A Transferable Causal Model for Predicting Roughness Progression in Flexible Pavements

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An empirical model of roughness progression is developed that differs in form from traditional performance and pavement design models, which attribute roughness changes only to structural factors, and from correlative models, which have often been unable to distinguish any causative factors other than age or environment. The incremental change in roughness is modeled through three groups of components, dealing with structural, surface distress, and environment-age-condition factors, respectively. The formulation and components were estimated statistically from field data of a very comprehensive factorial of in-service pavements in the major Brazil-United Nations Development Program (UNDP) road costs study. It was evident from the data that road roughness develops through multiple mechanisms, and the model resulting from detailed nonlinear statistical analysis shows that significant deterioration can occur even in the absence of structural weakness. This has important implications for pavement and rehabilitation design. Roughness progression follows a generally accelerating trend, with the rate of progression depending initially upon the rate of traffic loading relative to the pavement strength and on the environmental coefficient, and then rising more rapidly once surface defects such as cracking, potholing, and patching occur. Across-country and across-climate studies on independent data sets have quantified the macroclimatic effects and shown the model to be highly transferable.

Predicting the progression of roughness over the life cycle of a road pavement is one of the most important performance predictions for pavement management, pavement design, and road pricing. Vehicle operating costs increase by 2 to 6 percent per m/km IRI (International Roughness Index) of roughness. (The relation of IRI to other roughness scales is given elsewhere (*1*), and 1 m/km IRI equals 63.36 in. per mile, or approximately −0.5 serviceability index units.) Riding comfort targets and performance criteria in design methods and management systems are usually related to roughess. In road pricing studies, road damage is usually defined primarily by roughness, and the relative impacts of traffic and nontraffic factors influence the allocation of costs among users.

The accuracy required of the predictions is demanding, when it is considered that roughness generally increases at rates of less than 3 to 5 percent (about 0.1 m/km IRI) per year on high-standard roads and by double those rates on low-standard roads. The precision of common methods for monitoring roughness is either of the same order or worse (*2*). Thus, the impact on decisions regarding maintenance timing can be appreciable, and the development of empirical models from monitoring data is difficult.

This paper summarizes the empirical development of a roughness progression prediction model to meet these various requirements with a fundamental basis that permits its transfer to a wide range of climates and countries. It was developed as part of a wider analysis of road deterioration under the major World Bank collaborative study on highway design and maintenance standards, and is the main deterioration function of the resulting HDM-III computer model (*3*), which simulates pavement and user life-cycle costs.

Previous Approaches

Previous model forms for characterizing roughness progression are given in Table 1 (*4–14*). The two models that have been predominant for a decade or more relate roughness progression entirely to structural effects, the interaction between traffic loading and pavement strength. These are, first, the serviceability model (*5*) derived under accelerated controlled trafficking at the 1959–60 AASHO Road Test and, second, the British RTIM2 model (*6*) derived from 4-year monitoring of a network sample in a 1971–75 Kenya study, as summarized by models 1 and 2 in Table 1. The models differ in form (the AASHTO model being convex, the RTIM2 model being linear), in the level of initial roughness, and in the influence of roughness on the subsequent progression rate. They also differ in the rate of roughness progression predicted for pavements of similar strength. The rates predicted from the RTIM2 model are slower and approximately equivalent to those for pavements 60 percent stronger (after correction for subgrade strength) in the AASHTO model. However, the differences (presumed to be environmental) are not represented by a uniform regional factor applying to cumulative traffic as recommended in the AASHTO model, and the factor is at least five times smaller than the regional factor recommended (*5*) for a semiarid region (0.3–1.5).

The 1982 modification of the AASHTO model by Lytton and others (*7*) to an S-shaped function (convex-concave) (model 3 in Table 1) appears to have been influenced by the fact that serviceability is a nonlinear bounded function of roughness, tending to zero at high roughness levels but never being negative (*1*). It is considered to apply to cases in which the contributing modes of distress stabilize over time, such as rutting due to densification or where defects are repaired by maintenance.

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TABLE 1 SELECTED PREVIOUS MODEL FORMS FOR CHARACTERIZING ROUGHNESS PROGRESSION

MODEL FORMS	SOURCE AND COMMENT
Traffic Models	
1. $g_t = (p_o - p_t)/(p_o - p_r) = (N_t/\rho)^{\beta}$	AASHTO (5) from 1959 -60 Road Test, Illinois.
2. $R_t = R_o + s(S)\ N_t$	RTIM2 Model (6) from 1971-75 Kenya-TRRL Road Costs Study.
3. $g_t = \exp[-(\rho/N_t)^{\beta}]$	USA (Lytton et al. 1982 (7)): S-shaped curve of slope ρ and curvature β.
Time-related Models	
4. $\Delta R_t = a\ R_t\ \Delta t - b$	Arizona, USA (Way and Eisenberg 1980 (8)).
5. $R_t = R_o + a\ t^b$	Australia (Potter 1982 (9)).
6. $\Delta R_t/R \simeq 7\%$ per year	Canada (Cheetham and Christison 1981 (10)).
7, 20 - 30% per year	Spain, Belgium (Lucas and Viano 1979 (11)).
Interactive time, traffic or distress	
7. $R_t = a + b\ t + c\ f(S, \log N_t)$	Brazil (Queiroz 1981 (12)).
8. $\frac{\Delta R_t}{R_t} = \max(a\ CX^b, c)\ \Delta t$	Great Britain (Jordan et al. 1987 (13)).
9. $t = f[\ p_o, \text{var RD}, RD^{2.5}, (C+P)^{0.5}]$	(Uzan and Lytton 1982 (14)).

Note: g = damage function; p = serviceability index; N_t = cumulative number ESAs; R = roughness; S = pavement strength parameter; t = age of pavement since rehabilitation; CX = area of cracking; RD = rut depth; C+P = area of cracking plus patching. ρ, β are functions, and a, b are constants estimated empirically through research. The detailed formulations are listed in Appendix A of (4).

Source: After Paterson (4).

In sharp contrast to these models, a number of studies evaluating field data from in-service roads have been unable to determine any structural effects and have related roughness progression only to time or age (models 4 to 6 in Table 1). The correlation approach tends to be confounded by the inherent correlation of pavement strength to traffic loading brought about in the design process, and thus strong cross-sectional ranges of loading relative to strength are needed for structural effects to be determined by statistical methods. A significant influence of environment on the time-rate of progression was found in the Arizona study (*8*), with rates ranging from 2 percent per year in arid nonfreezing areas to 8 percent per year in freezing areas. The Australian study (*9*) reported about 2 percent per year for a semiarid climate, and other North American and European studies reported about 7 percent per year (*10,11*).

Very few have been able to quantify interacting effects of traffic and time, or of distress, on roughness. An age-traffic effect in Brazil was identified with a model in a simple log-linear form (model 7). A British study reported a strong link with area of cracking (model 8), and an American mechanistic model included rutting, cracking, and patching (model 9).

There is reasonably consistent agreement that the trend of roughness is generally convex over time or traffic, with the rate of progression increasing toward the end of the pavement life or as the roughness level increases. The degree of convexity, however, varies greatly across the studies—from nil in linear models to high for those reporting high percentage rates of increase. In some cases, the high rates appear to be associated with high levels of surface distress.

