

Deterioration and Maintenance of Unpaved Roads: Models of Roughness and Material Loss

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Empirical models of deterioration for the management of unpaved roads have been developed. Successive cycles of roughness progression and maintenance bladings are represented as a cyclic process reaching a steady-state pattern. One model predicts the minimum, maximum, and average roughness as functions of traffic volume, road gradient and curvature, physical material properties, rainfall, and the interval between bladings. In a second model, the rate of gravel loss is predicted from similar variables. Both were estimated from extensive data collected in Brazil, and both are compared with data from several other countries in Africa and South and North America, showing a good degree of transferability. The models have been incorporated in the HDM-III model for highway strategy evaluation.

An economic evaluation of alternative maintenance strategies for the management of unpaved roads is dependent on a reliable quantification of deterioration and the effects of maintenance. The frequencies at which maintenance blading and gravel resurfacing should be applied are dependent on the economic trade-offs between the costs of the maintenance and the benefits to be gained from reducing road-user costs. So, too, is the economic break-even point for upgrading an earth road with an all-weather gravel surface, or an unpaved road with a durable pavement. Empirical prediction models of deterioration, therefore, need to quantify the effective rates of deterioration, not only as a function of traffic, but also as a function of road geometry, material properties, climate, and the maintenance applied.

The following modes of deterioration are of primary relevance to the management of existing unpaved roads:

- Road roughness, which affects vehicle speeds and operating costs and is controlled by managing the maintenance blading of the surface so that the costs of blading are offset by the savings in operating costs; and
- Surface material loss on gravel roads, which makes them susceptible to rutting under traffic and raises the risk of losing passability in wet conditions, and is thus a primary determinant of the timing of regravelling operations.

In addition to these, rutting, passability, and looseness are modes of deterioration that are largely controlled at the design or construction stage through the selection of the surfacing material type and thickness necessary to support the traffic loading.

The models of roughness progression and material loss are suitable for use in economic analysis models intended to evaluate the trade-offs between different maintenance and construction policies. These models are considered in the World Bank's Highway Design and Maintenance Standards model, HDM-III (1), which is used in many countries with widely differing climates and materials. Therefore, the aim was to make the models as universal and transferable as possible. The work described is part of a broad study of road deterioration (2), which contains a fuller description of the individual modes and models.

For a management model, the life-cycle of deterioration and maintenance of unpaved roads can be depicted by the trends of roughness and surfacing material thickness over time, as shown in Figure 1. Roughness tends to increase rapidly under traffic at rates that may vary by season, and roughness is reduced by maintenance blading; therefore, the effect is a cyclic sawtooth trend. The effectiveness of the blading may depend on the material, its moisture content (and thus the time since the most recent rainfall), the type of motor grader or towed blade, the skill of the operator, and the roughness before maintenance. The average gravel surfacing thickness will be reduced gradually through whip-off and ingress into the subgrade. Regravelling may be triggered when a minimum thickness is reached, at which stage the traffic may be punching through to the weaker, underlying roadbed soil, resulting in major depressions and unevenness.

ROUGHNESS

Previous Work

The first model developed for predicting roughness progression on unpaved roads was a simple bivariate polynomial relating the roughness at any point in time to the cumulative number of vehicle passes since the last major reshaping or blading. This model was developed by the British Transport and Road Research Laboratory from data collected in Kenya from 1971 to 1974 (3). The model had a cubic form with different coefficients for each material type, determined by statistical regression from the data. A later Kenya (4) study used a similar model form but reported different coefficients for each material. The prediction curves from both studies, shown in Figure 2, displayed generally concave shapes of an increasing progression rate, but some displayed linear or slightly convex shapes. Different rates and stages of change were

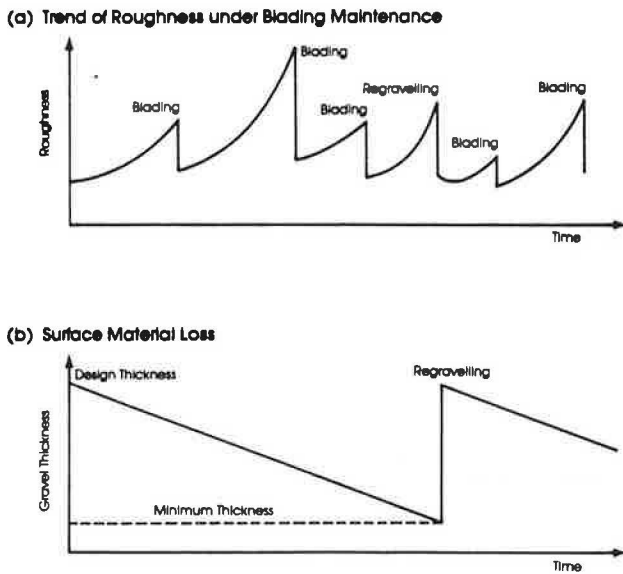


FIGURE 1 Trends of major deterioration modes of unpaved roads under maintenance.

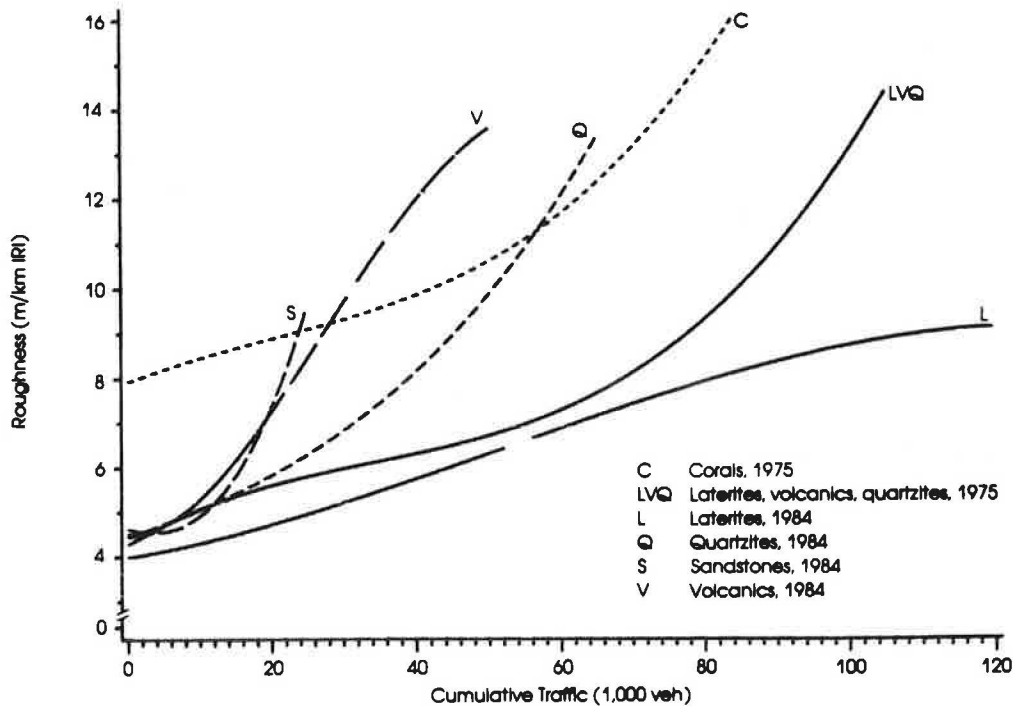
observed for different materials and between studies for a similar material. The result of blading was modeled as achieving a constant level of roughness, regardless of previous conditions. This level was 4.3 m/km on the International Roughness Index (IRI) for lateritic, quartzitic, and volcanic gravels, or 7.9 m/km IRI for coral gravels. Although material properties were measured, none were included in the models; thus, use of the models for other materials and other conditions was unreliable.

