavement condition between lanes with and without patching was performed. Figure 1(*e*) presents this evaluation: the average UDI for lanes with patching is 75, whereas the UDI is 86 for those without patching.

A statistical hypothesis test for population mean was used to determine the factors that significantly affect pavement condition. The statistical hypothesis is an assumption or statement, which may or may not be true, concerning one or more populations. The hypothesis test was used to investigate the significant effect of pavement age, traffic level, drainage condition, type of maintenance, and existence of utility cut patching on pavement condition. The following equation was used in the statistical test (*6*):

$$t = \frac{\mu_1 - \mu_2 - \mu_l}{\left[(S_1^2/n_1) + (S_2^2/n_2)\right]^{0.5}} \tag{2}$$

where

μ_1 = mean of first population,
μ_2 = mean of second population,
$\mu_l = \mu_1 - \mu_2$,
S_i^2 = estimated standard error of mean,
n = population size.

The null hypothesis H_0 assumed that the means of the UDI value of the independent variable are equal. The alternative hypothesis H_1 assumed that the means are not equal. The confidence level used was 95 percent. The results of the hypothesis test are presented in Table 2. It is clear from the data in Table 2 that all the factors considered have a significant effect on pavement condition.

DEVELOPMENT OF PERFORMANCE MODELS

In light of the different types of modeling techniques, it is clear that mechanistic and mechanistic-empirical models are not relevant for the present Riyadh pavement system because response parameters are not of prime concern and these two types are more complicated compared with the other two types, which are more practical. The

TABLE 2 Results of Hypothesis Test

Factor	t- values		Test Results
	Critical	Computed	
Pavement age:			
Young – Moderate	1.96	4.38	Reject H_0
Moderate – Old	1.96	4.31	Reject H_0
Traffic:			
Low – High	1.96	2.49	Reject H_0
Drainage System:			
With – Without	1.96	7.08	Reject H_0
Maintenance Type:			
No Maint – BRM	1.96	44.08	Reject H_0
BRM – Overlay	1.96	29.22	Reject H_0
Utility Cut Patching:			
With – Without	1.96	9.37	Reject H_0

probabilistic model requires very skilled and expert local pavement engineers who are capable of determining transition probability matrices for the different combinations of pavement condition.

The empirical technique (regression) was found to be very suitable for the situation in Riyadh City. It is practical, simple, and easy to develop provided that adequate data are available. The city does not have a long-term database for individual pavement sections. Therefore, it is necessary to group pavements into homogenous sections that have the same characteristics but different ages. This technique will help in acquiring pavement condition data covering a relatively long period.

In order to find the best model that envelops the data, different forms were tested. The following points describe the basic measures used to choose the best form and to examine the validity of the regression equations:

- The general trend of pavement performance data scatter plot,
- Number of data points (generally, a larger number of data points results in a more valid regression equation),
- Coefficient of determination (R^2), which indicates how much of the variation in the dependent variable is explained by the regression equation, and
- *P*-value for the model and for each independent variable.

After several trials, the following regression model was selected:

$$UDI = a + b \times AGE^n + c \times ADT + d \times DR \quad (3)$$

where

AGE = pavement age (years),
n = 1 or 2,
ADT = dummy variable to represent traffic level (0 = low traffic level, 1 = high traffic level),
DR = dummy variable to represent drainage condition (0 = without drainage, 1 = with drainage), and
a, b, c, d = regression coefficients.

Three maintenance strategies were considered in the analysis. They include no maintenance, BRM (patching and crack sealing), and overlay. Pavement lanes were grouped on the basis of type of maintenance strategy. A separate model was developed for each maintenance strategy. The *P*-values were all zeros, indicating that the developed relationships are significant. The graphical output of these regression models is shown in Figure 2. The statistical outputs of the developed models are presented in Table 3.

