Field-Observed Pavement Performance Relations for Low-Volume Roads

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Pavement performance and behavior have been monitored for up to five years on roads in central Brazil. Surveys of surface condition were made at 4- to 6-month intervals to obtain rutting, cracking, and patching data. At periodic intervals road roughness and deflection measurements were obtained by using Mays meters and the Benkelman beam and Dynaflect, respectively. Test pits were dug to measure in situ density, California bearing ratio (CBR), and moisture. Laboratory testing produced material gradings, Atterberg limits, laboratory CBR, and density of the road materials. This information, together with data on traffic volume and weight, is analyzed to produce equations that predict pavement roughness, patching, and cracking. Rutting was found to be slight in the study area and probably will not trigger maintenance. The influence of slurry sealing on cracking progression is also investigated. A model for the initiation of cracking after slurry sealing reflects the experience that the slurry seal is ineffective in sealing pavements.

Pavement surface condition, as measured by its roughness, is a major factor of influence in road user costs. Thus, prediction of pavement roughness is important from alternative construction and maintenance standards so that user costs can be evaluated for each alternative. Maintenance is performed primarily as a response to excessive pavement roughness, cracking, and rutting. The latter is related to roughness and has been assigned limiting levels by highway agencies because of the safety hazard it represents to vehicles, especially under wet conditions. Pavement cracking is a risk to the capital invested and, if high levels of cracking are allowed to develop, pavement reconstruction may be required in lieu of routine maintenance. Therefore, the amount, and consequently the cost, of timely maintenance will depend on the potential evolution of pavement roughness, cracking, and rutting. On the other hand, this potential evolution of pavement attributes depends on the pavement structure that, in turn, is related to construction costs. Therefore, pavement performance prediction models are an essential technological tool for economic analysis of highways.

This paper describes an analysis conducted to develop deterioration prediction models for paved roads. The dependent variables in the analysis are roughness, cracking, and rutting. Preliminary results of this study were presented at the Second International Conference on Low-Volume Roads (1).

ROUGHNESS PREDICTION MODELS

Roughness was expected to be a function of pavement structural variables, traffic loads and volumes, and environment. The pavement test sections in this study were located in a relatively narrow geographic area in the central plateau of Brazil (2). The environmental parameters--rainfall and temperature--varied very little, and consequently these factors were not considered in the analysis. However, the implicit influence of the environment over time was considered because the pavement age was included and found to affect roughness significantly. Details of the pavement test sections used are given by Visser and Queiroz (3).

Traffic loads and volumes were combined to give the number of cumulative equivalent 80-kN axles. Seven groups of variables that describe pavement strength were included in the analysis. These variables are as follows:

1. Pavement structural variables, which consist of the structural number, structural number corrected for the subgrade resistance, and subgrade, subbase, and base California bearing ratio (CBR);
2. Benkelman beam deflection;
3. Dynaflect deflection and curvature indexes;
4. Combination of 1 and 2;
5. Combination of 1 and 3;
6. Combination of 2 and 3; and
7. Combination of 1-3.

The symbols used in this analysis are defined in Table 1.

The roughness prediction models that best fit the data are presented next, according to the group of independent variables used.

Equation Including Structural Number

$$LQI = 1.487 - 0.1383\ RH + 0.007\,95\ AGE + 0.0224\ (LN/SNC)^2 \quad (1)$$

$R^2 = 0.26$
Standard error for residuals = 0.13

where

LQI = logarithm to the base 10 of quarter-car index (i.e., $\log_{10}QI^*$),
RH = state of rehabilitation indicator = 0 as constructed and 1 if overlayed,
AGE = number of years since construction or overlay,
LN = logarithm to the base 10 of the number of cumulative equivalent axles, and
SNC = structural number corrected for the subgrade strength.

The ridge trace in Figure 1 shows the high stability of the regression coefficients in Equation 1 (4). Included in this figure is the coefficient for ST, a surface-type indicator variable, that was subsequently deleted. This coefficient value is very close to zero, as can be observed in Figure 1, and is not significant even at the 25 percent level, as demonstrated by its F-value.

Equation Including Benkelman Beam Deflection

$$QI^* = 21.8 - 7.52\ RH + 5.16\ ST + 0.515\ AGE + 7.22 \times 10^{-5}\ (B \times LN)^2 \quad (2)$$

$R^2 = 0.48$
Standard error for residuals = 10.58

where

QI* = quarter-car index (counts/km),
ST = surface type dummy variable = 0 for asphaltic concrete and 1 for surface treatment, and
B = Benkelman beam deflection (0.01 mm).

