Examination of Pure Environmental Effects on Pavement Condition

TURKI I. AL-SULEIMAN, ADNAN A. BASMA, AND KHALED KSAIBATI

A study was undertaken to examine pure environmental effects on the condition of pavements. The road network within the campus of Jordan University of Science and Technology was utilized. More than half of this road network was untrafficked because of delays in several construction projects to which these roads lead. The condition of 71 primary and secondary pavement sections was evaluated periodically for 7 years. A methodology was proposed to investigate the pure environmental effects, pure traffic effects, and their interaction on pavement deterioration. The first order-second moment Taylor series expansion was used to estimate the variations in pavement service life under each of these effects. The results of the analysis showed that most of the pavement deterioration in lightly trafficked roads was caused by environmental factors. Heavily trafficked roads showed the widest range of pavement service life expectancy. To further improve the obtained results, continuous pavement monitoring is needed.

Pavement deterioration usually is caused by a combination of factors such as traffic load, environment, initial design, and quality of construction. Therefore, pavement deterioration may result from traffic-induced distress, environmentally associated distress, and the interaction of these two. For example, rutting and alligator cracking are regarded as traffic-induced distresses, whereas longitudinal and transverse cracking are viewed as environmental or non-load-related distresses (*1*). The relationship between traffic loading and pavement performance was developed through the AASHO Road Test in the early 1960s. This relationship is summarized in the *AASHTO Interim Guide for the Design of Pavement Structures* (*2*).

The pure effects of environmental factors such as moisture, soil conditions, and temperature on pavement deterioration were not investigated in the AASHO Road Test because it was conducted over a short period (2 years). The determination of respective proportions of traffic and environmental responsibilities is an old problem in highway pavement evaluation and cost allocation studies. There is not enough information to separate traffic-related effects from environmentally related effects during physical measurements of pavement condition. As a result, the responsibilities of these two effects have been determined subjectively in most cost allocation studies, and thus there has not been an acceptable solution to this problem. Indeed, researchers (*3,4*) have attempted to collect data on pavement performance to quantify relationships and propose mathematical models. Although the findings of these studies shed some light on the relative effect of pure environment on pavement performance, the number of pavement sections used to arrive at the results was limited. Consequently, there seems to be a need to improve and refine existing procedures dealing with this problem.

The basic objective of this study is to investigate and evaluate purely environmental effects on pavement performance. To accomplish this goal, the road network within the campus of Jordan University of Science and Technology (JUST) was utilized. Among the pavements examined, more than half were untrafficked because of delays in several major construction projects to which these roads lead. The untrafficked pavements were compared with similar trafficked pavements. A total of 71 sections of primary and secondary trafficked and untrafficked roads were considered. A complete description of the site and the road network follow.

T. I. Al-Suleiman and A. A. Basma, Department of Civil Engineering, University of Science and Technology, Irbid, Jordan. K. Ksaibati, Department of Civil Engineering, University of Wyoming, Laramie, Wyo. 82071.

SITE DESCRIPTION

JUST lies in the northern part of Jordan about 20 km east of the city of Irbid. The campus occupies approximately 13 km^2. Work on the road network started in September 1981 and was completed in April 1984 with an estimated cost of 11,870,000 Jordanian dinars (about $34,000,000 U.S.). Approximately 60 percent of this cost was for paving the roads and 40 percent was for the infrastructure services such as sewer systems, water treatment plant, and electricity. The overall length of the road network is about 30 km. Of this, 20 km is primary roads, and 11.5 km is secondary roads, with the rest being service roads used for various purposes.

The special conditions and financial difficulties that Jordan was experiencing caused delays in and postponement of many vital construction projects within the campus. Because of these difficulties, several parts of the road network were not being used, with the result that maintenance was limited to trafficked roads only. Untrafficked roads (exceeding half the total length of the road network), on the other hand, were neglected and not maintained, which caused serious damage to the pavements. These conditions provided an excellent opportunity to fulfill the objectives of this study.

ROAD NETWORK CHARACTERISTICS

Most of the information about the road network at JUST was obtained from the Department of Maintenance and Operation and the Department of Engineering Projects. The compiled information included the master plan of the road network and the materials used in the construction of the pavement layers.

The average annual rainfall and temperature variation data were also collected.