With few exceptions, the earlier models for predicting roughness progression treated roughness as an independent mode of distress, attempting to correlate it directly to primary factors, such as traffic loading and pavement strength or age, throughout the life of the pavement. Lacking in them was a clear mechanistic association between roughness and other modes of distress, such as cracking, potholing, and rutting, which themselves cause changes in roughness. The acceleration of roughness progression toward the end of the pavement life due to such defects was often implicit in the models but not an explicit function of the defects. While there is a need for aggregate models that simply relate roughness (or a performance index, such as serviceability) to primary factors, such models are inadequate for policy evaluation and management in two important respects.

First is the need to evaluate maintenance effects. Many maintenance activities repair or modify surface defects, usch as cracking, raveling, potholes, and depressions, with a negligible impact on pavement strength but with significant impacts on both current roughness and the rate of roughness progression. Thus, aggregate models provide no explicit mechanisms by which the effects of such maintenance upon roughness can be evaluated, especially in the short term.

Second is the recognition of variations in the behavior of road pavements, arising from both the mechanistic differences of pavements that fall within one strength group and also from the inherently stochastic nature of properties and behavior within one pavement and across similar pavements. For example, two pavements in the same general strength group and under similar traffic may probably crack at different times and, as the cracking influences roughness, so the roughness progression rates would differ.

Last, there is a need to incorporate traffic-related and time-related effects concurrently, recognizing that both should be included in a model of roughness progression.

Empirical Base

The empirical base chosen for developing the statistical models was the Brazil-UNDP-World Bank Road Costs Study (*15*) because it incorporates a very comprehensive set of parallel time-series data on roughness, cracking, raveling, rut depth, maintenance, traffic loading, and rainfall, for a broad, experimentally designed factorial of flexible pavement types and traffic volumes, on in-service roads, as outlined elsewhere (*4*). In particular, it is known that the roughness measurements were all calibrated to a reliable profile reference, so that the trends over the 5-year study period were free from long-term systematic bias. (See Figure 1.)

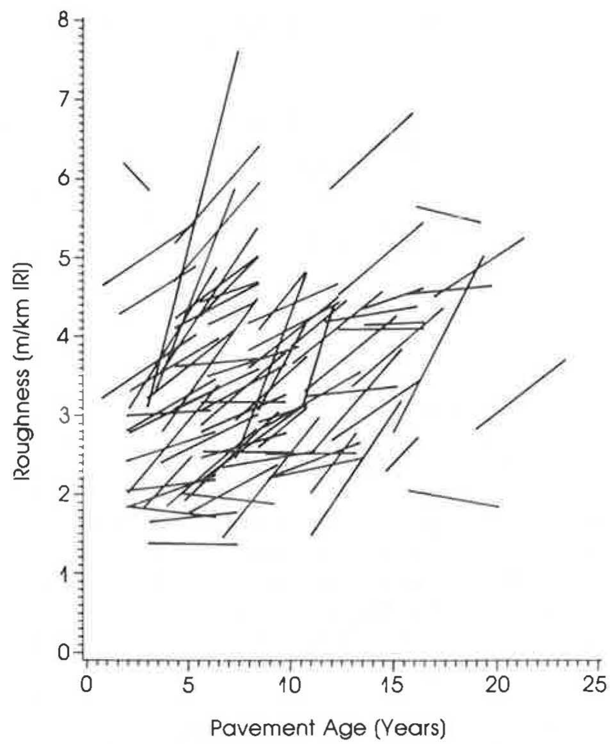
The characteristics and scope of the data available are illustrated in Figure 2 and Table 2. These show the changes of roughness on the 380 subsections of the Brazil-UNDP study, as determined from 3,149 measurements and aggregated by the smoothing technique just described. A number of important characteristics are evident from the figure in which, for the sake of clarity, the data represent just a 30-percent sample (one from each fully independent pavement) and the trends are simplified to straight lines. First, the initial roughness was clearly not a constant value for the study pavements, as had been adopted in the AASHTO and Kenya-TRRL formulations, but varied between about 1.0 and 3.5 m/km IRI for asphalt pavements and between 1.3 and 7.3 m/km IRI for surface treatment pavements. Second, the rate of increase of roughness was not a unique function of age in the sample. Some young pavements showed early rapid deterioration, while others showed negligible deterioration rates even at ages of 12 to 20 years, and still others showed a late rapid deterioration. Negative trends resulted from either minor maintenance or a combination of measurement errors; these latter were handled statistically and not excluded because such errors may also have affected apparently "good" data.

The average annual rates of roughness progression, as indicated in the table, were 5.2 percent for asphalt pavements, 4.8 percent for surface treatments, and 6.7 percent for cement-stabilized base pavements. The rates ranged from nil to maxima in the order of 22 to 29 percent per year, which are less than the maximum rates of about 46 percent per year noted in a British study (*13*). The higher rates tended to be associated with high levels of cracking, as shown in Figure 3. For uncracked pavements the rate averaged about 4 percent per year and was similar for all pavement types, while for cracked pavements the rates tended to be higher for those pavements in which the cracked layer was thicker, especially for cement-stabilized bases. It is evident that the study encompassed a broad range of circumstances, including, for example, a range of pavement age from new to 23 years, of traffic loading from 100 to 1.7 million ESAL per lane per year and up to a maximum of 17 million cumulative ESAL, and of pavement modified structural number from 2.1 to 8.7.

COMPONENT INCREMENTAL MODEL

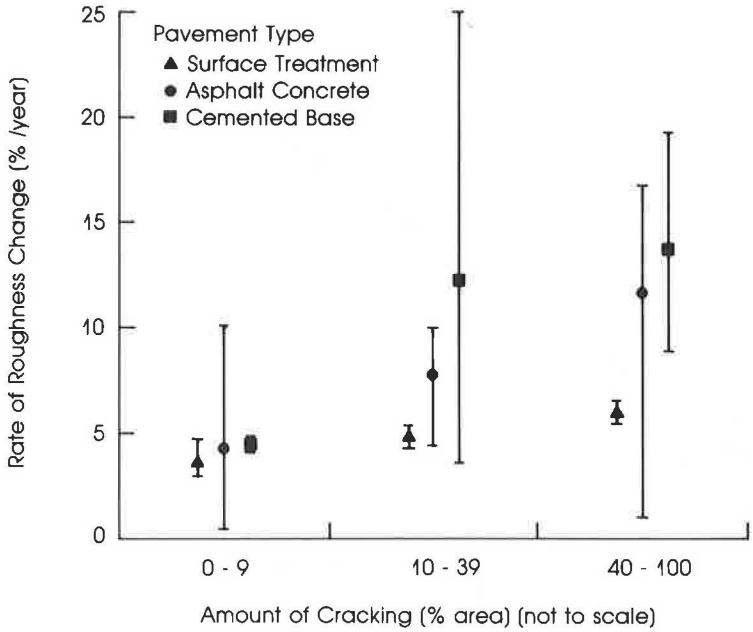
Principles

The basic hypothesis used in developing a comprehensive roughness progression prediction model was that the various



Note: Trends simplified to linear approximation for clarity. Sample shown is one subsection from each of 116 independent sections.
Source: Brazil-UNDP study data.

FIGURE 1 Sample of diverse roughness trends observed in Brazil-UNDP Road Costs Study.