All regression coefficients are very stable.

Equation Including Dynaflect Deflection

$$LQI = 1.391 - 0.1315\ RH + 0.0414\ P + 0.007\,51\ AGE + 0.0248\ D \times LN \quad (3)$$

$R^2 = 0.32$
Standard error for residuals = 0.13

where

LQI = logarithm to the base 10 of quarter-car index,
P = percentage of area that received repairs in the form of deep patches, and
D = Dynaflect maximum deflection (0.001 in).

All regression coefficients are very stable.

Equation Including Structural Number and Benkelman Beam Deflection

$$QI^* = 12.63 - 5.16\,RH + 3.31\,ST + 0.393\,AGE - 8.66\,(LN/SNC) + 7.17 \times 10^{-5}\,(B \times LN)^2 \quad (4)$$

$R^2 = 0.52$
Standard error for residuals = 10.22

where

RH = state of rehabilitation indicator = 0 as constructed and 1 if overlayed,
ST = surface type indicator = 0 for asphaltic concrete and 1 for surface treatment,
AGE = number of years since construction or overlay,
LN = logarithm to the base 10 of the number of cumulative equivalent axles,
SNC = corrected structural number, and
B = Benkelman beam deflection (0.01 mm).

Equation Including Structural Number and Dynaflect Deflection

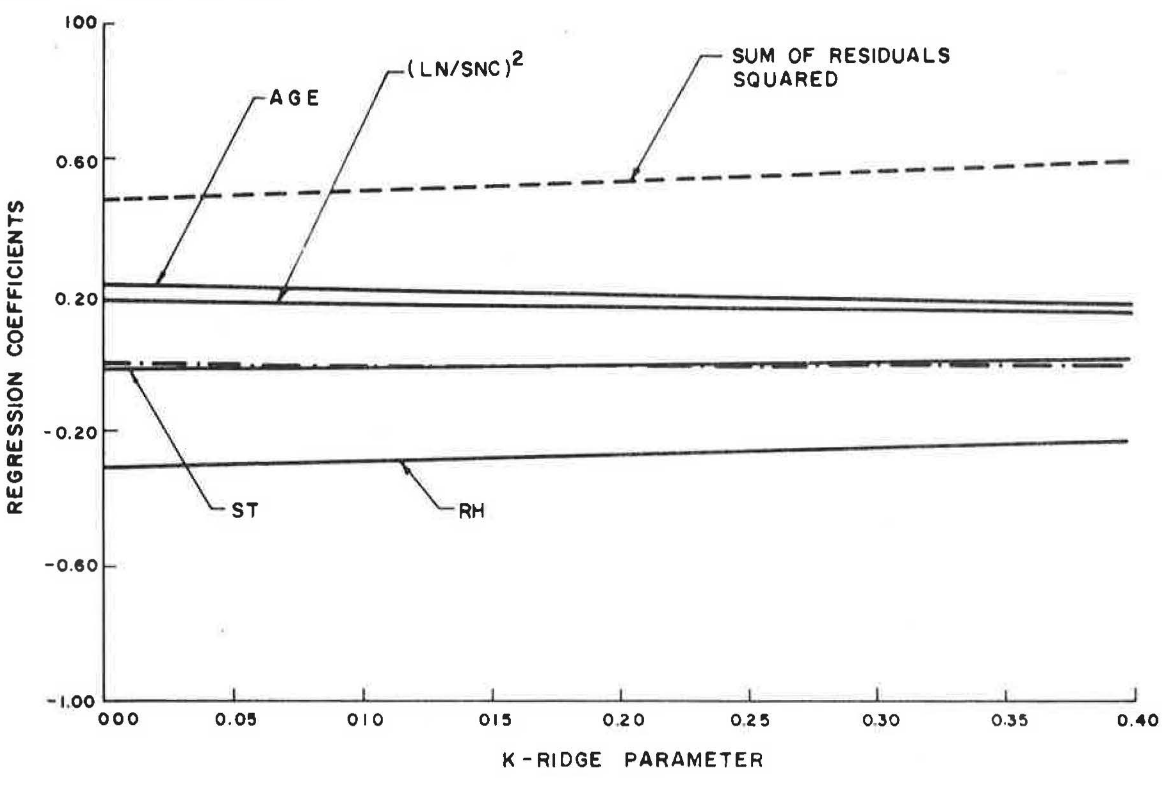
$$LQI = 1.299 - 0.1072\,RH + 0.0415\,P + 0.006\,23\,AGE + 0.0856\,(LN/SNC) + 0.0230\,D \times LN \quad (5)$$

$R^2 = 0.36$
Standard error for residuals = 0.13

Table 1. Definition of symbols used in analysis of roughness data.