Pavement Characteristics

The road network at JUST can be divided into three types: primary or main roads, secondary roads, and cycle paths. Figure 1 shows the thickness and materials used in the first two types. As indicated, primary and secondary roads are basically similar, with the exception of the additional 5 cm thickness in the subbase in primary pavements.

Daily Traffic Volume

The traffic volume was obtained by using traffic counters on the main ring road between 7:00 a.m. and 8:00 a.m. (peak hours). The traffic volume was found to range between 30 and 210 vehicles per hour, with most of the vehicles being small passenger cars. This volume was assumed to be half the daily volume because the traffic is not continuous. The reason behind this was that only university employees were allowed to enter the campus by automobile. Consequently, the daily traffic volume was found to range between 60 and 420 vehicles. On the basis of this information, the trafficked roads can be considered low volume. Accordingly, most of the existing damage to the pavement of the trafficked roads cannot be considered purely traffic related.

Rainfall

Figure 2 shows the average rainfall between 1984 and 1990, with a minimum of 124 mm in 1985 and a maximum of 376 mm in 1988. This range is relatively high when compared with those in other parts of the world. Most of the damage to the pavement (mostly in the form of potholes and cracks) became apparent after 1988 when the rainfall was at its maximum.

Temperature Variation

Figure 3 presents the maximum and minimum monthly ambient temperatures for 1983. It is unfortunate that complete temperature data for other years were not available. From Figure 3 it can be seen that the minimum recorded temperature was 1°C (January) and the maximum was 34°C (July), whereas the maximum monthly temperature variation was 20°C (May). These temperature variations, along with the variation in the amount of rainfall, are believed to be the major causes of pavement distress.

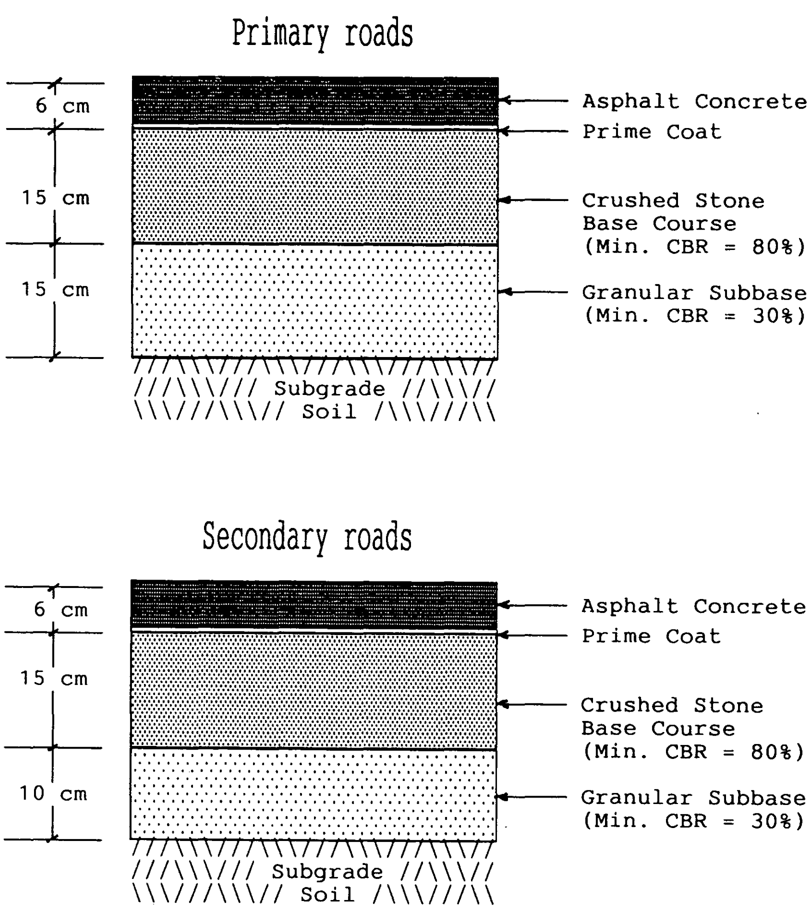

FIGURE 1 Pavement layer thicknesses and materials used in primary and secondary roads.