BRM is expected to delay deterioration rate of pavement performance. It is clear from Figure 2 that application of BRM alone will prolong the service life of pavement lanes to 19 years. At the end of this period UDI values will be less than 40 and the pavement will be in poor condition and incapable of fulfilling its intended structural and functional purposes. It can also be observed from Figure 2 that BRM will add 3 more years to the functional lifetime of pavements compared with unmaintained pavements.

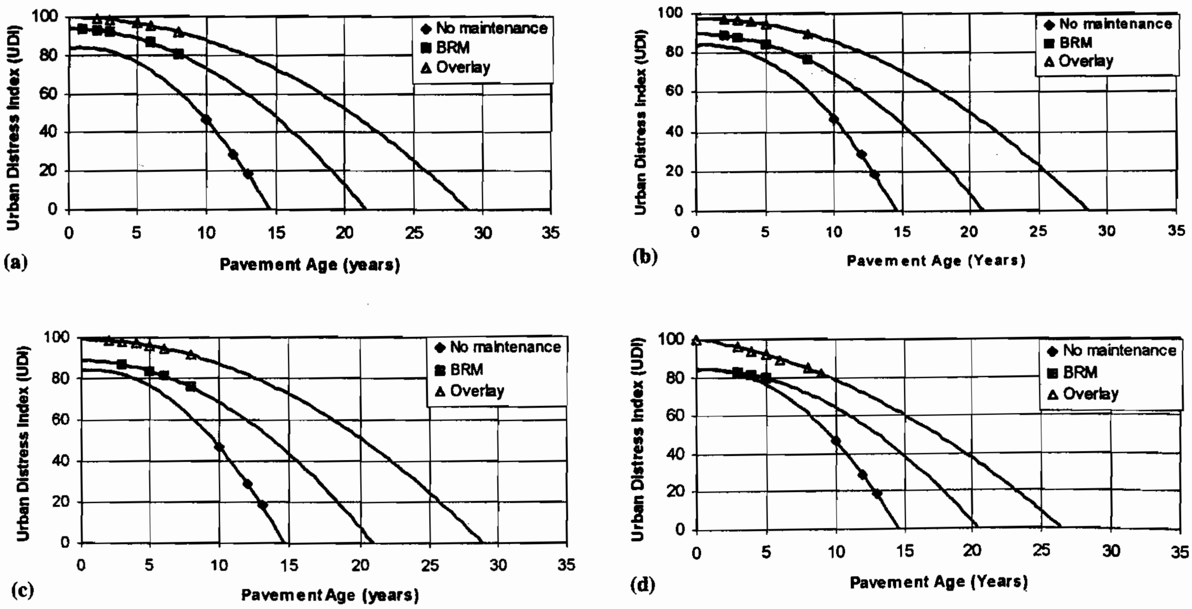

FIGURE 2 Pavement performance curves using UDI: (*a*) Case 1: low traffic, with drainage; (*b*) Case 2: high traffic, with drainage; (*c*) Case 3: low traffic, without drainage; (*d*) Case 4: high traffic, without drainage.

TABLE 3 Estimated Regression Parameters of Performance Models

$UDI = a + b \times AGE^2 + c \times ADT + d \times DR$								
Maintenance	Overall Model Statistics				Estimated Parameters			
Strategy	Number of Observations	R^2 (%)	Adj.R^2 (%)	P-value	a	b	c	d
No Maintenance	110	60.8	60.4	0.000	87.8	-0.410	0	0
Basic Routine Maintenance	460	40.3	39.9	0.000	88.8	-0.203	-4.140	4.981
Overlay	910	35.5	35.3	0.000	99.0	-0.119	-2.250	0.713

Overlay is performed to eliminate existing distresses and restore pavement condition to its original condition. Moreover, this type of maintenance is expected to affect pavement condition significantly and improve the structural support of pavement lanes. Therefore, overlay has the greatest effect on the pavement performance curve compared with other maintenance strategies.

Overlay maintenance activity preserves excellent pavement condition ($90 \leq UDI \leq 100$) for 9 years. Another 16 years will be needed before the pavement reaches poor condition ($UDI < 40$). In total, overlaid pavement lanes will last 23 years before they reach poor condition. Thus it is concluded that overlaid pavements will last 7 years longer than nonmaintained pavements.

