

# Summary Models of Paved Road Deterioration Based on HDM-III

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Two generalized models predicting roughness progression in flexible pavements are developed from the comprehensive and widely validated set of incremental and interactive pavement distress functions in the Highway Design and Maintenance Standards model. These are summary models intended for use in pavement management applications and as a performance model for pavement design. The first retains most of the powerful capability of the original incremental model and has a very close fit to it, using traffic loading, strength, age, environment, rutting, cracking, and patching to predict roughness at any pavement age. Variants, which can be used when one or more of the distress parameters are missing, are also presented. The second model is simpler and generally structural, omitting surface distress parameters and compensating for this through the primary structural, traffic, age, and environmental factors. It is adequate for use where moderately good maintenance standards are being applied but has an error six times larger than the full model when extended over the full range of distress.

Developing balanced expenditure programs for a highway network requires predicting the rate of deterioration of the pavement and the nature of the changes in its condition so that the timing, type, and cost of maintenance needs can be estimated. A deterioration model, or pavement performance model, is therefore a key component of the analysis supporting decision making in pavement management.

If the model is to be useful for evaluating the primary options available in maintenance and rehabilitation, it must show explicitly the primary effects of traffic, pavement strength, age, distress, and environment on the trend of condition. Then the tradeoffs between the intervention options of minimal maintenance, patching, resurfacing, or strengthening at different times and condition levels can be properly compared. This is particularly true if the model is to be used also for estimating the cost-share of various classes of road user. Many models of roughness or cracking developed from local performance data, however, are either time-based models or forced to be traffic-based because they can capture only limited effects. Such models are generally incapable of distinguishing all the desired factor impacts and are applicable only in limited conditions.

The search for a mechanistic pavement performance model has been elusive because the causes of pavement deterioration are complex; interaction between different modes of surface distress and maintenance inputs influences the progression of rutting and roughness, as do aging and the environment. The Road Deterioration and Maintenance submodel of the World

Bank's Highway Design and Maintenance Standards model (HDM-III) (1) is a comprehensive model that comes close to this goal because it quantifies these interactions and predicts all modes of distress and the impacts of maintenance. Formulated on mechanistic principles and developed from a broad empirical data base of a major international study, the model has been widely validated on data from several countries and has proved to be highly transferable (2). It provides detailed life-cycle simulation of physical conditions within a full economic evaluation model and has been applied in pavement management, highway planning, and highway economic evaluation in more than 40 countries.

The submodel quantifies all the primary effects, including the concurrent effects of trafficking and aging through an incremental recursive approach, calculating the change in each mode of distress sequentially for each year of the analysis period. Such a simulation approach requires an appreciable amount of computing time and capacity when applied to a large number of pavement sections and technical options, which is typical for network-level programming of maintenance and rehabilitation. Applications of HDM-III to pavement management for thousands of pavement sections have been limited by this time requirement. Thus, there is a strong need for simpler algorithms that approximate the primary effects captured by the full recursive model and permit rapid prediction of pavement roughness from a small number of primary parameters. If the reduced predictive accuracy has a negligible impact on the technical strategies chosen, then the improvement in computational speed will be highly advantageous.

The purpose of this study, therefore, was to develop summary algorithms for predicting pavement roughness that would be universally applicable and serve as a primary performance model for pavement management forecasting or a pavement design method. Basing these on the HDM-III model makes the results of that major international pavement research more generally available and produces a simple alternative for HDM users that is largely compatible with the full HDM-III model. The summary model is to predict absolute roughness rather than incremental roughness so it can serve as an independent performance model.