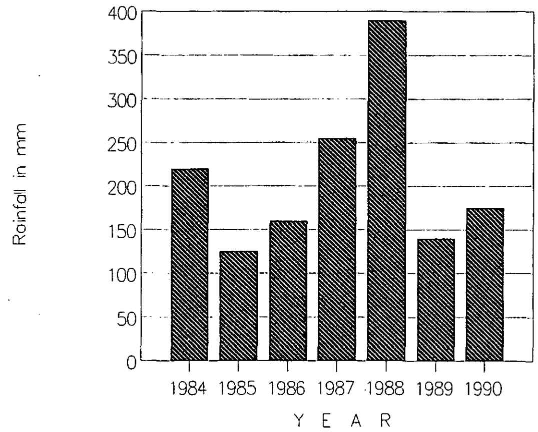

FIGURE 2 Annual rainfall during the period 1984–1990.

SOIL PROPERTIES

The objective of this part of the work was to provide a complete laboratory study of the subgrade soil. The intention of such a study is to provide insight into whether the soil was indeed a contributing factor to the pavement damage. To accomplish this task, soil specimens from two untrafficked pavement sections (about 200 m apart) were extracted and tested. The first section showed severe cracking, whereas the other section showed none. A thorough laboratory investigation was conducted on the soil samples, and the experimental data were compared. The experimental tests consisted of

- Field water content and field unit weight,
- Grain size distribution,
- Consistency limits determination,
- Compaction tests,
- Swell measurements, and
- Collapse measurements.

Table 1 summarizes the experimental results obtained on the soils beneath both the cracked and the uncracked pavement sections. From these results the following observations were made (see Table 1):

1. Both soils contain low percentages of clay and in general a relatively high percentage of sand.
2. Both soils are low in plasticity; however, the soil under the cracked pavement has a higher activity.
3. The relative compaction of the soil under the cracked pavement was well below the required standards for pavement construction. The usual minimum required degree of compaction is 90 to 95 percent.
4. Both soils have a low potential for expansion.
5. The soil beneath the cracked pavement shows a higher tendency to collapse.

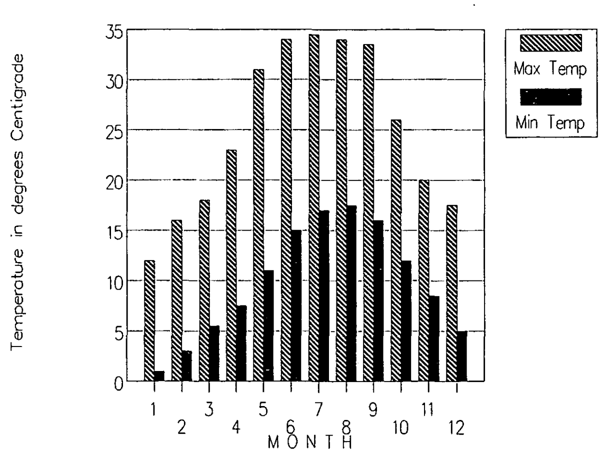

FIGURE 3 Minimum and maximum temperatures during 1983.

PAVEMENT CONDITION EVALUATION

To determine the pavement condition it was necessary to use a rating technique that is not costly and does not require much instrumentation. For this reason the PAVER method, developed by the U.S. Army Corps of Engineers (5), was adopted. The condition rating used in this method is the pavement condition index (PCI). It is an objective numerical indicator ranging from 0 (failed pavement) to 100 (excellent pavement) on the basis of the measured quantity and severity of each type of distress present in the pavement.

Evaluation Results

The evaluation of the road network entailed both trafficked and untrafficked primary and secondary roads. The entire road network was divided into 18 branches. The branches were further divided into a total of 71 sections, with each section divided into sample units. This resulted in a total of 487 sample units.

The pavement evaluation results revealed that 69 percent of the sections were in excellent condition, 26 percent in very good condition, 4 percent in good condition, and 1 percent in fair condition. In general, therefore, the pavement network at JUST would seem to require only routine maintenance.

Types of Pavement Distresses

The pavement survey showed a wide variation in the density and severity of distresses. The distresses encountered were

- Longitudinal and transverse cracks,
- Alligator cracks,
- Rutting,
- Depressions,
- Potholes,
- Weathering and raveling,
- Polished aggregate,
- Bleeding, and
- Patching.