A wider range of material types, traffic volumes, and road geometries for unpaved roads was monitored in a major study sponsored by Brazil, UNDP, and the World Bank. The study involved road costs in Brazil from 1976 to 1981 (5). Visser (6) developed from the data an exponential (concave) model that was bounded by an exogenously imposed maximum roughness. A logit model form had also been estimated satisfactorily, but the exponential model was preferred for its computational simplicity. Visser also used an exponential form for modeling the effect of blading on roughness.

The inclusion of some material properties and rainfall in the Visser models was a major advance toward transferability, and some validation has been reported (7). A serious drawback, however, was that the progression model significantly overestimated the roughness progression on roads with low blading frequency, because of the exponential form, as discussed by Paterson (2). Because low maintenance frequencies are common in developing countries, improvements to the models were sought through different model forms. In subsequent analysis of the Brazilian data, these forms were estimated with a greater variety of material properties and rainfall data than was previously used.

Data Characteristics

Unpaved roads develop roughness through deformation by shear, mechanical disintegration, and erosion of the surfacing material, caused by traffic and surface water runoff. Roughness levels range from 4 to 15 m/km IRI, but higher levels occur when potholes, deep erosion gullies, or large depressions are allowed to develop, particularly on short sections.



Note: Roughness conversion: $RI = 0.0032 RBI^{0.89}$ where $RBI = \text{mm/km TRRL Bump Integrator Trailer}$, and $RI = \text{m/km IRI}$.

FIGURE 2 Roughness progression for various materials in two Kenyan studies (3,4).

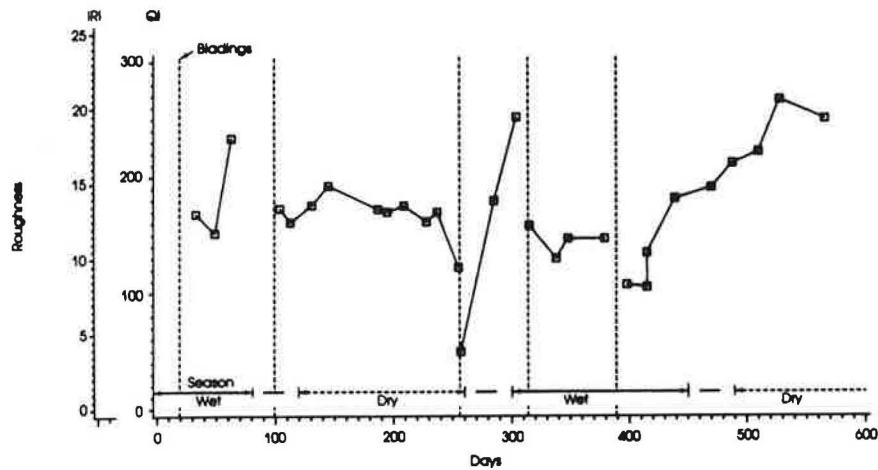
For the purposes of economic evaluation, the relevant roughness to be modeled is the profile in the prevalent wheelpaths of the traffic, since this influences the vehicle operating costs. As material properties, drainage, surface erosion, and the consequent location of the wheelpaths are variable, the roughness tends to be variable over time and the progression may not be regular.

Typical observations from the Brazil-UNDP study in Figure 3 show irregular patterns of both progression and blading effect. In some cases, an initial slight reduction in roughness results from a bedding-down effect under traffic, but a tendency to a convex trend shape is evident. Major differences in trend for any one road are evident between different cycles, some of which may be due to differences in weather. Also contributing to the irregularity is the high level of measurement errors (10 to 18 percent) found with response-type roughness instruments, which are the only type rugged enough

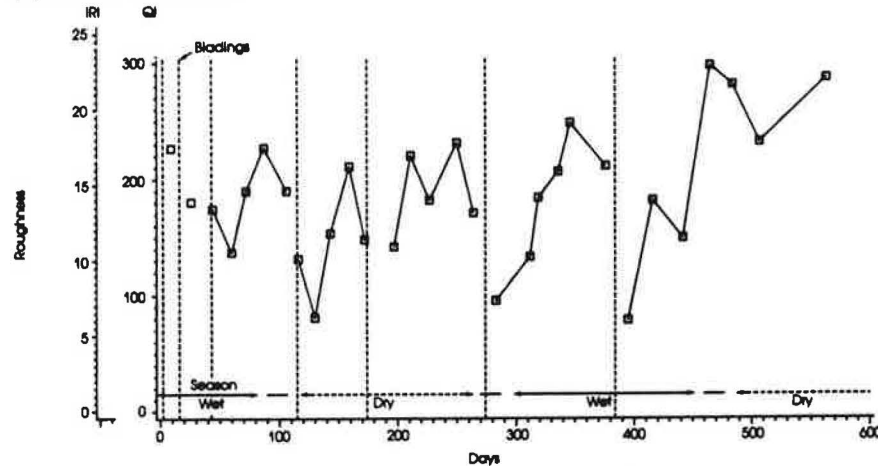
to measure unpaved roads. For these reasons, large data sets must be used for model development, to take advantage of the error-minimizing effect of numerous observations. The Brazil-UNDP data set consisted of 8,095 observations on 48 sections over 2 years; the summary statistics of the data is presented in Table 1.

Because the roughness trends and blading effects are so irregular, and because the management of unpaved road maintenance is best defined by a policy of scheduled regular maintenance rather than one that is responsive to condition, a prediction model should be responsive to the main factors that will influence the frequency of maintenance, and it should accurately predict the average trends and conditions, rather than an individual cycle. The cyclic nature of conditions favors a steady-state approach in which the average conditions over a medium-term period of 1 to 4 years may be predicted. Thus, a steady-state model was postulated in which the roughness

(a) Section 263 COM CS



(b) Section 259 COM CS



Note: (a) Traffic, 284 veh/day; grade, 0.6%; tangent; plastic quartzitic gravel. (b) Traffic, 156 veh/day; grade 0.8%, curved; plastic quartzitic gravel.

FIGURE 3 Examples of roughness progression in Brazil-UNDP study (5).