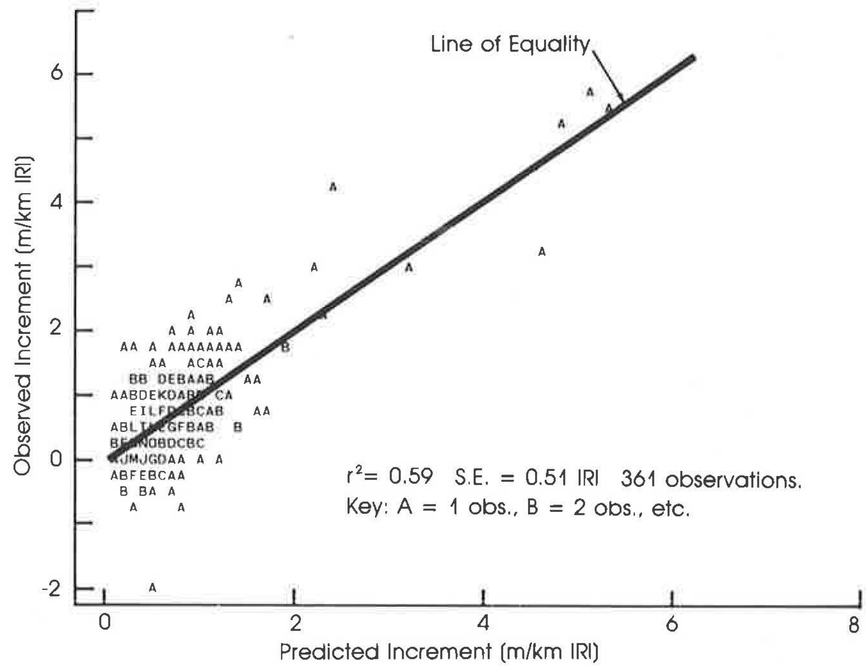
Note: Indexed amount of cracking weights wide cracking twice as much as narrow cracking.
Data are group-means of 30 groups representing 4-year trends of 361 subsections.
Source: Brazil-UNDP study data.

FIGURE 2 Influence of cracking on the rate of roughness progression observed in Brazil.

TABLE 2 INFERENCE SPACE OF ROUGHNESS AND OTHER DATA FROM BRAZIL-UNDP ROAD COSTS STUDY

Observed Parameter	Unit	Asphalt and asphalt overlays			Surface treatment, granular base			Cemented base		
		Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
Roughness progression										
- rate	%/yr	5.16	0	25.6	4.77	0	28.9	6.71	0	21.5
- increment	IRI	0.65	-0.50	7.36	0.58	-1.97	4.20	0.81	-0.08	3.09
- average	IRI	2.67	1.13	8.85	3.44	1.68	7.35	3.18	1.66	5.07
- initial	IRI	1.80	1.02	3.46	2.67	1.31	7.28	2.15	1.23	4.11
- final	IRI	2.98	0.93	9.91	3.75	1.37	9.35	3.63	1.86	5.95
Modified structural number	-	4.82	2.08	8.69	3.76	2.04	5.51	3.96	2.18	6.21
Benkelman deflection	mm	0.68	0.19	1.88	0.70	0.26	2.02	0.41	0.13	1.03
Age (average)	yr	7.09	2.15	20.8	8.33	2.43	18.87	9.83	3.46	17.3
Traffic loading										
- annual per lane	MESA/yr	0.35	.0001	1.68	0.09	.0009	0.55	0.20	0.014	0.48
- increment	MESA	1.40	.0006	7.55	0.39	.0039	2.41	0.83	0.02	1.90
- avg. cumulative	MESA	1.78	.0009	13.0	0.53	.0035	3.88	1.50	0.09	2.61
Cracking										
- average	%	15.1	0.	97.4	8.8	0	67.8	21.7	0	93.9
- increment	%	20.3	-22.5	89.6	13.4	-8	99.3	29.0	-38.4	88.6
Patching										
- increment	%	4.3	-3.3	84.6	5.8	-1.3	86.0	4.2	0	38.4
Rut depth - increment of standard deviation	mm	0.90	-0.22	9.68	0.89	0	8.73	0.50	0	4.88
Number of subsections			156			145			60	
Rainfall	mm/yr		1,040 - 1,800			1,040 - 1,800			1,040 - 1,800	

Note: Min - Minimum, Max - maximum.
Source: Author's analysis of data from Brazil-UNDP study (15).



Source: Estimation of Equation (2) on Brazil-UNDP study data.

FIGURE 3 Goodness-of-fit of component incremental model of roughness on original Brazil data.

mechanisms giving rise to roughness changes should be represented by separate components within the model. In broad terms, it was considered that these fell into three groups, according approximately to the parameters involved, the source depth within the pavement, and the resulting waveband of roughness, as follows.

Structural deformation, resulting from plastic deformation in the pavement materials under the shear stresses imposed by traffic loading, commonly appears as rutting in the wheelpaths. Rut depth alone will not give rise to roughness if the depth is uniform; instead, it is the variation of rut depth that relates to roughness as deviations in the longitudinal profile. These variations will therefore be a function of the uniformity of construction and environment of the pavement layers, and particularly of the subgrade.

Superficial defects such as potholes, patches, raveling, cracking or shoving, humps, and localized depressions are generally associated with shallow-seated distress originating in either the surfacing or base of the pavement. These defects typically range in size from less than 0.3 m up to about 2 m in diameter, with a corresponding waveband of about 0.1 to 5 m wavelengths.

The environmental factors that influence roughness through nonstructural effects include primarily temperature and moisture fluctuations, but also foundation movements such as subsidence, which cause volume changes or distortions in the pavement. Daily thermal expansion and contraction movements are a function of the diurnal temperature range, which is often large in desert climates; the effects of seasonal moisture movements depend upon the effectiveness of drainage and the shrinkage properties of the material; and in freezing climates, the combined volume/roughness effects of temperature and moisture are particularly severe.

The model was therefore structured as follows:

$$\begin{aligned}\Delta R_t = {} & f_1 \text{ (strength, condition, } \Delta\text{traffic, environment)} \\ & + f_2 \text{ (}\Delta\text{surface condition, } \Delta\text{maintenance)} \\ & + f_3 \text{ (condition, environment, } \Delta\text{time)} \\ & + \text{measurement error.} \qquad (1)\end{aligned}$$

This shows an additive combination of the three major components in the increment of roughness and provides at the same time for such interactions as may prove significant. During the course of analysis, many formulations of the terms comprising each component were tested, and the final choice was determined with respect to statistical significance and engineering reasonableness, ensuring that the model was mathematically integratable.

Empirical Model and Accuracy

After preliminary evaluation using linear regression techniques, the final statistical development of the model was made using a nonlinear least-squares regression technique. While the basic form of the model became evident in the early stages, many variants were examined in order to avoid the adverse effects of correlations between the explanatory parameters, to review alternatives to the parameters, and finally to ensure that the model was integratable and fundamentally consistent with trends of absolute roughness [details are given elsewhere (*4*)]. The model, as estimated on the Brazilian data, was as follows:

$$\Delta RI_t = 134\, e^{0.023\, t}\, SNCK^{-5.0}\, \Delta NE_4 + 0.114\, \Delta RDS + 0.0066\, \Delta CRX + 0.010\, \Delta PAT + Z_{pot} + 0.023\, RI_t\, \Delta t \quad (2)$$

where

- ΔRI_t = increase in roughness over time period t (m/km IRI);
- RI_t = roughness at time t (m/km IRI);
- ΔRDS = increase in rut depth standard deviation of both wheelpaths (mm);
- ΔCRT = increase in area of indexed cracking (percent; see note below);
- ΔPAT = increase in area of surface patching (percent);
- Δt = incremental time period of analysis (years);
- ΔNE_4 = incremental number of equivalent axle loads in period t (million ESA/lane);
- $SNCK$ = $1 + SNC - 0.0000758\, H\, CRX$;
- SNC = modified structural number of pavement strength;
- t = age of pavement or overlay (years);
- H = thickness of cracked layer (mm);
- CRX = area of cracking (percent); and
- Z_{pot} = dummy intercepts estimated for sections with potholing.