Symbol	Variable	Symbol	Variable
QI*	Roughness measured with a Mays meter and converted into quarter-car index through a calibration equation (counts/km)	D, SCI, BCI	Dynaflect maximum deflection, surface curvature index, and base curvature index (0.001 in)
SN	Pavement structural number	AGE	Surface age since construction or overlay (years)
SNC	Structural number corrected for subgrade resistance	P	Percentage of pavement area that received repairs in form of deep patches (%)
LN	Logarithm to base 10 of number of 80-kN cumulative equivalent axles	ST	Surface type dummy variable, 0 for asphaltic concrete and 1 for double surface treatment
B	Benkelman beam mean deflection (0.01 mm)	RH	State of rehabilitation dummy variable, 0 as constructed and 1 if overlaid

Figure 1. Ridge trace for Equation 1.



Equation Including Structural Number, Benkelman Beam Deflection, and Initial Roughness

$$QI^* = QI_o^* + [155.5 + 2.07G - 163.8\,(B/B_o) - 165.9\,(SNC_o/SNC) + 172.9\,(B/B_o) \times (SNC_o/SNC)] \times (N/10^6) \quad (6)$$

$R^2 = 0.56$
Standard error for residuals = 9.37

where

QI_o^* = an estimate of the pavement's initial roughness (i.e., QI* value at AGE = 0),
SNC_o = 5, and
B_o = 55.

The values of B/B_o and SNC_o/SNC are held to not less than 1. G is a function of the road gradient given by

$$G = 1 - [1/(1 + 10^{GR-4})] \quad (7)$$

where GR is the uphill gradient in percent. On the downhill, GR = 0.

Discussion of Roughness Prediction Models

Six roughness prediction models were developed. The independent variables included represent various degrees of sophistication in the data required for analysis. As an example, Equation 3 may be used when only Dynaflect deflections are available, but the use of Equation 4 requires that the Benkelman beam deflection and structural number be known.

The latter is considered more appropriate for analysis at the project level (e.g., for designing an individual overlay), whereas Equation 3 may be suitable for analysis at the network level (e.g., maintenance planning for a number of sections). Equation 6 may be used when an estimate of the pavement's initial roughness is available.

Efforts were made to improve the equations by including more information in the regression models, but the result was less significant and produced more unstable coefficients.

The roughness scale used in this paper was defined by the quarter-car simulator of a surface dynamics profilometer through its quarter-car index (QI). Accurate QI estimates can be obtained from profile data collected with rod and level by using a 500-mm sampling interval (5). The rod-and-level method is particularly appealing for developing countries, where the social costs of labor-intensive procedures may be significantly less than procedures that depend on sophisticated imported instruments.

ANALYSIS OF PAVEMENT CRACKING

The approach for studying pavement cracking was to monitor the percentage of area cracked at selected test locations on existing roads. Detailed information developed to characterize each test location included traffic loads and volumes, pavement structural number, and Benkelman beam and Dynaflect deflections (6).

The cracking variable used in this analysis is defined as the percentage of the pavement's total area that shows class 2-4 cracks or potholes. Class 1 cracks, which have widths of less than 1 mm and are normally called hairline cracks, were not included in the percentage calculation because they are not readily identifiable in the field and their measurement depends, to a great extent, on the observer's judgment and weather conditions. In addition, hairline cracks can result from poor rolling of asphalt mixtures during construction and, in this case, their prediction as a function of pavement strength and traffic loadings is meaningless.

Another reason for not including hairline cracks in the computation of the cracking variable is that this type of cracking would hardly ever warrant any pavement maintenance response. Moreover, class 1 cracks were not included in the cracking term used to estimate serviceability at the American Association of State Highway Officials (AASHO) Road Test (7). Therefore, it seems appropriate to quantify a cracking variable as defined previously.