TABLE 1 RANGE OF THE UNPAVED ROAD
DETERIORATION STUDY IN BRAZIL (5)

Variable	Standard		Range		No.
	Mean	Deviation	Min.	Max.	
Gradient	3.8	2.6	0.0	8.2	48
Curvature on curved sections, km ²	3.9	0.9	2.5	5.5	29
Road width, m	9.8	1.09	7.0	12.0	48
Maximum particle size, mm	18.3	9.8	0.07	39	48
Percentage passing the 0.075 mm sieve	36	24	10	97	48
Plasticity index, %	11	6	0	33	48
Average daily traffic (both directions)	203	-	18	609	48
Time relative to start of regravelling (days)	238	211	0	1,099	604
Roughness (m/km IRI)	8.7	4.2	0.8	32	8,095
Number of days between bladings	110	95	2	659	1,044
Last number of vehicle passes since blading in each blading period	16,080	17,880	63	136,460	1,044
Mean annual precipitation, mm	1571	56	1,506	1,746	48
Monthly precipitation, mm	131	-	0	608	48
Moisture index	59	16	35	100	48

Source: Compiled from GEIPOT (1982), study data files.

progression and roughness reduction by blading effects were solved simultaneously, producing a direct estimate of the average roughness applying over the successive cycles.

To achieve a simultaneous solution, a number of constraints must be assumed. First, the maximum roughness was postulated to be a function of the material and possibly the road geometry and weather, rather than a constant value. For instance, the roughness on positive grades is frequently less severe than the roughness on level sections, where potholes and depressions form if drainage and crown are poor. Second, the relevant roughness was assumed to eventually become asymptotic to the maximum roughness because of the combined effects of vehicles finding alternative wheelpaths and slowing down, as is partly evident in Figure 3. Ideally, this assumption could have used a sigmoidal curve to incorporate the concave road behavior that sometimes occurs immediately after blading, but none was amenable to a mathematical closed-form solution. Moreover, the major part of the progression phase is linear by all intents, and the assumed trend is essentially linear within the central part, which is the phase of interest. Finally, the roughness after blading was modeled as a linear function of how close it was to a minimum roughness. This minimum roughness is conceived of as the best condition that can be achieved by a motor grader on that particular surface material and is therefore expected to be a function of the material properties of the surfacing, and possibly of the foundation.

At a steady state, when the roughnesses before and after blading remain essentially constant for a regular blading maintenance at a given interval, the mathematical solution of these functions [which is detailed in another study (2)] gives the following equations:

Roughness progression:

$$RG_b = RG_{max} - p(RG_{max} - RG_a) \quad (1)$$

Roughness after blading:

$$RG_a = RG_{max} + q(RG_b - RG_{min}) \quad (2)$$

The long-term average roughness can then be expressed as a unique function of the limits and the vector functions p and q :

$$RG_{avg} = RG_{max} + (RG_{max} - RG_{min}) \times \frac{(1-p)(1-q)}{(1-pq)\ln p} \quad (3)$$

where

$p = \exp(XT)$, such that $0 < p < 1$;
 X = vector of explanatory variables that is to be estimated;

T = time between maintenance bladings, and $T > 0$;

q = vector of explanatory variables to be estimated, such that $0 < q < 1$;

RG_b, RG_a = roughness before and after blading, respectively; and

RG_{min}, RG_{max} = minimum and maximum roughness limits, respectively.

Using the comprehensive Brazil-UNDP study data, which covered 1,044 blading cycles lasting from 2 to 659 days on 48 sections with traffic volumes ranging from 21 to 609 vpd, the parameters in Equations 1–3 were estimated as follows:

$$p = \exp\{-0.001[0.461 + 0.0174(ADL) + 0.0114(ADH) - 0.0287(ADT)(MMP)]T\} \quad (4)$$

$$RG_{max} = 21.4 - 32.4(0.5 - MGD)^2 + 0.97KCV - 7.64GMMP$$

and $RG_{max} \geq 12$ (5)

$$q = 0.553 + 0.230 MGD \quad (6)$$

$$RG_{min} = 0.361D95[1 - 2.78(MG')]$$

$$0.8 < RG_{min} < 8 \quad (7)$$

where

ADT = annual average daily traffic in both directions (vpd);

ADL, ADH = annual average daily light and heavy vehicles per day, respectively (vpd);

MMP = mean monthly precipitation (m/month);

T = time between bladings (days);

KCV = average horizontal curvature [km^{-1} ($1 \text{ km}^{-1} = 180\pi \text{ deg/km}$)];

G = average absolute longitudinal gradient (percent);

D95 = maximum particle size of surfacing material, defined by size with 95 percent finer (mm);

MGD = dust ratio of surfacing material, defined as (P075/P425) when P425 > 0, = 1 otherwise; and

MG' = $\min(MG, 0.36)$, where MG = mean material gradation, defined so that the optimum value of 0.5 is also the maximum, as follows: MG = $\min(MGM, 1 - MGM)$;

MGM = mean (MG075, MG425, MG02);

MG075 = $\ln(P075/95)/\ln(0.075/D95)$ when D95 > 0.4, = 0.3 otherwise;

MG425 = $\ln(P425/95)/\ln(0.425/D95)$ when D95 > 1.0, = 0.3 otherwise;

MG02 = $\ln(P02/95)/\ln(2.0/D95)$ when D95 > 4.0, = MG425 otherwise; and

P075, P425, P02 = percentages of surfacing material finer than 0.075, 0.425, and 2.0 mm, respectively.

The gradation indices, MGM and MG, are thought to be a rational and useful basis for relating a gradation by its proximity to a Fuller type of maximum density gradation.

The respective t values for coefficients of p are 2.9, 5.9, 5.7, and 4.2; for coefficients of RG_{max} are 15.5, 5.0, and 1.0; for coefficients of q are 13.0 and 4.0; and for coefficients of RG_{min} are 7.1 and 4.6.

Roughness Progression

The rate of roughness progression, represented by the parameter p , was found to be a function of traffic and rainfall, with no significant effects of material properties being found. The maximum roughness, RG_{max} , was found to be a function of material properties, road geometry, and rainfall, which are all characteristics of the road that are essentially independent of age, traffic, and maintenance. RG_{max} represents the potential roughness that the road could reach under no maintenance. Although material properties were not explicit in p , which is the fraction of the roughness range, they are implicit in the rate of progression through the boundary RG_{max} , which determines the level and range of potential roughness for those materials and road characteristics.

The statistics show that the model is well determined, and the scattergram in Figure 4(a) indicates that the predictions fit the observed data very closely (the scattergram requires careful interpretation because of the high density of multiple observations on the line of equality). Much of the remaining variance derives from differences between cycles, for which there are very few explanatory parameters. For planning and management purposes, the aim is to select the best policies for different roads, and the scattergram in Figure 4(b) (which removes the between-cycle variance) shows that the model does this extremely well, with a significantly better fit, a standard error down to only 0.9 m/km IRI, and no bias apparent between the three material classes. The model thus takes good account of the major factors influencing policy decisions.