## MODELING APPROACH

In the HDM-III submodel, the pavement condition and change in condition are predicted year by year in the model for each mode of distress in the following sequence:

1. Surface age for initiation of all cracking (of width 1 mm and wider) and the increment in area of all cracking (if either

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the age is greater than the initiation age or cracking is already present), which are functions of surface type, annual equivalent single axle loads (ESALs), and pavement strength;

2. Initiation and increment in area of wide cracking (wider than 3 mm) similar to Item 1;

3. Initiation and increment in area of raveling (loss of surface stone), which are functions of age and annual heavy vehicles (not ESALs);

4. Initiation and increment in total area of all potholes, which are functions of existing surface distress and annual vehicles (not loading);

5. Increment in rut depth (mean and standard deviation), which is a function of the strength, ESALs, age, cracking, precipitation, rehabilitation status, and pavement compaction; and

6. Increment in roughness, which is a function of strength, ESALs, age, environment, cracking, roughness, and changes in rut-depth standard deviation, cracking, potholing, and patching.

The net results of this deterioration simulation are curves for roughness that show a fairly distinctive two-phase character, as seen in Figure 1. Before cracking, the rate of roughness progression is relatively slow. It is driven by deformations related to structure and components related to environment but not to traffic. Under light loadings the structural component is extremely small but roughness continues to develop through the environmental-age component (moisture and temperature cycles). Under traffic loadings that are heavy relative to the pavement strength, the structural component is large. After cracking has initiated, the rate of roughness progression increases—and increases still faster when potholing begins. Patching largely, but not completely, compensates for the latter increase. More-detailed presentations may be found in works by Paterson (2,3).

At the time of the original model development, various summary model forms, including those of existing pavement performance models, were evaluated on the field data, but all were found to be significantly inferior to the detailed re-

cursive model that was finally developed. The various statistical reasons for this include

- The state of surface distress was found to have a profound effect on the roughness but was not included in traditional model forms and complicated the form substantially;

- Age had a significant effect on roughness progression, through environment and largely non-traffic-related effects in addition to traditional parameters;

- Both age and cumulative traffic loading affected the roughness but were themselves correlated, and the loading effect was diminished by the compensating influence of pavement strength, which made it difficult statistically to distinguish the main effects; and

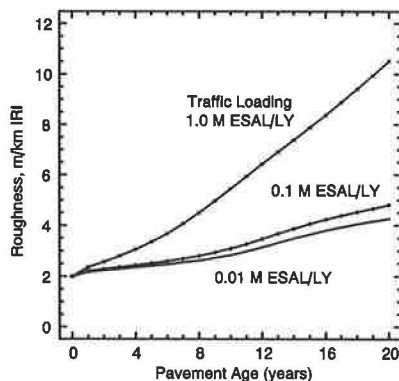
- Cross-sectional effects in the data, related to the different time windows and condition of the various pavements, confounded the estimation of traditional models such as the AASHTO performance model by producing a rate of deterioration that apparently decreased over time but conflicted with the shape of the time-series data for the individual sections that showed distinctly increasing rates.

Although a model was derived from the field data after resolving those problems [see a detailed discussion by Paterson (2)], experience has shown that it contains significant bias and has limited reliability compared with the full stimulation model.

## GENERATION OF DATA

In this study, therefore, an alternative approach is used to develop a summary model. The approach uses the full empirical simulation model to generate roughness data for a wide range of the primary parameters and estimates the summary models by fitting the generated data. The confidence in the generated data stems from the extensive verification of the empirical simulation model and the comprehensiveness of the interactive form of the primary parameters. Roughness data were generated using the new *RODEMAN* version of the *HDM-III* model. *RODEMAN* is a menu-driven PC version of the Road Deterioration and Maintenance submodel of *HDM-III* that produces the same detailed pavement results as *HDM-III*. It also includes simplified vehicle operating cost and other cost functions, which enable it to calculate the main economic parameters, although in less detail than *HDM-III*.

The actual data generated are discrete annual values of each parameter and distress mode as indicated in Table 1. Data were generated for an array of two pavement types (asphalt concrete and surface treatment flexible pavements) and three primary variables (pavement strength, annual traffic loading, and environment) for the side ranges shown in Table 2. Loadings ranged from 10,000 to 3 million ESAL/lane-year; strength from 2 to 8 modified structural number; and environment from arid, nonfreezing ( $m = 0.005$ ) to wet, freezing ( $m = 0.10$ ), where  $m$  is an environmental parameter. There were 33 combinations and a 20-year analysis period, resulting in 693 observations for each pavement type. For this application, the patching of all potholes as they appeared was adopted as the basic maintenance strategy.