Few of the surface treatment sections exhibited cracks. Consequently, test sections with this type of surfacing were not included in the analysis of pavement cracking.

Approach for Cracking Analysis

The data indicated that a pavement may take several years to show the first crack. After the initial cracks appear, however, the deterioration process is relatively fast. Therefore, it was necessary to develop two types of models--one to predict when cracks first appear and the other to predict how fast cracks progress in a specified pavement. The analyses corresponding to these models are called, respectively, crack initiation and crack progression.

The need for these two types of models was identified by Finn (6), who stated that, to be helpful to the highway engineer, the output variable of cracking as predicted from research should include not only some estimate of initial cracking, but also the rate of progression of cracking with time.

Crack Initiation

The dependent variable used in this part of the analysis is the number of equivalent axles supported by the pavement to crack first. The objective of this part of the study was to predict when cracks first appear; therefore, only test sections that showed their first crack during the study period were used.

A number of functional relations were investigated through regression analysis. The model found to best fit the data is

$$LN = 1.205 + 5.96 \log SNC \quad (8)$$

where

LN = logarithm to base 10 of the number of equivalent axles to crack first,
SNC = corrected structural number, and
log = logarithm to base 10.

Equation 8 has a correlation coefficient squared of 0.52, a standard error for residuals of 0.44, and is based on a sample size of 19. No acceptable regression equation could be developed with independent variables other than corrected structural number. We expect that test sections that have not shown any cracking (and therefore are not included in this analysis) will enhance the inference space for future analysis. This may make it possible to obtain reasonable models for the other combinations of independent variables.

Crack Progression

Two different dependent variables were used in this part of the analysis:

1. The percentage of area cracked at a specified pavement age, and

2. The age when the percentage of area cracked reaches a specified value.

Models developed for the first dependent variable are useful when, for example, the engineer wants to predict the cracking condition of a pavement t years from now if no maintenance is applied to the pavement. The resulting numbers could indicate the need to request additional funds for certain projects in the road network.

An example of application of models developed for the second dependent variable is the estimation of the time at which a pavement cracking condition will reach a limiting value at which rehabilitation is necessary. Limiting values for this condition depend on a number of factors, including the highway function, resources available, and local practice. Limiting values suggested by different researchers fall in a wide range of 5-35 percent; the average approaches 15 percent (1).

A number of functional relations were investigated in order to develop models to predict the amount of pavement cracking. The three models that best fit the data follow.

1. Independent variables include Benkelman beam deflections

$$CR = -18.53 + 0.0456\, B \times LN + 0.005\,01\, B \times AGE \times LN \quad (9)$$

$R^2 = 0.64$
Standard error = 12.61

2. Independent variables include Dynaflect deflections

$$CR = -14.10 + 2.84\, D \times LN + 0.395\, D \times AGE \times LN \quad (10)$$

$R^2 = 0.44$
Standard error = 15.84

3. Independent variables include corrected structural number

$$CR = -57.7 + 53.5\, LN/SNC + 0.313\, AGE \times LN \quad (11)$$

$R^2 = 0.34$
Standard error = 17.12

where

CR = percentage area cracked,
B = mean Benkelman deflection (0.01 mm),
LN = logarithm to base 10 of the number of cumulative equivalent axles,
AGE = pavement age since construction or overlay (years),
D = mean Dynaflect deflection (0.001 in), and
SNC = corrected structural number.

Stability of the regression coefficients in Equations 9-11 was examined through ridge analysis. The corresponding ridge traces showed that the three equations developed have very high stability. It was not possible to obtain acceptable regression equations (in terms of statistical significance and stability of coefficients) that involve other groups of independent variables.

As mentioned previously, an effort was also made to develop equations to predict the age when the percentage of area cracked reaches a specified value. Only one statistically acceptable model could be derived from this part of the analysis:

$$AGE = 11.46 - 0.0974\, B + 0.1454\, CR + 2.51 \times 10^5\, CR/(RLA \times B) \quad (12)$$

$R^2 = 0.42$
Standard error = 3.75

where

RLA = rate of load applications (i.e., average number of equivalent axles per year),
AGE = number of years since construction or overlay a pavement will take before a percentage of area is cracked (CR), and
B = Benkelman beam deflection (0.01 mm).

INTERPRETATION OF CRACKING MODELS

Equation 8 predicts the number of equivalent 80-kN single axle loads to crack first as a function of corrected structural number. The equation is shown in Figure 2 along with the data points obtained from 19 test sections that cracked first during the study period.