Predictions for the model are shown in Figure 5. The maximum roughness, in Figure 5a, is highest in rolling or hilly terrain, particularly in dry climates; it lowers as the rainfall or gradient increases, presumably because the gradient facil-

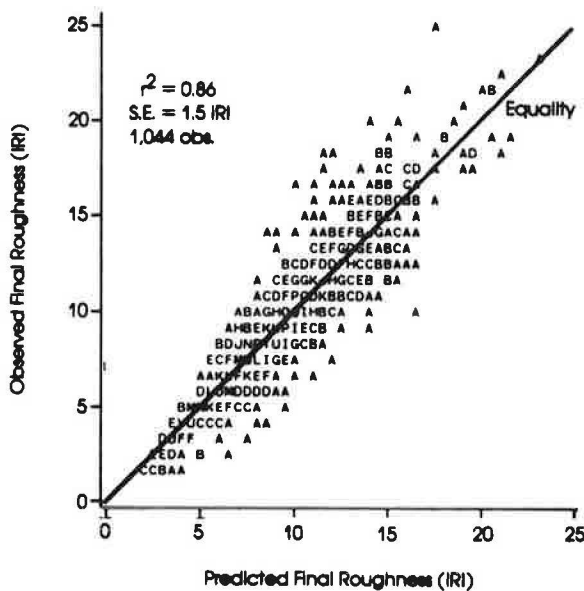
itates runoff of the surface water and because curvature accentuates transverse erosion (which influences roughness more than does longitudinal erosion of the roadway). Materials having a high dust ratio (i.e., clayey or poorly graded fines) appear to yield lower maximum roughness levels than well-graded materials, probably because earth roads tend to have lower roughness than gravel roads. The rate of progression, in Figure 5b, is dependent on traffic volume and is essentially linear in time or traffic over one-half to two-thirds of the roughness range. Light and heavy vehicles appear to have similarly damaging effects; the slight difference in the model is insignificant, which is a curious difference from Visser's models.

Effect of Blading

The model in Equations 6 and 7 indicates that the effectiveness of blading maintenance on roughness depends on the roughness before blading, the material properties, and the minimum roughness, RG_{min} . This minimum roughness, which is the minimum achievable by blading, was itself found to be a function of material properties, being least for fine materials and higher for coarse materials.

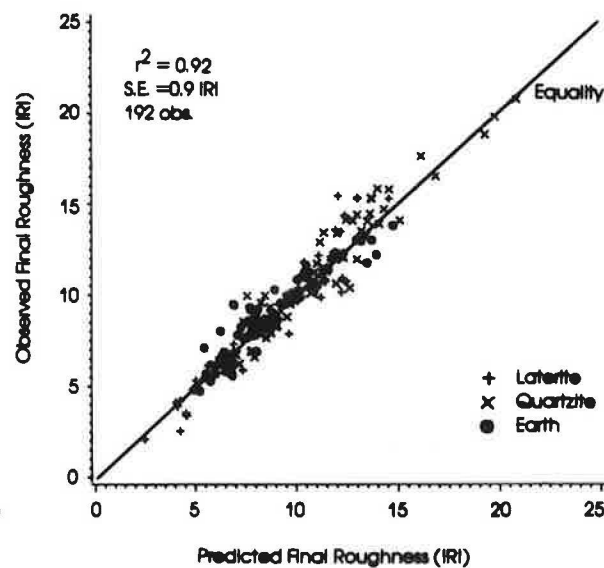
The model statistics and the goodness of fit indicate that the fit is as good as that of previous models. The variance derives largely from the operators' performance, because when the between-cycles variance has been removed for each section, the fit improves considerably to r^2 of 0.79 and the error reduces by 60 percent to 1.1 m/km IRI, or about the same level as for roughness progression. Lateritic and quartzitic gravels and earth surfaces are all well represented by the one model without undue bias. Details omitted because of space limitations may be found elsewhere (2).

(a) Progression: Full Sample



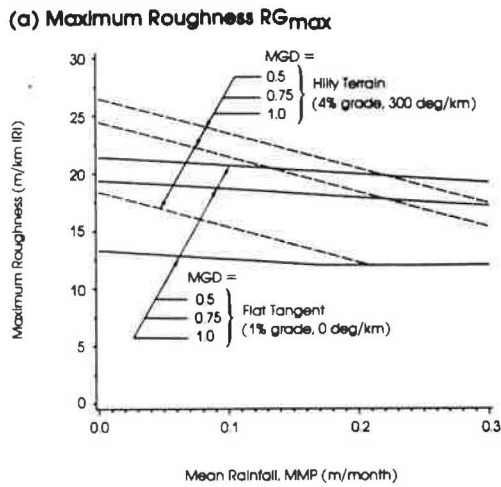
Note: Multiple observations: A =1, B=2, etc.

(b) Progression: Subsection Means

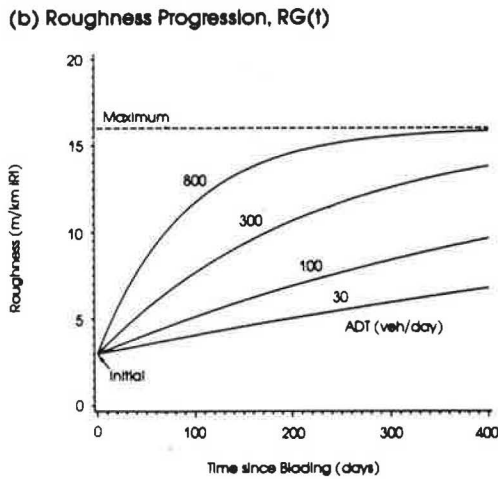


Note: Mean across all cycles of subsection.

FIGURE 4 Goodness of fit of model for roughness progression on one road, with and without the between-cycle variance.

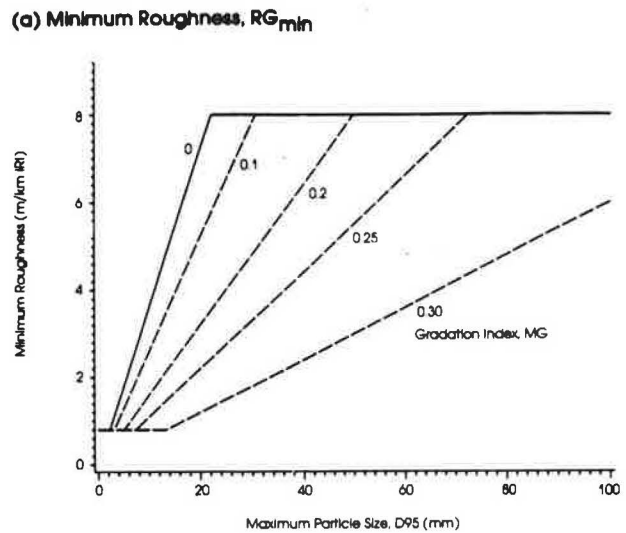


Source: Equation 1

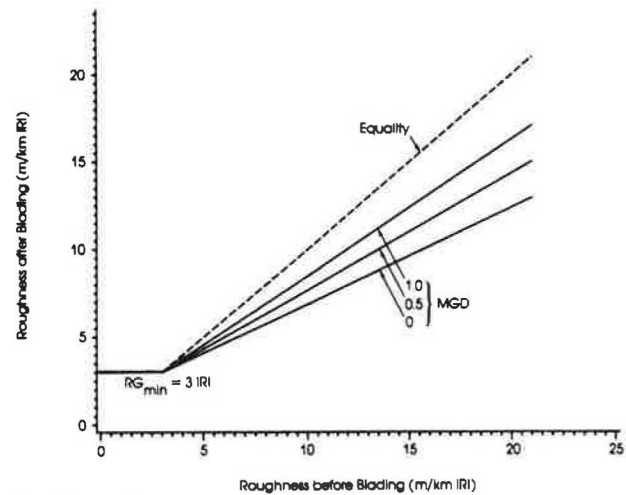


Note: MMP = 0.04 m/month; $RG_{max} = 16$ IRI
Source: Equation 1

FIGURE 5 Predictions of maximum roughness and roughness progression rates relative to traffic volumes.