**FIGURE 1** Example of roughness data generated by *HDM-III* [SNC = 3.0; wet, nonfreeze climate ( $m = 0.023$ ); LY = land year].

TABLE 1 EXAMPLE SUBSET OF DATA GENERATED BY HDM-III MODEL

SNC	Traffic veh/d	Loading M ESAL/ lane-yr	AGE (yr)	CRA (%)	CRW (%)	CRX (%)	RAV (%)	PHA <sup>1</sup> (%)	RDM (mm)	RDS (mm)	RI IRI <sup>2</sup>	PAT (%)	
3	1000	0.10	0	0	0	0	0	0	0	0	2.0	0.00	
			1	0	0	0	0	0	0	3.0	1.3	2.21	0.00
			2	0	0	0	0	0	0	3.4	1.4	2.28	0.00
			3	0	0	0	0	0	0	3.8	1.5	2.36	0.00
			4	0	0	0	0	0	0	4.1	1.5	2.43	0.00
			5	0	0	0	0	0	0	4.3	1.6	2.51	0.00
			6	2	0	1	0	0	0	4.5	1.6	2.59	0.00
			7	6	0	4	0	0	0	4.7	1.7	2.69	0.00
			8	12	3	8	0	0	0	4.9	1.7	2.80	0.00
			9	20	9	16	0	0	0	5.1	1.7	2.94	0.00
			10	31	19	26	0	0	0	5.2	1.7	3.09	0.00
			11	44	31	39	0	0	0	5.4	1.8	3.27	0.00
			12	59	45	54	0	0.03	5.6	1.8	3.47	0.03	
			13	72	61	68	0	0.04	5.8	1.9	3.68	0.07	
			14	82	74	80	0	0.06	6.0	1.9	3.87	0.13	
			15	90	85	89	0	0.07	6.2	2.0	4.06	0.20	
16	95	93	95	0	0.08	6.4	2.0	4.23	0.28				

1. Potholing area data shown is prior to patching, and is reduced to zero annually by the patching.  
 2. 1 m/km IRI = 63.36 inch/mi IRI.

Note: AGE = age of pavement since resurfacing, yrs; CRA = area of all cracking, %; CRW = area of wide cracking (3mm and wider), %; RAV = area of ravelling, %; PHA = area of potholing, %; RDM = mean rut depth, mm; and other terms are defined with eq. (1).

TABLE 2 COMBINATION AND RANGES OF PRIMARY PARAMETERS USED TO GENERATE CONDITION DATA

Environment	Surface Type	SNC	Surface Thickness	Traffic Loading (million ESAL/lane-yr)						
				0.01	0.03	0.10	0.30	1.0	3.0	
	AC	2	30	x		x				
		3	50	x		x			x	
		5	80		x			x		x
		8	100		x			x		x
DNF (0.005)	ST	2	12	x		x				
		3	12	x		x			x	
		4	15		x			x		x
		6	18		x			x		x
WNF (0.023)	A S F O R D N F A B O V E									
WF (0.100)	A S F O R D N F A B O V E									

Note: DNF = Dry, non-freeze; WNF = wet, non-freeze; WF = wet, freeze; ESAL = equivalent standard axle loadings (8,200 kg); AC = asphalt concrete; ST = surface treatment.