As in other parts of the analysis conducted in this investigation, an effort was made to develop crack initiation models that involve different groups of independent variables. However, no structural variable, other than corrected structural number, was able to explain the phenomenon of crack initiation.

A number of test sections, including most of the surface treatment sections, did not show any sign of cracking during the study period. Therefore, these sections were not used in the crack initiation (or crack progression) analysis. Data collection in the field is anticipated to continue, so we expect that crack initiation models, in terms of other structural variables, can be developed in future analyses.

Three models to predict the amount of cracking have been developed in terms of pavement age and traffic and one of the following: Benkelman beam deflection, Dynaflect deflection, or corrected structural number. Simultaneous inclusion of two structural variables into the equation (e.g., Dynaflect deflection and structural number) did not improve the equation significantly. In fact, this simultaneous inclusion caused high instability of the regression coefficients, as verified in the ridge analysis.

Equations 9-11 are relatively similar in form. Equation 9 is shown in Figure 3, which demonstrates the effect of Benkelman beam deflection on the estimated amount of cracking over time. The figure was constructed by assuming an average of 50 000 equivalent axle load applications per year.

A model has also been developed to predict the age when the percentage of area cracked reaches a specified value (i.e., Equation 12). This equation is illustrated in Figure 4, which shows the influence of Benkelman beam deflection on the number of years it takes a pavement to develop different cracking levels. The figure was constructed by assuming an average of 50 000 equivalent axle load applications per year.

EFFECT OF SLURRY SEAL

The cracking variable (CR) was the dependent variable studied to evaluate the effect of slurry sealing on pavement cracking. Class 4 cracks and potholes were, in general, patched before applications of slurry seal. Therefore, they are not included in the analysis of the effect of slurry seal.

Plots of the data were examined and the following observations were made:

1. After a slurry seal there always existed a period of time when no cracks reappeared and
2. The length of time before the first appear-

ance of a crack was related to the amount of cracking on the subsection when it was sealed.

The effects of grade, overlay, base type, number of equivalent axles per year, structural number, and CBR of the subgrade were investigated and found to be nonsignificant at α = 0.1. The model found to best describe the progression of cracking after a slurry seal was applied is

$$CR = T\,(0.219\,B + 1.43\,CR_o) \tag{13}$$

R^2 = 0.77
Standard error for residuals = 0.13

Figure 2. Number of equivalent axles to crack first for asphaltic concrete pavements as function of corrected structural number (Equation 5).