(b) Blading Effect on Roughness: Example for $RG_{min} = 3$ IRI



Note: $RG_{min} = 3$ IRI, for example.
Source: Equation 2

FIGURE 6 Predictions of minimum roughness and blading effects.

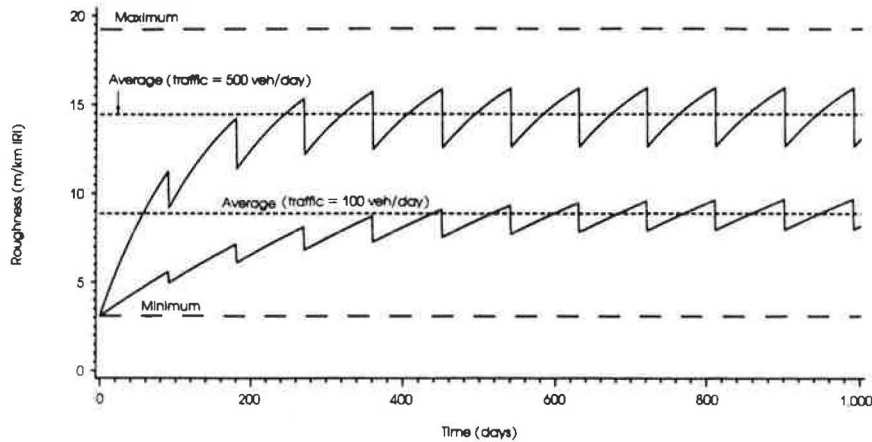
Typical predictions are shown in Figure 6. The minimum roughness, in Figure 6a, is quite sensitive to both the maximum particle size and the gradation of the material. Very low roughness levels can be achieved in fine or well-graded materials (e.g., less than 2 m/km IRI in all materials finer than 6 mm maximum size) or in well-graded materials ($MG = 0.25$ to 0.30) with a 20- to 30-mm maximum size. With poorly graded (MG less than 0.15) or very coarse materials, blading maintenance cannot reduce the roughness below 5 to 8 m/km IRI. The limits placed on RG_{min} were imposed to keep the predictions within the reasonable bounds of the inference space. The reduction of roughness achieved by blading, shown in Figure 6b, averages about 34 percent of the difference between the before-blading and minimum roughness levels, with only moderate sensitivity to material properties (ranging from 17 to 45 percent reductions as the dust ratio drops from 100 for clayey materials to 0 for sandy materials).

Predictions of Average Roughness Under Various Policies

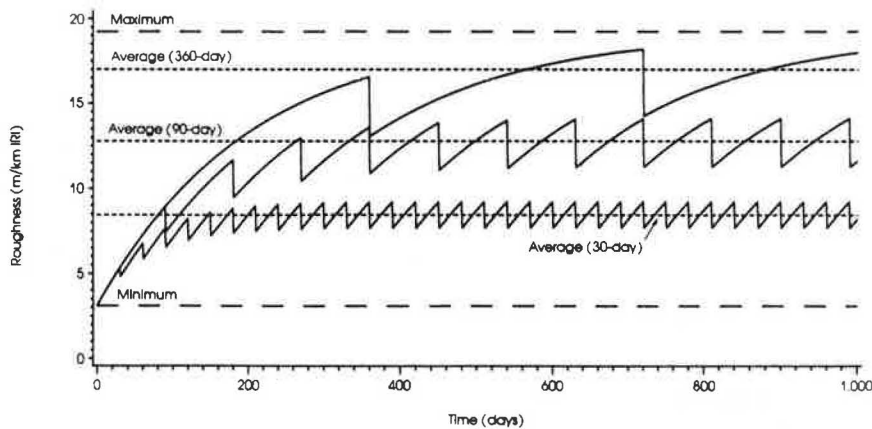
The roughness trends under regular blading policies, as predicted by the model, are illustrated in Figure 7 for (a) a road under regular 90-day blading maintenance and different levels of traffic, and (b) a road under different (30-, 90-, and 360-day) blading policies and one level of traffic. The surfacing material is a medium-sized ($D_{95} = 20$ mm), slightly plastic gravel with high dust ratio ($MGD = 0.80$) and moderate gradation ($MG = 0.20$).

Increasing the traffic volume under a constant blading frequency has the dual effect of raising the average roughness and advancing the time at which the long-term average is reached from the minimum possible roughness. Increasing the blading frequency lowers the average roughness and advances the time at which the long-term average is reached. The

(a) Effects of Traffic Volume under Regular 90-Day Blading Policy



(b) Effects of Blading Frequency for Traffic Volume of 300 Veh/Day



Note: Heavy traffic = 30% ADT; rainfall = 0.04 m/month; $RG_{max} = 19.2$ IRI; $MGD = 0.8$.

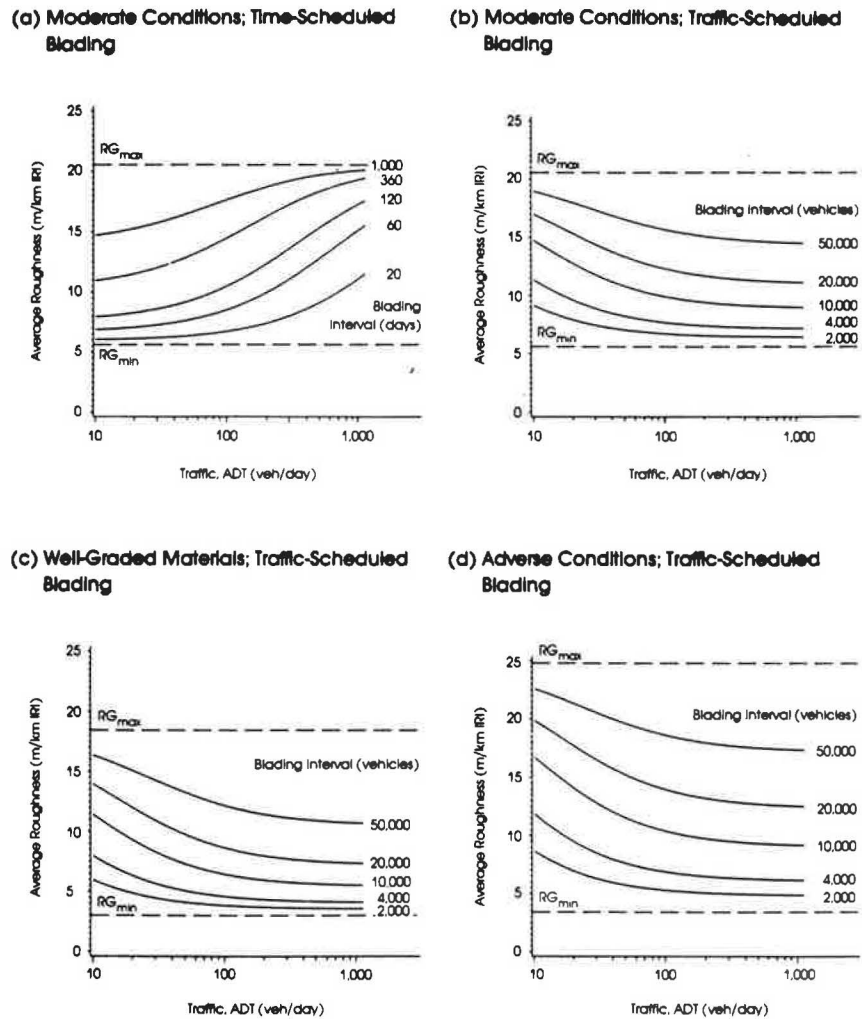
FIGURE 7 Predictions of roughness trends under regular maintenance.