Note: Indexed cracking is the weighted area given by $CRX = (4 \times \text{area of Class } 4 + 3 \times \text{area of Class } 3 + 2 \times \text{area of Class } 2 + 1 \times \text{area of Class 1 cracking})/10$.

The model fitted all pavement types without significant class differences, and detailed statistics of the parameter estimates and goodness of fit of the model are given in Table 3, under model A(2). In this final version, which is preferred to the unconstrained model A(1), the value of the γ-exponent of *SNC* has been constrained slightly to take account of strong effects present in the absolute (nonincremental) roughness data [see Paterson (*4*) for detailed discussion]. The robustness of the formulation is evident from the generally strong significance of the individual coefficients. It is also evident from the relatively strong contributions made by the individual components to the overall goodness of fit of the model, as shown by the Type II sums of squared errors presented in Table 4. With the model simplified to its underlying five-component form, the fit (by linear regression) improves to $r^2 = 0.75$, whereas the original fit of $r^2 = 0.59$ represented the variances due to all eleven parameters involved.

The goodness of fit that was achieved is shown as a scattergram of predicted and observed values in Figure 3. This shows that the model fitted the data well, over the wide range of roughness increments observed up to 7 m/km IRI, and that the prediction error of about 0.5 m/km IRI is rather uniform throughout the range. Thus small increments are predicted as accurately as large increments, in absolute terms. This corresponds to an error in an annual prediction of roughness that is of the order of only 0.12 m/km IRI, which is a highly acceptable result, especially given the diverse nature of the conditions studied.

Although the prediction error is small in absolute terms, it is apparent from Figure 3 that errors for the smaller increments can be large in relative terms and of a similar order to the increments being observed. However, about one-half of the apparent error derives from the observation measurement errors (*2,4*), a fact readily appreciated from the number of observed increments falling below the zero ordinate. Also, the residual errors were not correlated to any of the primary parameters. Thus the error component due to lack of fit of the model formulation itself was only about one-half of the values cited in the previous paragraph. The model prediction error, net of any measurement errors, is thus very small, amounting to only about 0.06 m/km IRI (4 in./mile IRI, 0.03 PSI, or 50 mm/km BI) per year.

Examples of the fit of model predictions to the observed roughness trends are shown in Figure 4 for a diverse range of sections, roughness levels, and ages. In each case, both traffic lanes, CS and SC, are depicted for one pair of subsections; the solid lines represent the prediction using condition and traffic data for each observation date, and the broken lines represent the observed roughness trend without smoothing. As the model estimation was based on the increment over the whole period, the predicted and observed trends should give similar total increments. It is apparent that the model fits the data of observed trends very well for a variety of flexible and semirigid pavements, and that the model was remarkably strong in representing the wide variety of conditions in the database.

Engineering Implications

The various components of the incremental model make differing contributions to the total roughness change predicted under different situations. In the statistical estimation, they all made generally similar contributions to the model fit, though with slightly less coming from the rut-depth and patching terms (as shown by the Type II errors in Table 4). The factors that were found to have statistically significant impacts on roughness progression included rut-depth variation, pavement strength, cracking, and traffic loading in the structural deformation component; cracking, patching, and potholing in the surface defects component; and roughness and time in the environment-age component. Among the variables that were not significant were mean rut depth, age, and deflection in the structural component; raveling and narrow cracking in the surface defects; and pavement strength, age, and rainfall in the nontraffic or environmentally related term.

The primary structural deformation term has a conceptual origin in the AASHTO performance model, incorporating traffic loading and pavement strength; but it also includes interactions with cracking and the environment-age variables. Cracking is seen to accelerate the roughness progression by causing a drop in the apparent strength (*SNCK*), which is the most severe for pavements in which the cracked layer(s) is thick and constitutes a major portion of the pavement's structural capacity. Thus this term distinguishes between the performances of two pavements that have similar modified structural number and traffic loading but different thickness of bound layer. The effects of pavement strength and traffic loading on pavement performance are determined by the exponent of the net pavement strength parameter, *SNCK*. The γ-value of 5.0 is very similar to the values found in rutting progression and the AASHTO and TRRL-Kenya performance studies. This deformation term has a strong impact on

TABLE 3 ESTIMATION OF COMPONENT INCREMENTAL ROUGHNESS PREDICTION MODELS.

Model A: $\Delta RI_t = b\, e^{m\,t}\, SNCK^{-\gamma}\, \Delta NE_t + \Sigma a_i\, \Delta SD_{it} + m\, RI_t\, \Delta t$; and $SNCK = 1 + SNC - c\, H\, CRX$.

Model B: $\Delta RI_t = \Sigma a_i\, \Delta SD_{it} + m\, RI_t\, \Delta t$.

Parameter coefficient	Parameter estimates1/ for given model form A(1) unconstrained	A(2) constrained2/	B constrained
m	0.0227 (6.4)	0.0230 (6.5)	0.0284 (8.4)
b	37.7 (2.8)	134 (2.8)	- -
γ	4.11 (16.9)	5.0 (-)	- -
c(x10^3)	0.0887 (7.0)	0.0758 (6.5)	- -
a(ΔRDS)	0.114 (4.4)	0.114 (4.4)	0.129 (4.8)
a(ΔCRX)	0.0066 (6.1)	0.0066 (6.1)	0.0057 (5.2)
a(ΔPAT)	0.0100 (3.9)	0.0099 (3.9)	0.0117 (4.4)
Standard error	0.5141	0.5145	0.5385
r^2	0.589	0.588	0.551
Number of observations	361	361	361

1/ t - statistics are given in parentheses; (-) indicates constraint of the parameter; - indicates not included in the model.

2/ This constraint equated the coefficient γ to the value of the unconstrained estimate for the aggregate level model, i.e., $\gamma = 5.0$.

Note: ΔSD_i comprised ΔRDS_i, ΔCRX_i; and ΔPAT_i as the only significant distress variables.

Source: Author's computations from data of Brazil-UNDP Study (15). Method nonlinear least-squares regression.

predictions, especially when the traffic loading is very heavy relative to the structural number and when cracking significantly reduces the structural capacity.

The second term of the structural component, the relation to rut-depth variation, is important because it provides a strong empirical quantification of the link with roughness. The coefficient is statistically well determined and robust, varying little in value over a range of model variants, including those in which the other structural term was omitted. Other forms of rut-depth parameters, including a quadratic function and mean value, were significantly inferior to the linear, standard deviation parameter. The value 0.11 can be compared with 0.14 from a study in Southern Africa, and with 0.15 to 0.25 from the AASHO Road Test [see Paterson (*4*)].