FORMULATION OF MODELS

In modeling the performance over the pavement life cycle, the important features to capture are the two phases of deterioration rate, before and after cracking, and the different mechanisms causing roughness. This complicates the formulation, but the original HDM-III algorithm does this well by relating the change in roughness to three separate mechanisms, namely,

incremental roughness = structural deformation (function of modified structural number, incremental traffic loadings, extent of cracking and thickness of cracked layer, incremental variation of rut depth) + surface defects (function of changes in cracking, patching and potholing) + environmental and non-traffic-related mechanisms (function of pavement environment, time and roughness)

Thus, the starting point for the new model formulation was the multiparameter incremental model for roughness (2,3) in

HDM-III and RODEMAN. The integral form of the model with respect to time is the following:

$$RI_t = e^{m[RI_0 + 134 SNCK^{-4.99} NE_t]} + 0.114 RDS_t + 0.0066 CRX_t + 0.16 PHV_t + 0.01 PAT_t \tag{1}$$

where

- RI<sub>t</sub> = roughness at pavement age t [m/km international roughness index (IRI)];
- RI<sub>0</sub> = initial roughness (m/km IRI);
- NE<sub>t</sub> = cumulative ESALs at age t (million ESAL/lane);
- t = pavement age since rehabilitation or construction (years);
- m = environmental coefficient (0.023 for wet, non-freeze climate in the original estimation);
- SNCK = (1 + SNC - F HS CRX<sub>t</sub>);
- SNC = structural number modified for subgrade strength;
- F = coefficient that was 0.0000758 in original incremental model and that in integrated form is ap-

proximated by half that value, that is, 0.00004 (see discussion in text);

HS = thickness of bound layers (mm);

CRX<sub>t</sub> = area of indexed cracking at time *t* (%), in which the areas of each class of cracking are weighted by the crack width (2 mm for narrow cracks and 4 mm for wide cracks);

RDS<sub>t</sub> = standard deviation of rut depths (mm);

PHV<sub>t</sub> = volume of potholing (m<sup>3</sup>/lane-km);

PAT<sub>t</sub> = area of patching (%).

The first terms, comprising the function in brackets, represent the primary performance function comparable to the AASHTO and other performance models in which roughness progression is purely structural and a function of cumulative traffic loading. However, unlike the AASHTO-type models, that term is a linear function of cumulative loadings because the acceleration of deterioration that occurs over time is reflected in the separate distress parameters of the model. Other noteworthy features are the time-environment factor,  $e^{mt}$ , which introduces a nontraffic time-related component, and the distress terms that introduce a component, quantifying the superficial effects that can be altered through surface maintenance. The mathematical form of Equation 1 is a slight approximation because the rutting, cracking, and pothole distress terms are traffic-dependent and ideally would have been within the bracketed function if the original incremental relationship had been purely integratable with respect to time. This is a second-order effect that would have required only a small change to the original incremental form and would not change the original coefficient estimates by much. The SNCK term is also an approximation because the cracking parameter, CRX, is both time-dependent and discontinuous, for which there is no simple integral form. A value half of the original estimate is a theoretically close approximation, that is, 0.00004.

The pavement performance model estimated directly from the field data in the original study (2) focused just on the structural-time term, as follows:

$$RI_t = e^{0.0153t} [RI_0 + 725 (1 + SNC)^{-4.99} NE_t] \quad (2)$$

The exclusion of the distress terms was a convenience for the user to avoid having to estimate all modes of distress. A subsequent estimation from generated data using the technique of this paper found values of 0.035 and 190 for the first two coefficients and kept the third coefficient fixed as -5 (4). In these cases, the models are compensating for the ex-

clusion of the other terms by major changes in the time-environment coefficient *m*, from -30 percent to +50 percent compared to the original value of 0.023. Because this misrepresents the distress effects as environmental, it is not satisfactory.

Two sets of models were formulated for the new estimation. In the first, the integrated form of Equation 1 was estimated to verify the coefficients and produce an absolute value version of the multiparameter roughness model that could be used in studies in which distress data could be used but only a single relationship was desired. Some variants of this, omitting certain terms, were developed for cases where not all distress parameters are available. In the second set, all effects were concentrated in the general structural performance terms, similar to Equation 2, and the variants sought to improve the fit and reliability of the model without introducing other distress measures. The models tested are given in Table 3. The statistical analysis program used was Statgraphics Versions 5 (5).