roughness progression is essentially linear in most cases and only becomes noticeably convex at blading frequencies as low as once per year. Although the model is thus a reasonable approximation to reality for the long-term effects, the initial period of a slow rate of progression immediately following construction, recompaction, or deep blading (Figure 1) is not present, so that short-term effects may be poorly represented for such an initial cycle.

The average roughness predicted and the impacts of maintenance, traffic, and road characteristics are shown in Figure 8. The performance of an average case with moderate quality of materials, moderate climate, and moderate geometry, defined in Table 2, is illustrated in Figures 8a and 8b. The maintenance policy is scheduled by regular time intervals in Figure 8a, and in terms of the number of vehicle passes in Figure 8b. For traffic volumes of up to 200 to 400 vehicles per day (vpd) and bladings more frequent than every 120 days, the average roughness is relatively insensitive to either traffic volume or blading frequency. At higher traffic volumes or under less frequent blading, however, the average roughness levels

increase more sharply. When the maintenance policy is defined in terms of vehicle passes, as in Figure 8b, the average roughness appears more clearly to be virtually independent of traffic volume, except for low volumes. Economic analyses using the model (8) indicated that a policy of blading at intervals of about 4,000 vehicles is close to optimal.

The influences of material properties and road or climatic characteristics are shown in Figures 8c and 8d. With materials of good gradation (even fairly coarse materials of the 50 mm size) and moderate conditions of climate and geometry, the levels of roughness predicted by the model are relatively low, as shown by Figure 8c. For poorly graded materials and adverse conditions, such as an arid climate or strong curvature, the range of roughness levels tends to be much wider and relatively high, as shown in Figure 8d. By way of comparison, the maintenance policies needed to meet a standard of 12 m/km IRI average roughness under a traffic volume of 200 vpd require regular blading at intervals of 54,000 vehicles for the well-graded materials in Figure 8c, 22,000 vehicles for the moderate conditions in Figure 8b, and 16,000 vehicles for the



Note: The characteristics of the materials, geometry, and climate are defined in Table 3
 Source: Equation 3.

FIGURE 8 Predictions of average roughness under various maintenance blading policies for various material and road geometry conditions.

poor material and adverse conditions in Figure 8d. These requirements correspond to blading frequencies of 270, 110, and 80 days, respectively, or a range of maintenance costs varying by a factor of about three.

Transferability

The transferability and validity of the models were tested on data from Kenya (3,4), Ghana (9), Ethiopia (10), and Bolivia (11). The blading effects model (Equations 2, 6, and 7) was tested on data from Ghana (9), which had sufficient information for the model. Six roads covered a wide range of material properties: very poor to very good gradation ($MG = 0.13$ to 0.43), fine to very coarse maximum size (9 to 80 mm), 0 to 19 percent plasticity, 1090 to 1910 mm/year rainfall, and 6.9 to 12.2 m/km IRI roughness before blading. Using the linear model (Equation 2), the average bias in the predicted roughness after blading was only +5 percent; the prediction error was 15 percent or 0.88 m/km IRI for the section-

mean values. This accuracy is highly acceptable and even smaller than the estimation error of the original model (1.1 m/km IRI). By comparison, the Kenyan model prediction of 4.3 m/km IRI after blading is too optimistic for the Ghanaian data, which averaged 8.1 m/km IRI.

One test of the roughness progression model was on 186 km of lateritic gravel roads in the sub-Saharan country, Niger. With maximum stone sizes from 5 to 80 mm and roughness ranging from 5 to 11 m/km IRI, the predictions for the average roughness were accurate, within 7 percent of the observed averages, ranging from -6 to +7 percent (2).

Another test was on the data from 12 roads in four climatic regions of Ghana (9). These predictions, plotted in Figure 9, show a high correlation and close fit, with only a small bias causing the average of predictions to be 7 percent high. Individual predictions varied considerably (up to 40 percent different from the observed average); however, the overall prediction error was only 1.9 m/km IRI, which is similar to the error of the original estimation (Equations 4 to 7) and therefore as good as can be expected. Key data on the maximum

TABLE 2 PARAMETER VALUES USED IN EXAMPLES OF PREDICTED AVERAGE ROUGHNESS FROM THE STEADY-STATE MODEL

Parameter	Units	Road and climatic conditions		
		Moderate	Well-graded	Poor material
			material	semiarid, hilly
G		3	3	3
KCV	km ³	3	3	5
(curvature)	(deg/km)	(170)	(170)	(290)
MG		0.2	0.3	0.1
MGD		0.6	0.3	0.6
D95	mm	35	50	13
ADH/ADT		0.5	0.5	0.5
MMP	m/month	0.15	0.2	0.05
(rainfall)	(mm/yr)	(1,800)	(2,400)	(600)

Note: Parameter names defined in text.

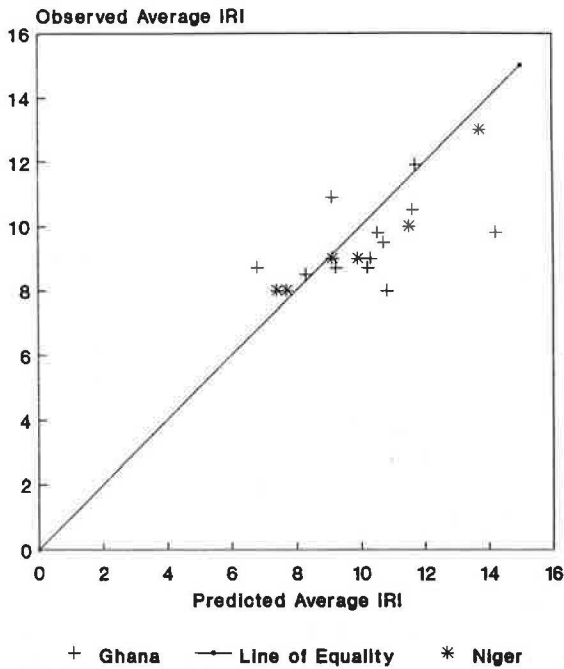


FIGURE 9 Comparison of observed and predicted average roughness and progression rates for Ghana and Niger.

stone size and blading timing were missing, which may partly account for the slight bias. The rate-of-progression predictions were consistent with the observations across climatic and material zones, although averaging 18 percent higher on a per-day basis, as shown in Table 3.