Figure 4 shows the extent of damage to some of the untrafficked pavement sections. It is important to note that the

TABLE 1 Summary of Subgrade Soil Properties

Property	Cracked Pavement	Uncracked Pavement
Date of sampling	July 8, 1991	July 8, 1991
Depth of sampling, m	0.55	0.60
Field water content, %	5.10	4.90
Field unit weight, kN/m^3	17.17	16.93
Grain size distribution		
Percent Sand (S)	56.0	40.0
Percent Silt (M)	32.0	44.0
Percent Clay (C)	12.0	16.0
Percent Fines (F=M+C)	44.0	60.0
Consistency Limits		
Liquid limit, (LL) %	36.0	36.8
Plastic limit, (PL) %	20.5	25.6
Plasticity index, (PI) %	15.5	11.2
Activity, A = PI/C	1.29	0.70
Compaction		
Optimum water content, %	12.0	16.0
Max. dry unit weight, kN/m^3	19.6	17.3
Relative compaction, %	83.2	93.1
Expansion		
Swell potential*, (SP) %	0.41	1.23
Swell pressure*+, (p_s) kPa	47.0	56.0
Percent Collapse*# under an applied pressure of		
50 kPa	2.36	1.60
100 kPa	3.40	1.86
200 kPa	5.45	4.61
400 kPa	10.36	8.05
800 kPa	12.47	11.40
1600 kPa	14.43	13.60
Unified soil classification	Sandy-silt (SM)	Low plastic silt (ML)

* Specimen tested at field water content and unit weight
+ Values obtained by zero swell test
# Values obtained by single odometer collapse test

distresses in most of the untrafficked pavement sections were in the form of longitudinal and transverse cracks. Some of these cracks were 10 m long, 5 cm wide on the surface, and deep enough to reach the subgrade soil (see Figure 4, *top*).

PREDICTING PAVEMENT CONDITION

Predicting pavement condition aids not only in assessing the pavement service life but also in estimating the cost and the most effective maintenance strategy. It is well recognized that pavement performance is affected by several factors, such as traffic loads, environment, age, initial design, and construction materials. Generally speaking, however, pavement performance is a result of the combined effects of pavement characteristics and the imposed conditions. Hudson and Flanagan (*4*) attempted to estimate separately the relative effects of pure traffic and pure environment and their interaction on pavement performance. However, their study included only 14 pairs of sections (trafficked and untrafficked). They stated that, to solve this problem, one must have access to unused (untrafficked) pavements and "the results will be 5 to 10 years, or longer, in coming." Clearly, the existence of such pavements is very rare. That more than half of the road network at JUST was untrafficked provided an opportunity for such a study.

Description of Methodology

The methodology followed was based on the assumption that pavement distresses after *n* number of years are a result of three factors:

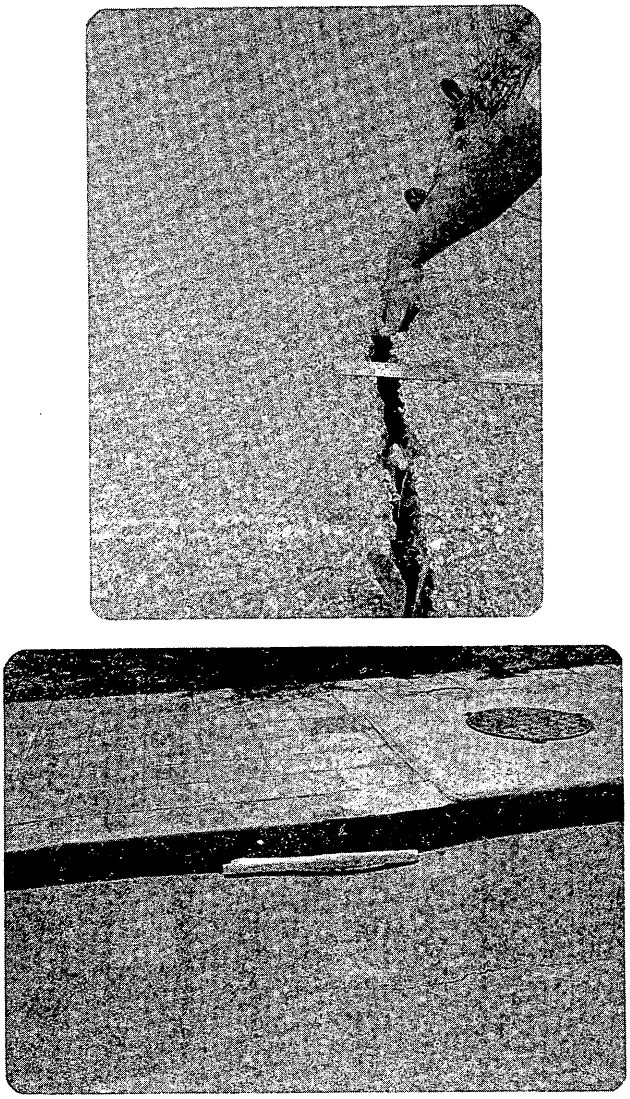

FIGURE 4 **Pavement distresses in untrafficked roads: *top*, longitudinal cracking; *bottom*, cracking associated with depression.**