It is clear from Table 4 that the effect of traffic level and drainage on pavement lanes with BRM is greater than that on overlaid pavement lanes. With BRM, the coefficient of drainage is greater than that of traffic level because water (in nondrained pavement lanes) can pass through potholes and cracks to the lower layers and cause the pavement to deteriorate rapidly. On the other hand, in the overlay model traffic level has more effect on pavement lanes than drainage. Overlay eliminates existing distresses and prevents water from passing to base and subbase layers.

PERFORMANCE OF PAVEMENT WITH UTILITY CUT PATCHING

As was discussed earlier, lanes with patching were evaluated and compared with those lanes that do not contain patching. Moreover, the statistical test indicated that patching has a significant effect on pavement condition. Therefore, a separate model was developed to study the influence of utility cut patching on pavement performance. The polynomial trend was found to be the most suitable form for utility cut patching lanes. The regression model took the following form:

$$UDI = 85.8 - 0.123 \times AGE^2 - 7.09 \times ADT + 3.33 \times DR \qquad (4)$$

where R^2 = 42.9 percent, R^2(adj.) = 42.6 percent, and P-value = 0.000.

Figure 3 shows the performance curve of the adopted model. The performance of lanes with patching was found to be close to that of unmaintained lanes. On average, pavement lanes reach the terminal UDI value ($UDI < 40$), at which these lanes should be resurfaced, in 19 years. Thus the difference in time between the two performance curves (no maintenance and lanes with patching) was about 1 year.

TABLE 4 Validation of Pavement Performance Models

Maintenance Type	Traffic Level	Drainage Availability	Pavement Age (Year)	Measured UDI	Predicted UDI	Percent Difference
Basic Routine Maintenance (BRM)	Low	Does not exist	1	96	94	2
			5	80	84	-5
			2	86	88	-2
			7	68	79	-16
			7	78	79	-1
			1	81	89	-10
			1	96	89	7
			3	79	87	-10
			5	72	84	-17
		Exists	13	52	59	-13
			6	90	86	4
			8	69	81	-17
	High	Exists	4	72	86	-19
		Does not exist	9	57	68	-19
			1	93	89	4
Overlay	Low	Does not exist	6	100	95	5
			11	72	85	-18
			2	97	99	-2
			2	97	99	-2
			1	100	99	1
			4	100	97	3
			3	100	98	2
			2	100	99	1
			12	74	82	-11
			1	100	99	1
	High	Does not exist	1	97	97	0
			1	97	97	0