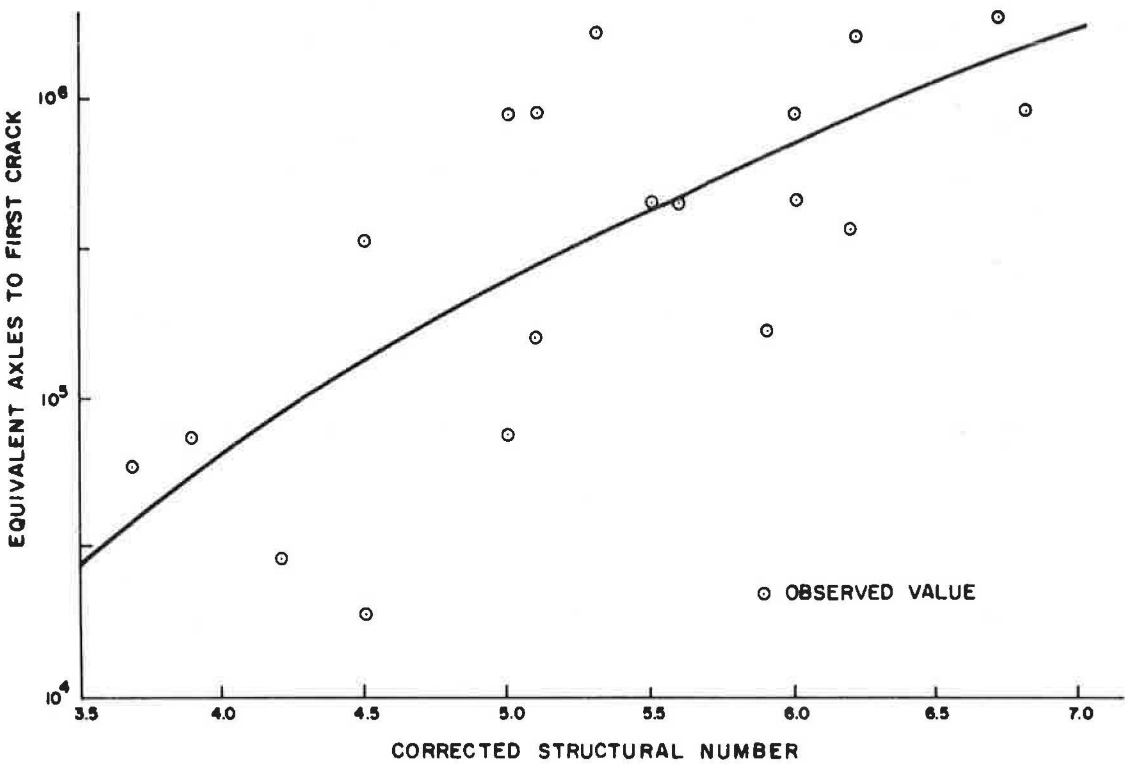


Figure 3. Example of pavement cracking estimated from Equation 9.

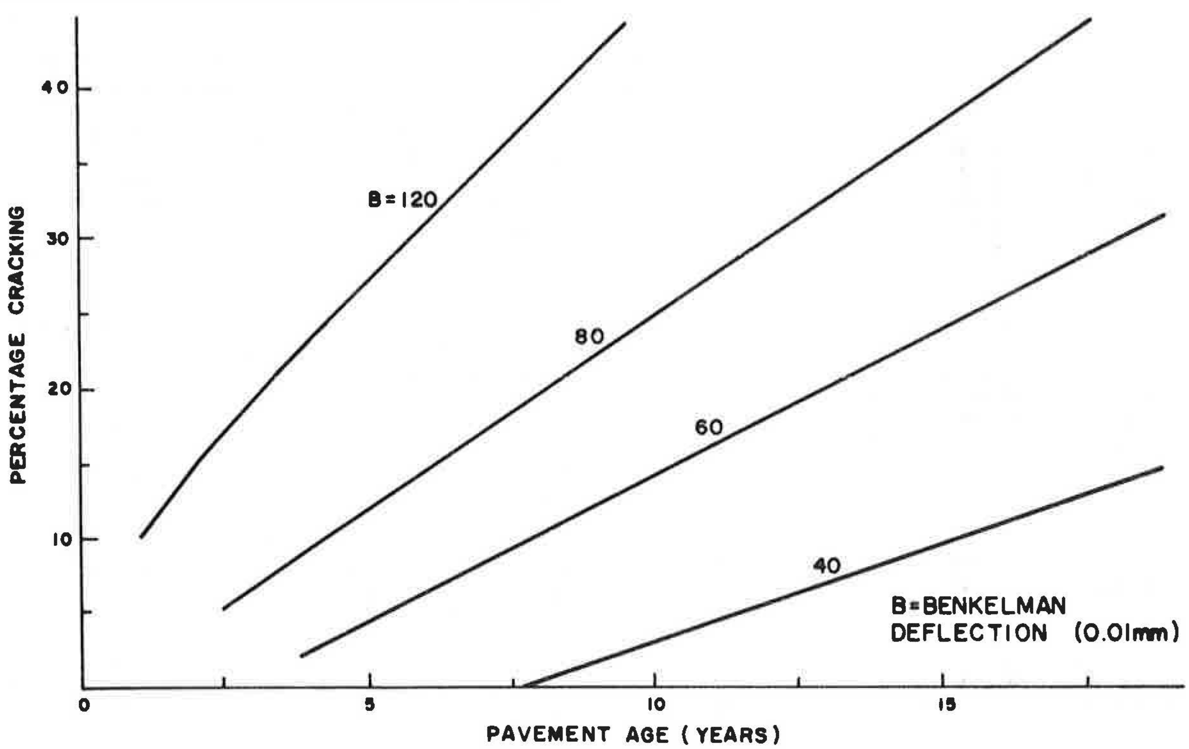


Figure 4. Example of ages to different levels of cracking predicted by Equation 12.