1. Environmentally related effects,
2. Traffic-related effects, and
3. Interaction between traffic and environment.

Consequently, pavement deterioration or the change in pavement condition index (ΔPCI) after n years can be mathematically expressed as

$$\Delta PCI = \Delta PCI_e + \Delta PCI_{te} + \Delta PCI_t \qquad (1)$$

where

ΔPCI = total loss in PCI,
ΔPCI_e = loss in PCI due to environment,
ΔPCI_t = loss in PCI due to traffic, and
ΔPCI_{te} = loss in PCI due to the interaction between traffic and environment.

Figure 5 shows a schematic representation of Equation 1. Figure 6 presents the general relationship between pavement age and the loss in PCI under the aforeméntioned effects. An earlier study (*6*) indicated that such a relationship can be mathematically expressed as

$$PCI = 100 - a\,(\text{age})^b \qquad (2)$$

or

$$\Delta PCI = 100 - PCI = a\,(\text{age})^b \qquad (3)$$

where PCI is the pavement condition index (0 to 100), ΔPCI is the loss in PCI after age of n years, a is the slope coefficient, and b is the parameter controlling the degree of curvature of performance curve. The values of a and b vary depending on the affecting factors, as indicated in Figure 6.

Application of Methodology

To study the effect of pavement initial design on its performance level, the above-mentioned approach was applied to both primary and secondary roads. Furthermore, to investi-

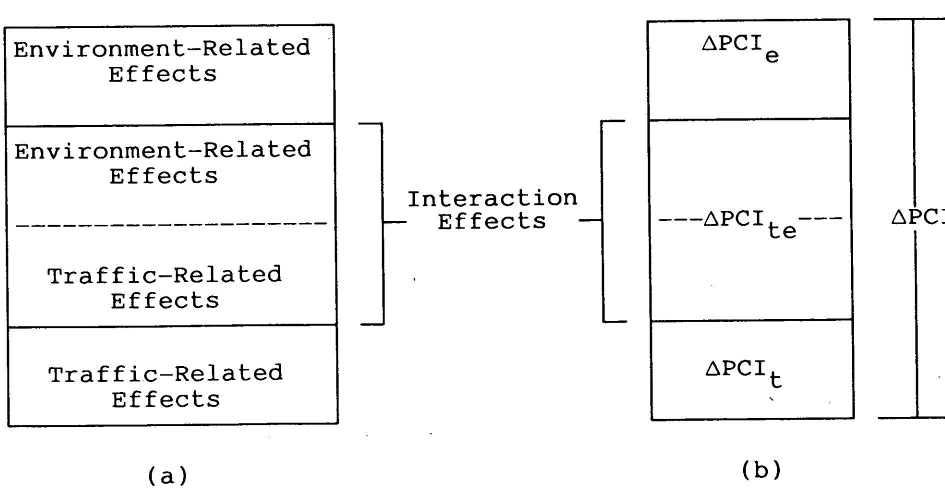

FIGURE 5 Schematic diagram: (*a*) traffic-related and environmentally related effects; (*b*) corresponding pavement deterioration.

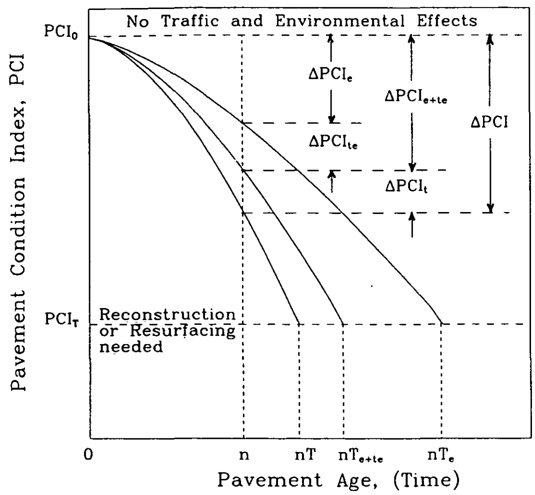

FIGURE 6 Schematic diagram showing pavement conditions over time under traffic-related and environmentally related effects.

gate the effects of traffic and environment and the interaction between them, the road network was divided into five groups on the basis of their service status:

1. Untrafficked primary,
2. Lightly trafficked primary,
3. Untrafficked secondary,
4. Lightly trafficked secondary, and
5. Heavily trafficked secondary.