Cracking was found to contribute a small but significant amount of roughness progression in the additive term, which supplements the effects found in the rut-depth variation and structural deformation terms. It is included independently of patching and becomes negative when patching is applied to repair cracking. The term comprises the fractional extent of cracking, weighted for severity so that wide, spalling cracks dominate the effect. The mechanisms inducing roughness here are the effects of spalling and unevenness generated across cracked blocks of surfacing and the birdbath-type of depression that often results from localized deformation in the base as a result of surface cracking. A 60 percent increment in the area of cracking, which is equivalent to full cracking in both wheelpaths, contributes about 0.4 m/km IRI of increase in roughness. Worse consequences result when the cracking is unrepaired and leads to potholing.

The patching term in the model refers to surface patching that, in the study, comprised either replacement of a distressed area of thin surfacing by cold bituminous mix or a superficial patch of fine slurry seal (5-mm maximum size

TABLE 4 RELATIVE CONTRIBUTIONS AND SIGNIFICANCE OF INDIVIDUAL COMPONENTS IN THE INCREMENTAL ROUGHNESS MODEL

Model component	Model terms	Sequential effects Type I SS(%)	Sequential effects F-value	Individual effects Type II SS(%)	Individual effects F-value
Structural	e^{mt} SNCK^{-5} ΔNE_4	40	401	10	36.5
Age-environment	m R Δt	41	435	13	45.6
Rut depth s.d.	ΔRDSD	3	36	5	19.2
Cracking	ΔCRX	6	59	11	38.1
Patching	ΔPAT	5	59	4	15.6
Potholing	Zpot	5	30	25	29.8
Total		100			

Notes: Determined by general linear least-squares regression of the component terms above, based on Equation (2) where m = 0.023. Parameters are defined with Equation (2).
Type I SS (sums of squares) is the incremental improvement in error SS for consecutive additions of further terms, expressed here as a percentage of the model SS(276.6). Type II SS are the reduction of error SS due to adding the relevant term into the model after all others have been included; it is independent of sequence and is expressed as a percentage of the error SS(93.3). The fit for the linear combination of components is $r^2 = 0.748$.

Source: Author, on data from Brazil-UNDP study (15).

aggregate). The coefficient indicates that surface patching increased the roughness by 0.01 m/km IRI per percentage of area patching, which, after deducting the decrease due to repaired cracking, is equivalent to the effect of an average protrusion (either positive or negative) of 2 to 5 mm, which is in the same order as the height of the patches. Independent data from a Kenya network survey indicate a coefficient of 0.08 m/km IRI per percentage area for patch protrusions of 15 to 25 mm. In general, the coefficient could thus be replaced by 0.003 H_p, where H_p is the average patch protrusion, in millimeters.

The last term of the surface distress component represents pothole and other major surface profile deviations. As potholes were usually repaired immediately during the study on both high- and low-maintenance sections, and as open potholes were avoided in the roughness measurement when they were present, direct statisitcal estimation of the effect of potholes on roughness was not possible. In the model estimation, dummy intercept terms were estimated for five subsections that had significant defects, amounting to about 2.1 m/km of IRI on the four subsections in section 112, which was cited as having "100 percent wide cracking, potholes and patches," and about 1.2 m/km IRI on subsection 022 SEM CS, which showed shoving distress due to an overfilled soft asphalt mix. A separate simulation study was used to derive the roughness-pothole effect (*4*), so that the following substitution could be made in the model:

$$Z_{pot} \simeq 0.16\ \Delta VPOT \text{ (m/km IRI)}$$

where $\Delta VPOT$ equals the increment in volume of open potholes, in m³/lane/km.

The final component in the model, referred to as the environment-age component, represents a uniform annual percentage increase in roughness independent of traffic loading. The component indicates that an average of 2.3 percent annual increase in roughness was estimated to occur that could not be attributed to traffic, either as the equivalent axle loading or as the number of all vehicle axles. The rate amounts to a total roughness increase of 22 percent over 10 years or 50 percent over 20 years. The coefficient is well determined, and its value increases if the roughness increments are constrained to be non-negative or if the structural deformation function is omitted, as shown in Table 3. Considerable effort was made to find other factors influencing the value of the coefficient, but it was found to be independent of pavement age (the S-curve phenomenon), pavement type or strength, and traffic volume, for example. The value is almost certainly influenced by the pavement environment; but no significant, sensible effect of climate could be determined within the fairly homogeneous climate of the Brazil study area, using either the Thornthwaite Moisture Index, which ranged from 10 to 100 in the study region, or the mean annual precipitation, which ranged from 1,040 to 1,790 mm per year. Instead, further work at the macroclimatic level, applying the model to data in widely different climates and countries, has established that the coefficient does vary with climate over a range of about 0.005 in arid climates to 0.10 to 0.20 in freezing wet climates, as shown in Table 5 (*4*).

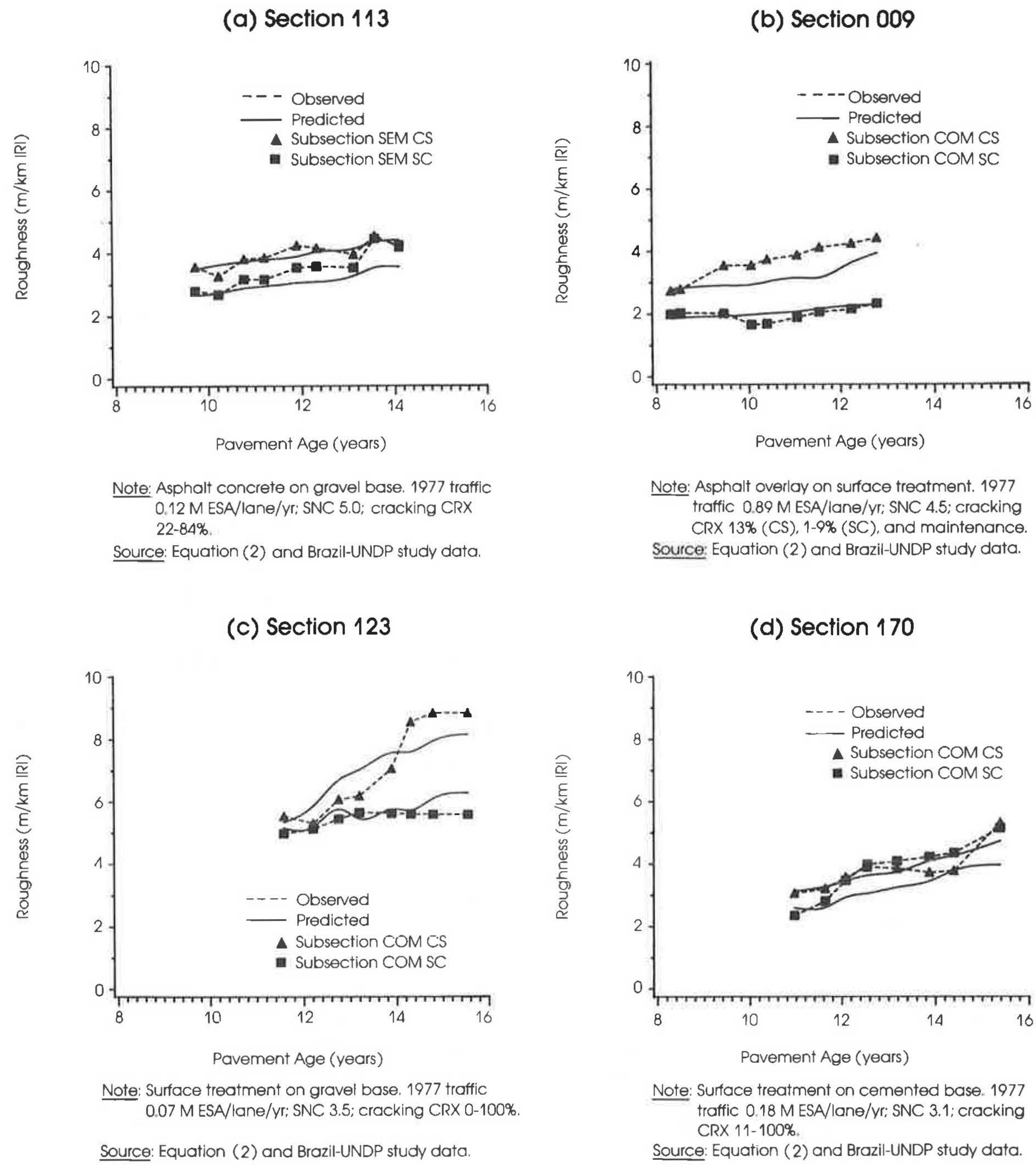


FIGURE 4 Sample comparison of predicted and observed roughness trends in Brazil data.