### MODEL ESTIMATES

The results of linear multiple regression for the full generalized model, including distress parameters, are presented in Table 4. Here it can be seen that Model A.1, which is a direct estimate of Equation 1, has coefficients extremely close to the original estimates and extremely tight, with standard errors of less than 0.2 percent of the coefficient. Only the patching coefficient is different in relative terms, but this is still numerically very small. The error of estimate of 0.084 m/km IRI of the model is very small, and the fit ( $R^2 = .9997$ ) is extremely tight. These inferences were confirmed by a study of the residuals. Thus, Model A.1 is considered a highly satisfactory absolute form of the original incremental model. It will have primary uses in deterioration prediction when cracking and rutting distress data are available and in design when the maintenance intervention level can be defined in terms of these parameters.

Other variants of the model in Table 4 represent cases in which some of the distress parameters are omitted. Model A.4 shows that the mean rut depth can be substituted for the standard deviation of rut depth with very little loss of precision. This is primarily because of the functional similarity of the algorithms in the HDM-III model, but there is also a generally high correlation in practice except where there are substantial differences in rut depth and variability between wheel tracks. Model A.2, which omits the rut-depth term, is

TABLE 3 SIMPLIFIED MODEL FORMS OF ROUGHNESS PROGRESSION

Name	Parametric Form	Range
A	$RI_t = e^{mt} [RI_0 + a(1+SNC-FHS\ CRX)^d NE_t + c\ RDS_t + d\ CRX_t + e\ PAT_t]$	$0 \leq CRX \leq 100$
B	$RI_t = e^{mt} [RI_0 + a(1+SNC)^d NE_t + c\ RDS_t + d\ CRX_t + e\ PAT_t]$	$0 \leq CRX \leq 100$
C	$RI_{t_{max}} = e^{mt} [RI_0 + a(1+SNC)^d NE_t]$	$0 \leq CRX \leq 5$
D	$RI_t = e^{mt} [RI_0 + a(1+SNC-FHS\ CRX)^d NE_t]$	$0 \leq CRX \leq 100$
E	$RI_t = e^{mt} [RI_0 + a(1+SNC)^d NE_t]$	$0 \leq CRX \leq 100$
F	$RI_t = e^{mt} [RI_0 + a(1+SNC-fHS\ CRX)^d NE_t]$	$0 \leq CRX \leq 100$
G	$RI_t = e^{mt} [RI_0 + a(1+SNC)^d NE_t]$	$0 \leq CRX \leq 100$
H	$RI_t = e^{mt} [RI_0 + a(1+SNC)^d NE_t^b]$	$0 \leq CRX \leq 100$

Note: Variable names are defined in text with Eq. (1).

TABLE 4 ESTIMATES FOR GENERAL MODEL WITH DISTRESS PARAMETERS

Model	erg0	esnk4	RDS	RDM	CRX	PAT	SEE	R <sup>2</sup>	D-W
A.1	0.980 <i>0.001</i>	132 <i>0.6</i>	0.143 <i>0.003</i>	-	0.0068 <i>0.0001</i>	0.056 <i>0.0003</i>	0.084	1.000	0.335
A.2	1.013 <i>0.002</i>	147 <i>1.0</i>	-	-	0.0090 <i>0.0001</i>	0.058 <i>0.0005</i>	0.147	0.999	0.241
A.3	0.990 <i>0.005</i>	187 <i>2.9</i>	-	-	0.0118 <i>0.0004</i>	-	0.471	0.989	0.233
A.4	0.984 <i>0.001</i>	130 <i>0.7</i>	-	0.046 <i>0.001</i>	0.0067 <i>0.0001</i>	0.057 <i>0.0003</i>	0.088	1.000	0.311
A.5	0.955 <i>0.006</i>	173 <i>3.8</i>	-	0.107 <i>0.005</i>	-	-	0.515	0.987	0.196