Table 2 presents the average and standard deviation of PCI (7 years after construction) for each road group. These results show that, for primary untrafficked and lightly trafficked pavement sections, the average loss in PCI was 7.36 and 8.38, respectively. This loss indicates that most of the deterioration in primary roads was caused by environmental factors. Secondary pavements, on the other hand, show similar results for untrafficked and lightly trafficked pavements. However, in these sections, most of the damage was caused by heavy traffic, resulting in a loss of 13.05 in PCI compared with a loss of 9.65 in PCI caused by the environment. In both cases, though, environmental effects on the condition of the pavement were substantial. To determine the values of *a* and *b* in Equation 2 (or Equation 3) the road groups in Table 2 were monitored periodically for 7 years (1984–1990). The average loss in PCI (ΔPCI) versus age (in years) for the five road groups can be seen in Figure 7. These data are used to estimate the values of *a* and *b* (Table 3); the general form of the equation is that of Equation 3. These values can be used to predict the service life of the pavement, that is, when PCI reaches its terminal value. Columns 3 and 4 of Table 4 show the expected number of years required for PCI to reach 70 and 40, respectively. Between these two values, the pavement might require an overlay or reconstruction. However, because the plots in Figure 7 are for the average values of PCI, the predicted numbers of years to terminal PCI in Table 4 are

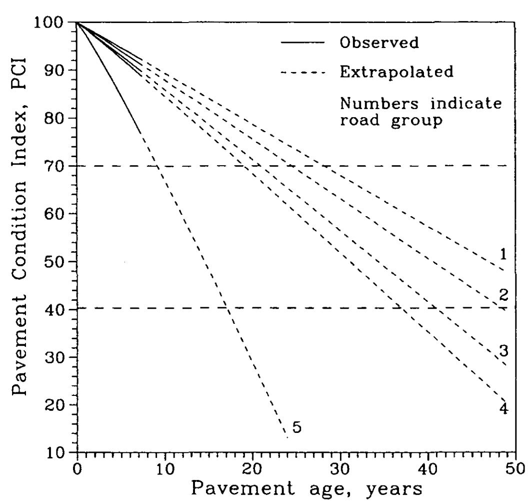

FIGURE 7 Expected pavement service life for each road group.

TABLE 2 Averages and Standard Deviations of PCI for Each Road Group

Road Class	Service Status	Pavement Deterioration	PCI 7 years after construction: Average	PCI 7 years after construction: Standard Deviation
Primary	Non-Trafficked	ΔPCI_e	92.64	7.45
	Light-Trafficked	$\Delta PCI_e + \Delta PCI_{te}$	91.62	5.00
Secondary	Non-Trafficked	ΔPCI_e	90.35	1.63
	Light-Trafficked	$\Delta PCI_e + \Delta PCI_{te}$	89.43	4.48
	Heavy-Trafficked	$\Delta PCI_e + \Delta PCI_{te} + \Delta PCI_t$	77.30	11.8

TABLE 3 Values of *a* and *b* for Monitored Road Groups

Road Class	Service Status	Road Group	a	b
Primary	Non-Trafficked	1	1.043	1.0054
	Light-Trafficked	2	1.160	1.016
Secondary	Non-Trafficked	3	1.305	1.029
	Light-Trafficked	4	1.405	1.037
	Heavy-Trafficked	5	2.602	1.104

averages. In other words, the average (or expected) number of years to terminal PCI (70) for primary untrafficked roads is 28.3 years. Clearly, this value is not constant and will vary from section to section because PCI of the surveyed sections is a variable (see Table 2). Consequently, the interest here is the predicted range of the pavement service life. This matter is treated in the following section.

VARIATION IN PAVEMENT SERVICE LIFE

Because PCI values vary, the age to reach terminal PCI will vary. To evaluate this variation the first order-second moment Taylor series expansion was used. An explanation of this technique follows.