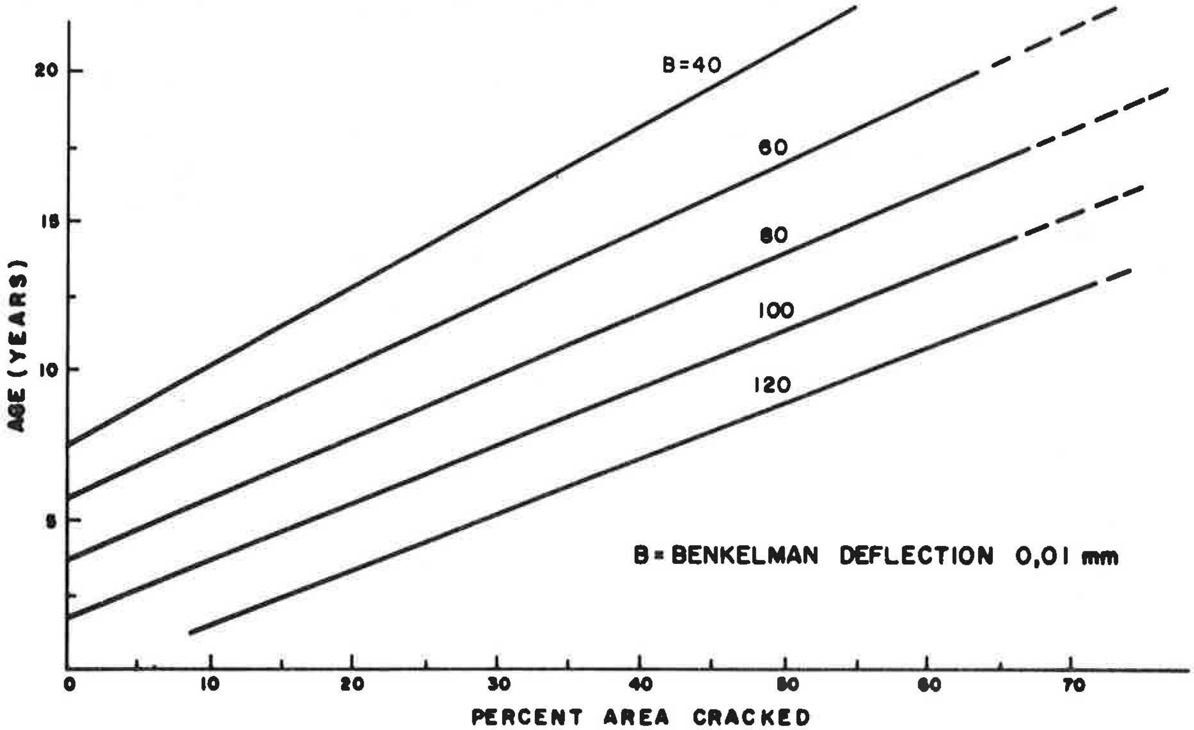


Table 2. Mean, standard deviation, and range of variables studied to evaluate rut depth.

Variable	Mean	SD	Min	Max
No. of sections	45			
Age (years)	7.71	4.80	1.5	20.5
Benkelman beam deflection (mm)	0.78	0.43	0.17	2.13
Corrected structural no.	5.00	0.88	3.40	7.50
Log_{10} cumulative equivalent axles	5.56	0.74	3.20	7.23
Rut depth (mm)	2.53	0.90	0.40	7.40

where

CR = percentage of area cracked,
B = Benkelman beam deflection (0.01 mm),
CR_o = last observed value of CR before slurry sealing,
$T = 0$ if $A_o - (A_s + 10/CR_o) \le 0$ or $A_o - (A_s + 10/CR_o)$ otherwise,
A_o = pavement age when it is being observed, and
A_s = pavement age when it is slurry sealed ($A_o > A_s$).

Equation 13 shows that once cracks appear after slurry sealing their rate of increase is relatively high.

RUT DEPTH STUDY

The objective of this part of the study was to develop models to predict rut depth as a function of age and structural and traffic variables. The mean, standard deviation, and range of variables studied are given in Table 2. The observed rut depths on the test sections were very low (maximum of 7.4 mm).

Although the limiting criterion for pavement rut depth varies among authors, it falls within the range of 10-25 mm (9). Rutting was found to be slight in the study area, with an average of 2.5 mm. This means that rut depth probably will not act as a trigger to initiate maintenance on the pavements studied in this investigation.