Analysis using data from Bolivia (11) indicated that the model predicted the rate of roughness progression well for a high traffic volume (1,700 vpd) and regular, repeated blading maintenance. However, for new surfaces during the initial stage of the first cycle after regravelling and compaction, the roughness rose slowly under traffic for the first 60 to 80 days, much more slowly than predicted by the model. At later stages, the model again predicted the rate of progression well both for high- and low-volume traffic (1,700 and 575 vpd). Binding and compaction of the surface may beneficially suppress roughness progression temporarily, and the model needs adjustment if it is to reflect that specific condition. Data and further discussion of this case are provided by Paterson (2, pp. 107–108).

In other studies of roughness progression, using data from Kenya and Ethiopia, the steady-state average roughness was usually difficult to determine from the reported data. The data, however, have a wide range of progression rates, ranging 7-fold on a per-vehicle rate from 0.05 to 0.37 m/km IRI (although most were in the range of 0.14 to 0.24 m/km IRI) per 1,000 vehicles, or 20-fold on a daily rate from 0.003 to 0.065 m/km IRI per day (4).

The progression model explained well most of the wide range of rates observed under different conditions through the material, traffic, and environment parameters, but it clearly applied primarily to roads under regular blading maintenance, even if at very low frequencies. The model apparently does not reflect the influence of maintenance compaction, which results in a much slower initial rise in roughness, as indicated most strongly by the Bolivian study. In the Brazilian study, bladings were performed frequently without special compaction, apparently resulting in a higher average progression rate; in the other studies, only one or at most five blading cycles were observed, and the roads generally began in a well-compacted and well-shaped state.

The progression model is, therefore, transferable in terms of material, traffic, and environment parameters, but it may tend to overestimate the rate of roughness progression when special treatment has been made to the running surface. The practice of compaction and providing cohesion to the surfacing material after major blading or regravelling, and the practice of providing a light running course of small stone, appear to reduce the rate of progression in a manner not reflected by the model. This effect was taken into account in the implementation of the model in the HDM-III model by the imposition of an arbitrary constraint on the first cycle. Future modeling work should quantify these effects. Future modeling should also possibly take a linear progression model form, as a compromise between the convex- and concave-shaped models, and focus on improving the estimation of the primary material and construction parameters that influence the performance.

MATERIAL LOSS

Regravelling is the major rehabilitation operation on unpaved roads, so the frequency required represents an important deci-

TABLE 3 VALIDITY OF PREDICTIONS FOR UNPAVED ROADS MONITORED IN GHANA

Road Sect.	Parameters ¹		Coefficients ²		Avg. Roughness		Daily Rate		Per-veh. Rate		
	ADH	RC _m	RC _m	p	q	RC avg.	IRI/100 d	IRI/100,000 veh.	Pred.	Obs.	
1G1	60	7.7	18	.80	.72	10.7	9.5	0.76	0.92	.18	.15
2G1	39	6.5	18	.84	.74	10.8	8.0	0.70	0.50	.15	.13
3G1	42	3.3	18	.83	.69	8.3	8.5	1.01	0.92	.27	.22
1G2	35	6.0	16	.86	.73	9.2	8.7	0.56	0.23	.21	.07
2G2	74	6.4	19	.80	.73	11.6	10.5	0.91	0.19	.10	.03
4G2	60	1.5	16	.82	.71	6.8	8.7	1.01	1.40	.24	.23
2G3	167	6.1	20	.61	.70	14.2	9.8	1.58	1.80	.09	.11
3G3	44	5.8	20	.83	.68	10.5	9.8	0.99	0.31	.23	.07
2G4	24	8.0	17	.88	.70	10.3	9.0	0.47	0.61	.28	.26
3G4	24	7.7	16	.88	.74	10.2	8.7	0.41	0.27	.35	.11
4G4	117	1.3	20	.74	.65	9.1	10.9	1.82	1.46	.17	.12
5G4	121	7.3	17	.74	.69	11.7	11.9	0.89	0.69	.09	.06
S.E.						1.86					
Average						10.2	9.50	0.92	0.78	.19	.13
Avg. error						+0.70					
Bias						+7.4%					

Notes. 1. Variables as defined in text. 2. Predictions based on maintenance of 2 bladings per year; roughness in IRI units of m/km (or ft/1000 ft) derived from car-mounted Bump Integrator data where 1 m/km ≡ 715 mm/km BI; Ghanaian data from Roberts (9).

sion. Gravel loss is defined as the change in average gravel thickness over a period of time. Gravel loss was evaluated for the interval between regravels, which initiated a new analysis cycle, or from the time of the first observation until a regravelling occurred.

Three major factors identified as affecting gravel loss were weathering, traffic, and the influence of blading maintenance. Material properties and road alignment and width influence the gravel loss generated by each of these factors. In the Kenyan study (4), no seasonal pattern existed in the data; this also appeared to be the case for the Brazilian data. Furthermore, seasonal influences do not have any practical implications, because the agency responsible for regravelling wishes to know its frequency in terms of years, and seasonal influences are of secondary interest.

Estimation of Model

The following relationship was estimated from the Brazilian data for predicting the annual quantity of material loss as a function of monthly rainfall, traffic volume, road geometry, and characteristics of the surfacing material:

$$MLA = 3.65[3.46 + 2.46(MMP)(G) + (KT)(ADT)] \tag{8}$$

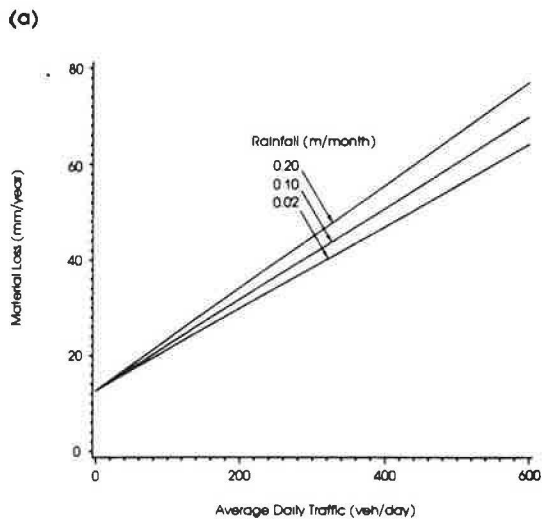
where

MLA = predicted annual material loss (mm/year); and
 KT = traffic-induced material whip-off coefficient, expressed as a function of rainfall, road geometry, and material characteristics.