Consider the following relationship:

$$y = g(x) \quad (4)$$

Expanding this function in a Taylor series about the mean and truncating at the linear term yields

$$\mathrm{Var}[y] = (dy/dx)^2 \,\mathrm{Var}[x] \quad (5)$$

or

$$\mathrm{SD}[y] = (dy/dx)\,\mathrm{SD}[x] \quad (6)$$

where Var[.] and SD[.] are, respectively, the variance and standard deviations, whereas (dy/dx) is the derivative of y with respect to x evaluated at the mean of x.

Rewriting Equation 3 to become Age = $g(\Delta PCI)$ and applying Equation 6 gives

$$\mathrm{SD}[\mathrm{age}] = \mathrm{SD}[\Delta PCI]\left(\frac{1}{ba}\right)\left[\frac{E(\Delta PCI)}{a}\right]^{[(1/b)-1]} \quad (7)$$

where $E[.]$ is the expected value. The range of the pavement service life can be evaluated as an interval estimate using the following equation:

$$E[\mathrm{age}] = \overline{\mathrm{age}} \pm D \quad (8)$$

where

$E[\mathrm{age}]$ = expected age

$\overline{\mathrm{age}}$ = average age (from Equation 3),

D = $t_{1-\alpha/2,d}(\mathrm{SD}[\mathrm{age}]/N)$,

t = t − value,

α = significance level,

N = number of pavement sections, and

d = degrees of freedom or $N - 1$.

TABLE 4 Pavement Age to Terminal PCI for Each Road Group

Road Class	Service Status	Pavement Age (years)	
		$PCI_T = 70$	$PCI_T = 40$
Primary	Non-Trafficked	$nT_e = 28.3$	56.5
	Light-Trafficked	$nT_{e+te} = 24.6$	48.6
Secondary	Non-Trafficked	$nT_e = 21.0$	41.3
	Light-Trafficked	$nT_{e+te} = 19.1$	37.4
	Heavy-Trafficked	$nT = 9.2$	17.2

TABLE 5 Values of D in Equation 8 for Monitored Roads at Various Significance α-Levels

Road Class	Service Status	Average age, years		Sign. α	D years
		PCI=70	PCI=40		
Primary	Non-Trafficked	28.3	56.5	0.1	13.4
				0.05	16.7
	Light-Trafficked	24.6	48.6	0.1	7.0
				0.05	8.4
Secondary	Non-Trafficked	21.0	41.3	0.1	7.2
				0.05	14.6
	Light-Trafficked	19.1	37.4	0.1	5.0
				0.05	6.3
	Heavy-Trafficked	9.2	17.2	0.1	20.7
				0.05	25.1

The results for Equation 8 are given in Table 5, which shows that lightly trafficked secondary roads have the narrowest range of life expectancy. At $\alpha = 0.1$ and by Equation 8, the time for PCI to reach 40 is between 32.4 and 42.4 years (37.4 ± 5.0). In other words, 90 percent $(1 - \alpha)$ of pavements in this group of roads might require overlay or reconstruction between 32.4 and 42.4 years. In untrafficked pavements in the same road class and with the same α-value, the PCI will drop to 40 between 34.1 and 48.5 years. The widest range is observed in heavily trafficked secondary pavements. This result is not surprising because secondary pavements are 5 cm thinner in the subbase than are primary pavements. Consequently, heavy loading will cause a wider variation in PCI (see Table 2), resulting in a wider range of expected life.

SUMMARY AND CONCLUSIONS

The basic objective of this study was to investigate purely environmental effects on pavement condition. The road network at JUST was utilized. Of this road network, more than half of the roads were untrafficked because of construction delays in structures to which these roads lead. A total of 71 primary and secondary pavement sections were considered. These sections were divided into five groups, depending on their class and service status. The sections were surveyed periodically for 7 years to determine the pavement condition index on the basis of this monitoring period, the results of this study warrant the following main conclusions.

1. Most of the deterioration in primary and secondary roads was caused by environmental factors, especially for lightly trafficked pavements.
2. The effect of traffic loading on pavement performance becomes more evident in heavily trafficked roads.
3. Heavily trafficked secondary roads showed the widest range of life expectancy. The narrowest range was observed in secondary lightly trafficked pavements.

It is important to note that this is a continuing study. Most of the untrafficked roads within the JUST campus are expected to remain so for at least the next 10 years. All the sections included in this study will be continuously monitored to further improve the data.

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Publication of this paper sponsored by Committee on Flexible Pavement Design.