Notes: All coefficient estimates have significance level better than 0.00005. Italics = standard error of coefficient. SEE = standard error of estimate, m/km IRI. R<sup>2</sup> = adjusted coefficient of determination. D-W = Durbin-Watson statistic. Number of observations = 1274 for all models. erg0 = e<sup>m</sup> RI<sub>0</sub>. esnkf = e<sup>m</sup> SNCK<sub>f</sub>. F = f/100,000. RDM = rut depth mean. SNCK<sub>f</sub>, RDS, CRX, and PAT are defined with eq.(1). For model A.1 R<sup>2</sup> = 0.9997, and for Model A.4 R<sup>2</sup> = 0.9996.

also strong and shows that good predictions of roughness can be made by adding at least the amount of cracking to the structural factors in the prediction. Omitting the patching terms as well (Model A.3), however, greatly increases the error of prediction in the upper range when potholing and patching become substantial contributors to the level of roughness. Finally, adding just rut depth to the structural terms of the primary model, as shown in Model A.5, is satisfactory but poorer than any of the other forms. These observations are confirmed by the statistical analysis of variance of the variables in Model A.1.

Model forms that concentrate on the primary structural function and attempt to compensate for the development of surface distress and the effects of surface maintenance within the traffic, strength, or time terms are shown in Table 5. In Models D.0 to D.2, the impact of the degradation in effective structural number due to cracking (represented by the SNCK term with different values of the coefficient *F* of Equation 1) is shown, when all other distress parameters are omitted. In these instances, the power values of the structural number and traffic loading terms were held at the original values. It is evident that the fit is good but clearly poorer than the A-models in Table 4; standard errors range from 0.57 to 0.67 m/km IRI. The best of these models in fact is Model D.0, which shows no degradation effect in the structural number.

Study of the residuals shows that the predictions of the D-models degrade for extremes of heavy or light trafficking relative to the pavement strength. Model H shows, however, that the nonlinear form does not produce a better result than Model D.0, which has the original power values for strength and loading. But it does indicate a greater sensitivity of deterioration to the relative levels of pavement strength and traffic loading and approaches closer to the rho and beta parameters of the AASHTO performance model. This appears to indicate that the strong nonlinearity in the form of the AASHTO performance model of serviceability is primarily a surrogate for the concurrent development of other modes of pavement distress that accelerate the evolution of pavement roughness. The results for Model C, which was estimated from only observations with cracking less than 5 percent, show that the primary structural term in Model A.0 and Equation 1 is adequate and valid for predictions for the period before cracking occurs.

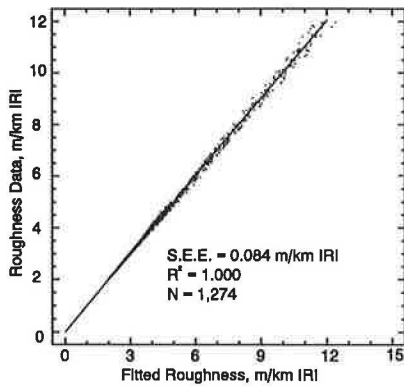
The results presented were derived from the combination of all the data generated according to Table 2. Separate estimations were also made for each pavement type, but the differences due to pavement type were not significant. The incidence of potholing and patching was highest in the surface treatment data, however, so that had a dominant influence in determining the coefficient of the patching term. This does