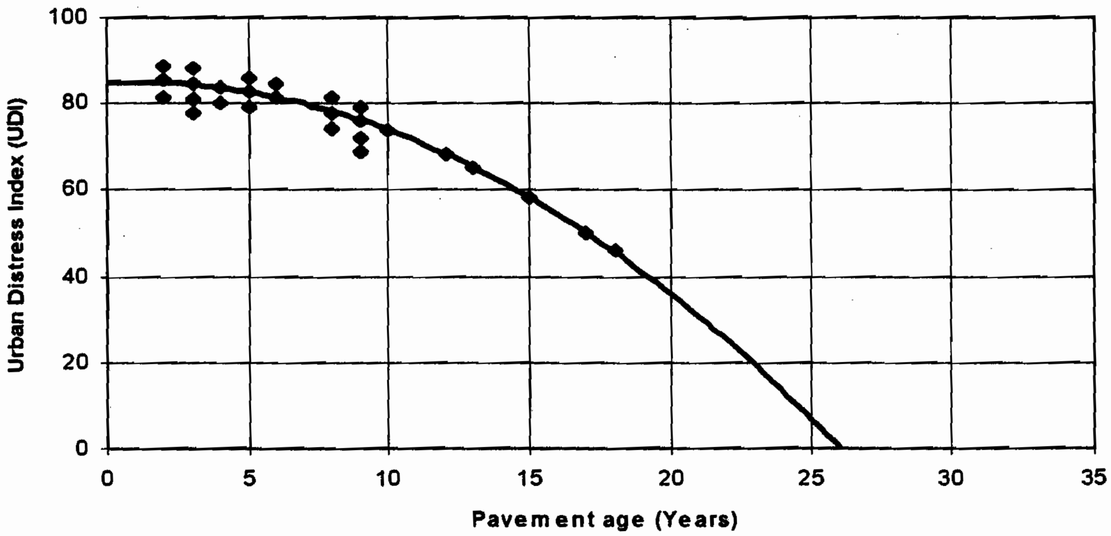

FIGURE 3 Performance of pavement with utility cut patching.

_ .s result shows to what extent utility cut patching affects pavement performance.

The model also showed that traffic, represented by ADT, had more effect on the performance of lanes with patching than did the drainage factor. This result may be attributed to the loss of structural capacity of the pavement because of the utility cut. If a utility cut is constructed today on a lane in excellent condition, the condition of the lane with patching will deteriorate immediately from UDI = 100 to 84 ± 5, depending on the level of traffic and availability of a drainage system. The resurfacing of the utility cut will weaken the pavement and the layers underneath.

VALIDATION OF PAVEMENT PERFORMANCE MODELS

Pavement condition data not included in the model development were used to validate the models. The predicted UDI values were compared with the actual measured values to check the reliability and the level of accuracy of the developed models in explaining the actual data points. Table 4 presents a comparison between the mea- ›d and the predicted UDI values for BRM and overlay, respectıvely. The last column shows the percent difference between the measured and predicted UDI values.

In the validation of the BRM model, 60 percent of the verified lanes have a percent difference less than or equal to 10 percent and 40 percent have a percent difference less than 20 percent. This indicates that the BRM model is acceptable and reliable. Validation of the overlay model showed better results. The percent of lanes that have less than 10 percent difference between the measured and the predicted UDI values was 83. This result indicates that the overlay model has an acceptable degree of reliability. The remaining models were not verified because of lack of data.

SUMMARY AND CONCLUSIONS

In this paper, the analysis involving the development of the pavement performance models was presented. This analysis included preliminary testing of the data validity, factors affecting pavement condition, model development, and model validation. The following conclusions can be drawn:

- All independent variables (pavement age, drainage, traffic level, and maintenance type) are significant factors in the prediction of the pavement performance measure.
- Three pavement performance models were developed, for pavement with no maintenance, pavement with BRM, and pavement with overlay. In addition, a separate model was developed for pavement lanes with utility cut patching. The developed models used the UDI as a measure of pavement performance. All developed models were found to be statistically significant in predicting pavement condition.
- Validation of the developed models showed a reasonable difference between the predicted and measured UDI values. Taking into account the time and cost that may be spent in acquiring pavement condition data, these models are considered acceptable.

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REFERENCES

1. Al-Swailmi, S., et al. *Development of Pavement Maintenance Management System for Riyadh Street Network.* Progress Report 1. King Abdulaziz City for Science and Technology, Riyadh, 1996.
2. Sebaaly, P. E., S. Lani, and A. Hand. Performance Models for Flexible Pavement Maintenance Treatments. In *Transportation Research Record 1508,* TRB, National Research Council, Washington, D.C., 1995, pp. 9–21.
3. *Pavement Condition Evaluation Manual.* Riyadh Pavement Maintenance Management System, Riyadh Municipality, 1997.
4. Al-Mansour, A. Evaluation of Pavement Condition and Identification of Common Types of Distress on Riyadh Street Network. Presented at Maintenance of Buildings, Public Structures and Preventive Measures Symposium, Umm al-Qura University, 1996.
5. Al-Swailmi, S., et al. *Development of Pavement Maintenance Management System for Riyadh Street Network.* Progress Report 2. King Abdulaziz City for Science and Technology, Riyadh, 1996.
6. Walpole, R. E., and R. H. Myers. *Probability and Statistics for Engineers and Scientists.* 5th ed., 1993.

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