Empirical models apply to the inference space governed by the observed variables. Thus, any rut depth prediction model developed from the data currently available will apply for rut depths below 7.4 mm, as given in Table 2. However, it is important to predict rut depths of at least 10 mm in order that the prediction models find practical application. Therefore, no attempt has been made in this investigation to develop equations to predict pavement rutting.

SUMMARY AND CONCLUSIONS

The primary objective of this study was to develop models to describe pavement performance and behavior for Brazilian pavements. The models are needed to relate road user costs and road maintenance costs to roadway conditions in order to predict total highway transportation costs.

The experimental design sampling matrix addresses the major factors considered to influence pavement performance and behavior. Existing road sections were selected and used to satisfy the requirements of the sampling matrix. Detailed information on traffic volumes and weights and material characteristics was collected for each section. The dependent variables measured were roughness, rut depth, cracking, and patching. Rut depth measured on the study sections was very low. Consequently, no effort was spent on developing an equation for predicting rut depth.

Prediction models for paved road roughness were developed as a function of traffic, age, and one of the following independent variables: (a) corrected structural number; (b) Benkelman beam deflection; (c) Dynaflect deflection; (d) corrected structural number and Benkelman beam deflection; or (e) cor-

rected structural number and Dynaflect deflection.

Empirical relations for predicting asphaltic concrete cracking were developed as a function of traffic, age, and one of the following: (a) Benkelman beam deflection; (b) Dynaflect deflection; or (c) corrected structural number. In the prediction of cracking it was shown that, if more than 10 percent of the area of the road is cracked, cracking will reflect through a slurry seal within one year. Further, the rate that reoccurring cracking develops following a slurry seal exceeds the progression rate associated with the original cracking. Therefore, the utility of using a slurry seal for resealing may be questioned.

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Performance, Design, and Maintenance Relationships for Unpaved Low-Volume Roads

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Although paved roads are widely studied, unpaved roads are far more widely used throughout the world. Recently, problems have been encountered in transferring experience and technology with unpaved roads to environments other than those in which they were obtained. In addition, low available funding demands that these funds be used with maximum benefit, and this requires the use of pavement management system methodology. An approach for evaluating unpaved road performance and deterioration is developed. The method is based on an extensive study in Brazil, and equations for predicting roughness, rut depth, and gravel loss are developed. Important criteria for the passability of an unpaved road and a minimum gravel thickness to protect the roadbed are presented. The maintenance and design system (MDS) presented combines these relationships with user cost equations in a systematic manner, which permits an evaluation of the interaction of the factors. Most important, traffic was found to have the greatest influence on regraveling and blading strategies as well as on the total cost of unpaved roads. The MDS has been tested by comparing predicted and actual maintenance on the unpaved road network in the Bronkhorstspruit District of South Africa and excellent agreement was found, which signifies that on average the MDS developed for Brazilian conditions can be applied to South African conditions.

The important designed performance details of unpaved roads differ from those of paved roads. For example, in using granular materials for paved roads we try to remove almost all clay or plasticity from the material. On the other hand, surface gravels were better when they contained some plasticity. Thus, taking their cue from nature, road builders of ancient and modern worlds have added clay to sandy roads to make them stable and have added sand and gravel to clay surfaces to prevent them from rutting and becoming impassable in wet weather. The clay acts as a binder, whereas the sand and gravel particles bear on each other and resist traffic loads. Reference to this type of construction appeared as early as 1806 (1). Textbooks of the 1920s (2) contain descriptions of the design and construction of earth, sand-clay, and gravel roads, which reflects the experience that was then available in the use of these roadbuilding materials.

In recent years there has been a remarkable expansion of the world's paved-road networks. Nevertheless, unpaved roads, i.e., earth, sand-clay, and gravel-surfaced roads, constitute a major part of the network in most countries. In developed countries the proportion varies between 5 and 63 percent of the total, whereas in developing countries they range from 70 to 97 percent of the network (3). In South Africa, 75 percent of the rural road network was unpaved in 1980 (4).

The fact that maintenance and design procedures for unpaved roads are normally based on local experience poses a problem, since these procedures cannot be transferred directly to other environments and material types. In addition, investment and maintenance alternatives for paved roads are studied by using pavement management systems that were developed to achieve the best value possible for the available public funds (5). To apply pavement management concepts to gravel-surfaced roads, it is necessary to quantify the behavior and performance of unpaved roads. The problems that are addressed in this paper are twofold:

1. The need for rational experienced methods to