TABLE 5 ESTIMATES OF MODELS WITH PRIMARY STRUCTURAL FUNCTION ALONE

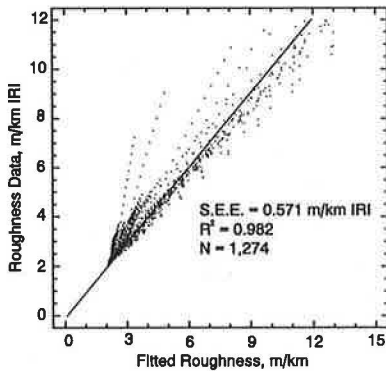
Model	erg0	esnk <sub>0</sub>	esnk <sub>4</sub>	esnk <sub>g</sub>	g	h	SEE	R <sup>2</sup>	D-W
C <sup>a</sup>	1.024 <i>0.002</i>	211 <i>4.8</i>	-	-	-5 <sup>b</sup>	1.0 <sup>b</sup>	0.106	0.999	0.403
D.0	1.039 <i>0.005</i>	273 <i>3.2</i>	-	-	-5 <sup>b</sup>	1.0 <sup>b</sup>	0.571	0.984	0.211
D.1	1.046 <i>0.005</i>	-	236 <i>3.0</i>	-	-5 <sup>b</sup>	1.0 <sup>b</sup>	0.606	0.982	0.218
D.2	1.056 <i>0.006</i>	-	-	201 <i>2.9</i>	-5 <sup>b</sup>	1.0 <sup>b</sup>	0.665	0.979	0.222
H	1.111 <i>0.012</i>	237 <i>73</i>	-	-	-6.89 <i>0.30</i>	1.786 <i>0.056</i>	0.878		

Notes: General notes as for Table 4. a. Valid for indexed cracking less than 5 percent of area, from 651 observations. b. Value of parameter was fixed as for original incremental model, not estimated. g,h. Coefficients are defined in Table 3, Models F, G, and H.





**FIGURE 2** Fit of best generalized model: full model with distress parameters (Model A.1; data include all values of pavement type, strength, loading, and environment).



**FIGURE 3** Fit of alternative simple model: basic structural model (Model D.0; data include all values of pavement type, strength, loading, and environment).

not imply that the deterioration models are overinfluenced by surface treatment pavements at all. In fact, it indicates that satisfactory performance predictions of roughness for a variety of pavement types and environments can only be made when the concurrent evolution of other modes of surface distress is included in the predictive model.

The predictive fits of the two best generalized models are shown in Figure 2 for the full model with distress parameters (Model A.1) and in Figure 3 for the basic structural model (Model D.0). It is evident that Model A.1 is superior in explaining the trends for the large majority of the factor combinations. The differences between the two that give rise to the respective predictive errors are apparent in the few combinations in which Model D.0 is under- or overestimating the rate of deterioration.

**PREFERRED MODELS AND THEIR USES**

For applications in which data or predictions of rutting, cracking, and patching are available, the recommended model is

A.1, namely,

$$RI_t = 0.98 e^{mL} [RI_0 + 135 SNCK_4^{-5} NE_t] + 0.143 RDS_t + 0.0068 CRX_t + 0.056 PAT_t \quad (3)$$

where  $SNCK_4 = 1 + SNC - 0.00004 HS CRX_t$ , for  $HS CRX_t < 10,000$ .

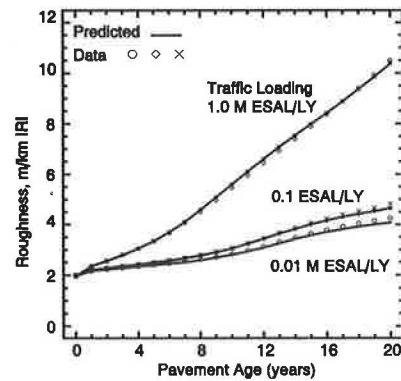
Predictions of this model for three levels of traffic loading are shown in Figure 4, alongside the observed data that were used to generate the model. The adherence of the predictions to the data is seen to be strong, and the model thus shows the change in roughness progression that occurs once surface distress commences, similar to the original model. Any valid predictions of cracking and rutting can be used with the model in Equation 3, because the underlying model is based on observed cracking and rutting behavior and is not dependent on any particular set of cracking and rutting models. Inputs from field data or other cracking and rutting models will produce a trend that differs slightly from that shown in the figure (which assumes the HDM-III and rutting predictions) and that will be more valid if the cracking and rutting inputs are more valid for the application than those from HDM-III.