It was noted during the modeling that traditional model forms, such as the traffic-related models of Table 1, fitted the observed data very poorly, and no sensible estimates of their coefficients could be achieved. This was due mainly to the shortcomings of the traditional forms, as discussed earlier, and in part to the inherent collinearity that exists between various parameters, for example, between traffic loading and pavement strength, roughness, age and surface distress, and so forth. Also, many interactions were investigated, in combinations and powers of parameters and in substitutions, with negligible improvement on the final model presented in Equation 2.

The Brazilian model given by Equation 2 was then generalized, in light of this discussion, to give the following general version:

$$\Delta RI_t = 134\, e^{m\,t}\, SNCK^{-5.0}\, \Delta NE_4 + 0.114\, \Delta RDS + 0.0066\, \Delta CRX + 0.003\, H_p\, \Delta PAT + 0.16\, \Delta VPOT + m\, RI_t\, \Delta t \qquad (3)$$

TABLE 5 RECOMMENDED VALUES OF ENVIRONMENTAL COEFFICIENT M IN ROUGHNESS PROGRESSION MODEL FOR VARIOUS CLIMATES

		Temperature classification[1]		
Moisture classification	Moisture index[2]	Tropical nonfreezing	Subtropical nonfreezing	Temperate freezing
Arid	-100 to 61	0.005	0.010	0.025
Semiarid	-60 to -21	0.010	0.016	0.035
Subhumid	-20 to +19	0.020	0.030	0.065
Humid, wet	20 to 100	0.025	0.040	0.10-0.23

Source: Author's recommendation based on evaluations of model in several countries and regions (3).

[1] Tentative definition of these classes: Tropical includes warm temperatures 15 to 40°C and small range; Subtropical includes warm, high range (5 to 50°C) and cool, moderate range (-5 to 30°C); Temperate freezing includes climates with annual pavement freezing.

[2] Thornthwaite's Moisture Index.

where

m = environmental coefficient, as given in Table 5;
$\Delta VPOT$ = increment in volume of open potholes (m^3/lane/km);
H_p = average rectified protrusion of patch repairs above or below surrounding surface (mm);

and other parameters are as defined for Equation 2.

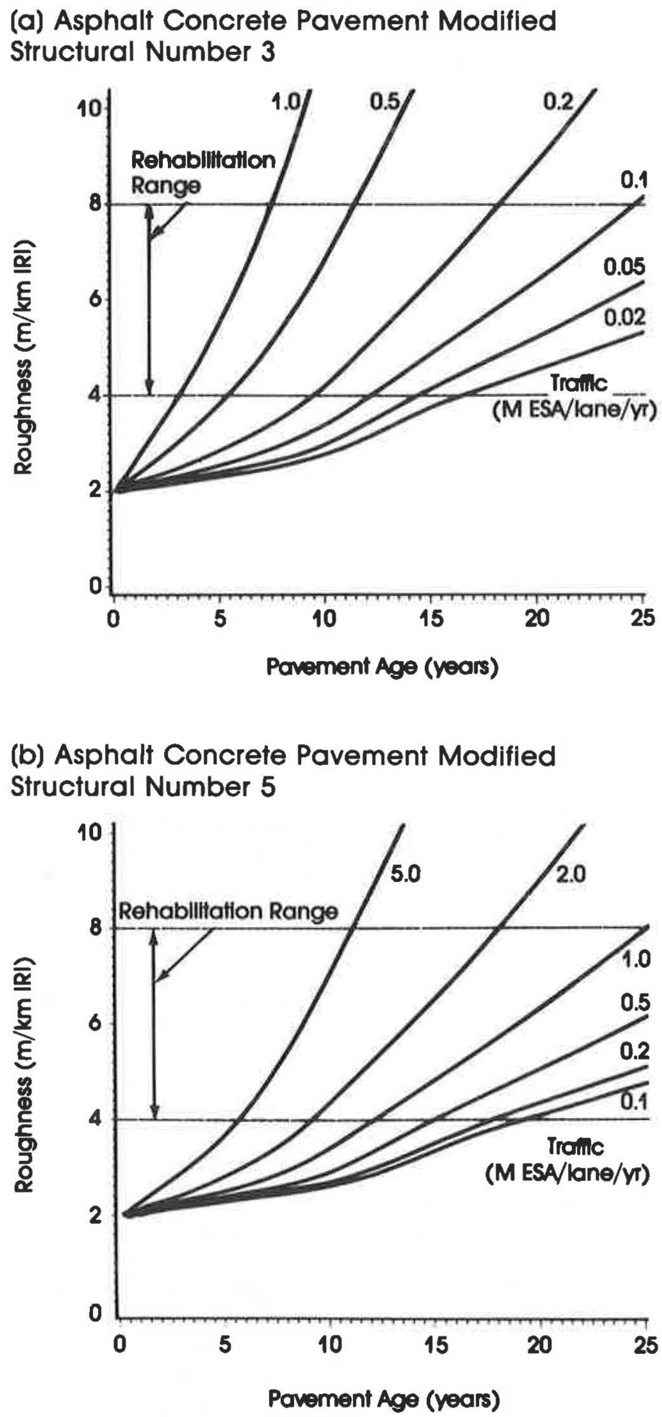
The parameter coefficients have been found to transfer well to other circumstances, through a detailed validation exercise in which the model was applied to data from seven countries or regions with climates and characteristics widely different from those in the Brazil study, as described elsewhere (*4*). These areas included Arizona, Colorado, Illinois (the AASHO Road Test), and Texas in the United States, Kenya (two), South Africa, and Tunisia. Thus, the values of the coefficient m, presented in Table 5, were derived from climates ranging from arid- to humid-nonfreezing and from arid- to humid-freezing, but did not include regions of very high rainfall (i.e., more than 2,500 mm per year).

Predictions and Damage Causes

Examples of the predictions of roughness progression given by the incremental model of Equation 3, using distress data generated by empirical models (*3,4*), are presented in Figure 5. Two pavement strengths are shown, with six levels of traffic loading on each and minimal maintenance of patching all potholes. The curves show clearly differing trends that reflect the impacts of the different traffic loadings and surface distress on roughness. At extremely low, negligible traffic levels, roughness nevertheless increases because of the effects represented in the environment-age component; the rate of increase depends on the environment coefficient m and the initial roughness level. At higher traffic levels, the rates of roughness progression are both higher and also changing more rapidly due to the impact of surface distress.

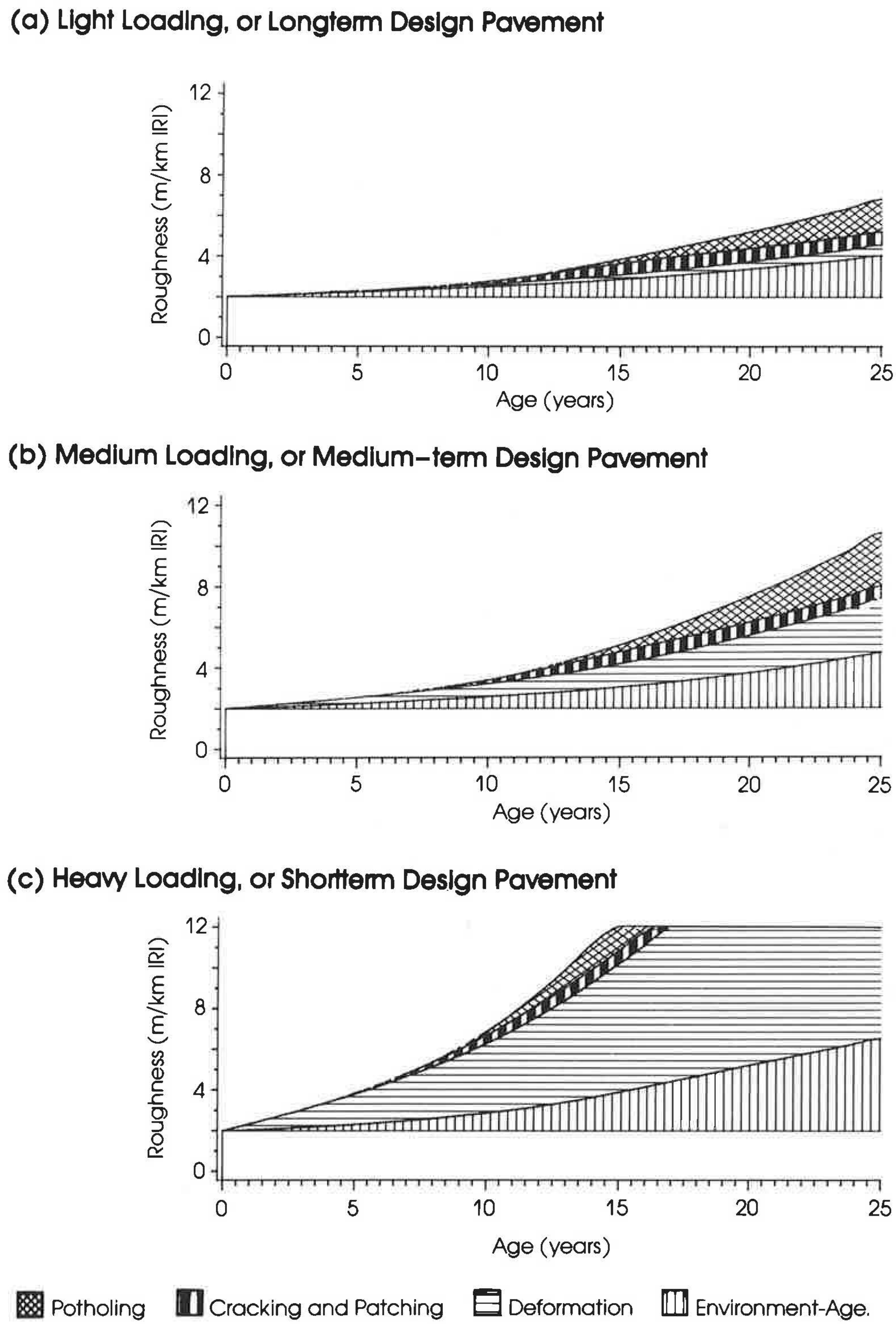
All the curves have a generally convex shape, with the rate of roughness progression increasing as the levels of roughness and surface distress increase. The rates reach about 10 percent per year in the case of normal design (e.g., 100,000 ESA per year for SNC 3) and 20 percent per year for the overloading/underdesign cases (e.g., five times more traffic), which are plausible in relation to most other reported studies.

The differing contributions made by the various causes of roughness are illustrated in Figure 6 for one pavement under light, medium, and heavy traffic loadings (representing long-term, medium, and short-term design life cases, respectively). For this example, no maintenance is being applied, so the effects of potholing are evident. Under the light loading case in chart a, very little damage derives from the deformation or distress components. In the medium design case in chart b, the contributions from deformation, surface distress, and environment are more or less similar. In the case of overloading shown in chart c, the deformation component dominates the performance. In each case, the roughness in the first several years of the pavement's life increases slowly and almost linearly at a rate that depends on the design standard and the environment. The rate increases after cracking begins and becomes very rapid if potholing is allowed to progress in the absence of maintenance. Thus the consequence of short-term designs or overloading can be seen to be a very rapid disintegration in the later phase of the pavement's life, an almost L-shaped function, but one that is controllable by timely maintenance.



Note: Maintenance comprised patching of all potholes in the year in which they appeared.
Source: Equation (3) applied through Road Deterioration and Maintenance Submodel of HDM-III.

FIGURE 5 Roughness progression prediction curves for a maintenance policy of patching all potholes.



Note: Surface treatment on granular base pavement, SNC 3, with traffic loading of (a) 0.02, (b) 0.10, and (c) 0.50, million ESA/lane/year, respectively.
Source: Equation (2) applied through Road Deterioration and Maintenance submodel of HDM-III.

FIGURE 6 Illustration of component sources of roughness damage under different levels of traffic loading as predicted by model.