When a general model is required without knowledge of the surface distress, then the preferred model is D.0, as follows:

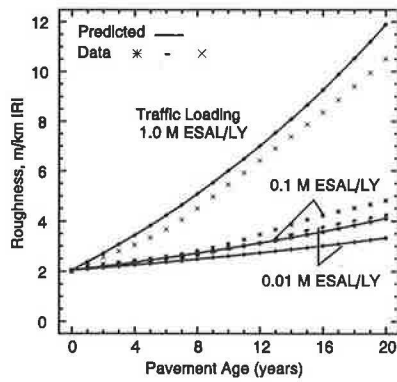
$$RI_t = 1.04 e^{mL} [RI_0 + 263 (1 + SNC)^{-5} NE_t] \quad (4)$$

Some predictions of this model are shown in Figure 5, also against the generating data to illustrate the adherence of the model to the originating trends. As the model does not account well for the impact of high levels of surface distress, it should preferably be applied for predictions of roughness of flexible pavements that are maintained at low amounts of cracking, up to about 30 percent (from a comparison of the model with the originating data).

Some guidance on quantifying the environmental effects is important to applications of Equations 3 and 4. First, the SNC value represents the in situ strength of the materials, not a conservative soaked value or design value. Thus, impacts of drainage on the California bearing ratio of the subgrade and



**FIGURE 4** Example of predictions from full model with distress parameters (Model A.1;  $SNC = 3.0$ ;  $m = 0.023$ ;  $LY = \text{lane year}$ ).



**FIGURE 5** Example of predictions from basic structural model (Model D.0; SNC = 3.0;  $m = 0.023$ ; LY = lane year).

modulus of the pavement layers should be included in the SNC value. Where strong seasonal variations occur, a weighting (by inverse fifth power) must be applied to obtain the effective annual average SNC value. Second, the value of the coefficient  $m$  varies with climate approximately as follows:

- Dry, nonfreeze:  $m = 0.005$  to  $0.015$  ( $0.010$ ),
- Dry, freeze:  $m = 0.010$  to  $0.035$  ( $0.020$ ),
- Wet, nonfreeze:  $m = 0.015$  to  $0.030$  ( $0.023$ ), and
- Wet, freeze:  $m = 0.030$  to  $0.150$  ( $0.070$ ).

The value increases with increased rainfall or diurnal temperature differences, and the values in parentheses are typical for the zonal classification. As it really represents the immediate environment of the pavement, the presence of specific environmental design provisions, such as material selection to avoid frost-susceptibility, free-draining materials, and sealed shoulders, are expected to be reflected by a reduction in the effective value of  $m$ . However, valid empirical guidance quantifying these effects is not available at this stage. The origin and further discussion of the  $m$ -values may be found in work by Paterson (2).

## CONCLUSION

The strongest summary performance model is that in Equation 3, which predicts the roughness of flexible pavements from traffic loading, pavement structural number, age, environment, rutting, cracking, and patching. It is a successful and very strong representation of the original incremental, multidistress model incorporated in HDM-III. It is useful when distress data are available in a road data base through road monitoring and when other predictive models for rutting, cracking, and patching are available. The validity of the predictions does not depend on the use of the distress models of HDM-III. The accuracy of fit was  $0.08$  m/km IRI for the

generated model, but the predictive accuracy overall for empirical data was about  $0.55$  m/km IRI (including the predictive error of the original model).

It is generally applicable to flexible pavements but most accurate for those maintained before the area of cracking exceeds about 30 percent. The overall predictive error for empirical data (taking into account the predictive error of the original model) is likely to be about  $1.0$  m/km IRI over the full range up to  $12$  m/km IRI, but the error reduces to about  $0.6$  m/km IRI for maintained pavements. Other model forms similar to the AASHTO performance model did not fit the generated data as well as the generalized model because of their exclusion of the nontraffic, environmentally related components.

The two summary models are suited for applications to pavement performance prediction in pavement management systems and economic evaluation analyses. On the basis of the wide validation of the originating HDM-III road deterioration model, especially its mechanistic component form, these simplified models too can be expected to be valid in most countries and environments. They are limited to flexible and semirigid pavements and are primarily valid for pavements with asphalt less than  $150$  mm thick. In addition to the published climatic effects on the environmental coefficient, drainage provisions may reduce the coefficients through their effect on the microenvironment of the pavement.

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