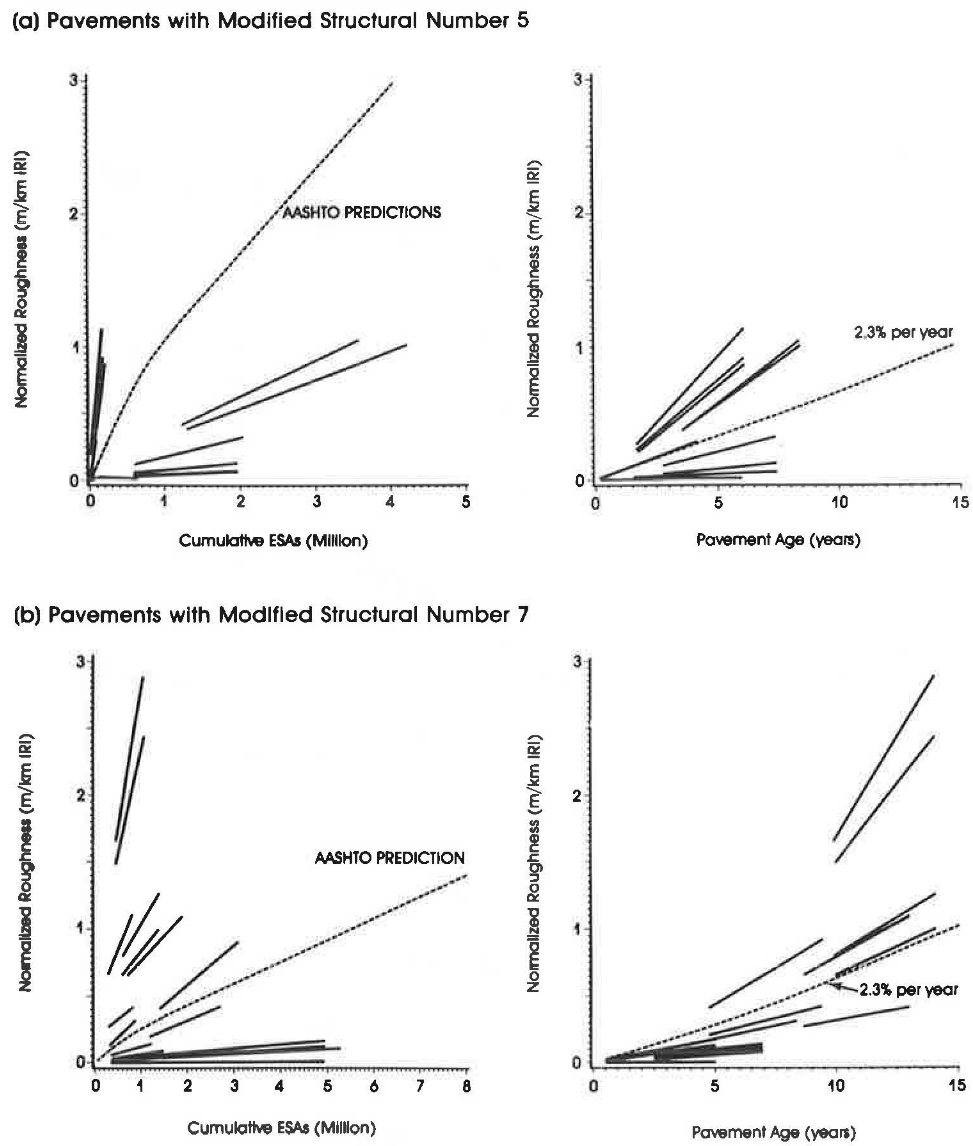
INFLUENCES OF TRAFFIC, TIME, AND STRENGTH

Traffic Loading and Pavement Age

The empirical evidence of the dual effects of traffic and time that supports the model is revealing and instructive. Figure 7 presents all the roughness trends observed in the Brazil-UNDP Study for two groups of pavements, each falling in a common flexible pavement strength category. The examples shown are asphalt concrete pavements with modified structural numbers rounding to 5 (a), and rounding to 7 (b). The roughness trends are presented as the increase of roughness since construction or rehabilitation, which normalizes the data across different pavements. The trends are shown against cumulative equivalent standard axle loadings in the left-hand charts and against age in the right-hand charts.

If roughness progression were a function only of traffic loading and pavement strength, as indicated by the traffic-related models, then all the trends in the cumulative loading charts would tend to be coincident within a reasonably narrow band. Instead, a broad scatter is noted, with some extremely rapid rates of progression at low levels of cumulative ESA and some extremely low rates at high levels of cumulative ESA. By way of comparison, the AASHTO predictions fall at about the center of the scatter, giving rates of 1 m/km IRI roughness increment per 1.3 million ESA and per 8 million ESA, respectively, for modified structural numbers 5 and 7.

On the other hand, the same trends appear much more closely grouped when depicted in relation to pavement age,



Note: Normalized roughness = RI(t) - RI(0). Trends shown as straight lines for clarity. Each group comprises pavements with SNC values rounding to the nominal value, e.g., 4.5 to 3.5 for SNC 5.
Source: Brazil-UNDP study data.

FIGURE 7 Comparing effects of traffic loading and aging on roughness progression observed in Brazil.

as seen in the age charts. The trends cover a range of about 1 to 3 percent growth per year and can be compared with the statistically estimated overall trend of 2.3 percent per year shown on the charts. The correlation is not perfect because both traffic and age are influencing the roughness, but the improvement over the correlation with traffic is clear.

The evidence is thus compelling that aging effects were strong in the data and explain a sizeable proportion of the roughness trends observed. Similar effects were evident on surface treatment pavements, although the patterns were less pronounced. Thus it is imperative that predictive models include both traffic and aging effects if they are to be reliable and applicable for the wide range of circumstances usually extant in a road network. In the case of the data illustrated in the figure, for example, the range of traffic flows in the SNC 7 pavement category was from as low as 1,000 ESA per year to as high as 2 million ESA per year, per lane.

Strength Parameter

The modified structural number was clearly the strongest predictor of the strength parameters tested in the roughness progression models. The Benkelman beam surface deflection, which is moderately correlated with the modified structural number, was not statistically significant in the deformation term of the component incremental model but did yield a fair alternative to *SNC* in a model of absolute roughness (*4*). Although the modified structural number itself has deficiencies as a strength parameter (because it is a thickness index that is somewhat insensitive to material properties and layer configuration), no improvement to the *SNC* formulation could be estimated from the data.

One inference is that surface deflection, while being an excellent indicator of relative strength along a nominally homogeneous pavement, is apparently not sufficient as a strength comparator to provide satisfactory predictions of roughness across different pavements and conditions. The reason for this is that material stiffness is not a sufficient indicator of deformation potential across different materials, although it is of course a good indicator for any one material, because deformation depends on the shear strength of the material as well as the induced stresses. Thus surface deflection, which aggregates the material stiffness effects under essentially common stress levels, is inferior to a parameter such as structural number that accounts for both shear strength and induced stress level through the material-layer coefficients utilized in its computation.

The Dynaflect deflection indices of maximum deflection and curvature proved to be yet weaker indicators of roughness progression, although having fair correlations to both the Benkelman beam deflection and structural number; and no statistical models for roughness progression could be found. Apparently, the stiffness derived under the low stress levels induced by this method are even further removed from the deformation behavior of the pavements than those under the heavier loading of the Benkelman beam method. While Falling Weight Deflectometer (FWD) deflection data were not available in the study, available evidence indicates that FWD deflections equal Benkelman beam deflections as a first approximation for equivalent levels of loading (*4*, p. 143).

CONCLUDING COMMENTS

This paper has focused on the conceptual and statistical development of the roughness model and its characteristics. The model advances understanding of roughness progression through identifying and quantifying the different mechanisms or sources of roughness change, namely, structural effects, surface defects, and environmental-aging influences. The scope, size, quality, and factorial design of the database from the Brazil Road Costs study made the analyses feasible, and the combination of mechanistic principles and empirical estimation make the model robust.

The robustness and versatility of the model are best demonstrated by its validity for conditions and environments other than the original Brazilian study, and a detailed evaluation has been made elsewhere (*4*). The estimation of the environmental coefficient (Table 5) and the evaluation of the model's transferability were made on data from major field studies in Arizona, Texas, Illinois, Colorado, Kenya (two), South Africa, and Tunisia, covering a range of climates including dry-nonfreezing, dry-freezing, wet-freezing, and wet-nonfreezing. Thus, the environmental factors given in Table 5 are considered applicable in the United States and elsewhere, at least as a first estimate. Further research may help to define better the environmental categories, particularly for high-rainfall climates (more than 2,000 mm per year).

The model leads to interesting interpretations concerning, *inter alia*, the attribution of damage and cost allocation among users. High-standard pavements (the long-term design case in Figure 6a) suffer small levels of damage, but high proportions of that damage are attributable to non-traffic factors, including the environment (*4*). The impact of different maintenance strategies can be evaluated through the influence of surface defects on the rate of roughness progression. The model is thus useful as a general damage model in addition to its use for predicting roughness progression.

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