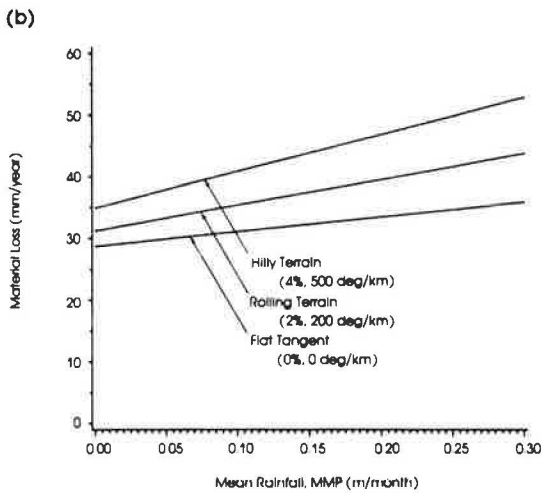
$$KT = \max\{0; [0.022 + 0.969(KCV) + 0.00342(MMP)(P075) - 0.0092(MMP)(PI) - 0.101(MMP)]\}$$

(r² = 0.313; the standard error was 49 mm/year; the sample consisted of 456 observations; and the t-statistics were 3.1 and 2.6 for the coefficients of MLA and 3.7, 1.1, 3.9, 3.0, and 2.8 for the coefficients of KT.)

Figure 10 shows the predictions for a surfacing material of slightly plastic, fine, silty gravel, showing the effects of (a) traffic and rainfall for flat terrain and (b) rainfall and geometry for a traffic volume of 200 vpd. The effect of traffic volume



Note: $P_1 = 10\%$; $P_{0.75} = 66\%$; $C = 50$ deg/km; $G = 0\%$



Note: $P_1 = 10\%$; $P_{0.75} = 66\%$; ADT = 200 veh/day;
Source: Equation 8.

FIGURE 10 Predictions of surface material loss related to traffic, terrain, and rainfall: *a*, effects of traffic and rainfall on flat terrain; *b*, effects of terrain and rainfall under 200 veh/day.

was found to dominate the rate of gravel loss, with the annual rate increasing linearly by about 10 mm for every 100 vpd increase in ADT, and the average rate being about 30 to 40 mm per 100,000 vehicles, depending on other factors. Increasing the horizontal curvature increased the loss rate through whip-off under traffic, but the effect was not large and amounted to only a 20-percent increase over the full range of curvature from 0 to 5.5 km^{-1} (0 to 300 degrees/km). Rainfall also affects the loss rate, but by amounts that vary with gradient and with the fines' plasticity of the material; for materials with more than 50 percent fines, the loss rate is likely to increase, and for others it may decrease. Typically, rainfall may increase the loss rate by about 10 percent per 100 mm/month of rainfall. An influence of blading maintenance on the loss rate could not be identified.

Transferability

Comparison of four studies on gravel loss provided conflicting evidence on the effects of road gradient and rainfall, but a broad similarity on the effects of traffic, as presented in Table 4. Very strong rainfall effects were shown in the Kenyan model; an increase of from 1,000 to 2,000 mm of rainfall per year caused a 200 to 400 percent increase in loss rate, but this is now believed to be an overestimate caused by the analytical method used. In the Brazilian model, the comparable rainfall effects are only 7 to 10 percent, and in Ghana, the effects were slightly negative. In all studies, the effect of increasing the road gradient was to increase the loss rate by about 16 percent for each percentage point of gradient, but road gradient interacted with the amount of rainfall, increasing the loss rate slightly as rainfall increased. A slight reduction of loss under light rainfall is probably caused by suppression of dust loss, and loss because of erosion becomes significant under heavy rain.

Loss rates are thought to be best expressed on a per-vehicle basis, although the Brazilian model separates the traffic-induced and erosion-induced sources of loss. When the results of Table 4, including the U.S. Forest Service studies (12), are normalized to a common basis of mixed traffic with 50 percent heavy vehicles, the loss rates range from 25 to 45 mm per 100,000 vehicles for gradients of 0 to 3 percent. These rates are similar to the 30 to 70 mm per 100,000 vehicles reported by Jones (4) from a comparison of seven African studies, including data on Ethiopia, Cameroon, Niger, and the Ivory Coast in addition to those mentioned here. Only the Brazilian model contains estimates of the influence of material properties.

The best consensus on a universal model that can be deduced from these studies is the following general model, which incorporates the major traffic, gradient, and rainfall effects, but excludes material properties:

$$GL = 10^{-5} [30 + 180(MMP) + 72(MMP)(G)](h)(ADT)(T) \quad (9)$$

where

- GL = average gravel or material loss (mm);
- MMP = mean monthly precipitation (m/month);
- G = average absolute gradient (percent);
- ADT = annual average daily traffic (vpd);
- h = proportion of heavy vehicles in traffic (fraction);
- and
- T = time period (days).

The form of the new Brazilian model shown in Equation 8 is, however, believed to be the most representative of all the underlying mechanisms, and future research should seek to improve the universal model along such lines.

CONCLUSIONS

The approach to modeling the roughness of unpaved roads as a cyclic phenomenon of progression under traffic and

TABLE 4 COMPARISON OF GRAVEL LOSS RATES FROM VARIOUS STUDIES (3-5.9.12)

Rate of gravel loss (mm per 100,000 vehicle units)						
for gradient (%) and annual rainfall (mm/yr)						
Study	Units	0%		3%		Percentage heavy vehicles
		1,000	2,000	1,000	2,000	
Brazil	V	30	32	39	43	50
Ghana	HV	(20-100)	(10-60)	40-160	(30-60)	*
	V	30	13	41	26	50
Oregon	AV	-	-	-	(240)	100 ¹
	V	-	-	-	(40)	50
Kenya A	V	(7)	(21)	(12)	(60)	(35)
	V	10	30	17	86	50
Kenya B	V	10	29	16	82	*

1/ Assumed value.

Notes: V = per 100,000 vehicles; HV = per 100,000 heavy vehicles when light vehicles are present but not counted; AV = articulated logging vehicles, rated as AV = 3 HV = 6 V. -, Not available. (*), Original data not adjusted for vehicle mix.

reduction under maintenance blading is a useful one for policy analysis. This approach provides a facility for predicting the average roughness levels under different maintenance blading frequencies and traffic volumes without having to resort to a year-by-year simulation process. The quantification of the influence of various material, road geometry, and rainfall factors in the model represents a significant advance in predictive capability and in the transferability of such a model.

The evaluation of the validity of the model against six independent studies in other countries indicated that the roughness after blading and roughness progression components explain the majority of effects and are sensitive to the major factors. However, there is an apparent tendency to overestimate the progression rate and the average roughness in the initial phase, when there has been compaction or other special treatment of the gravel surface. This tendency would result in a slight overestimation of the amount of maintenance input required for a given road, unless it is allowed for in the application of the model, as has been done in HDM-III, for example. The effects of compaction and transverse profile (crown) are outstanding issues that need to be studied and incorporated in future research and modeling efforts. A secondary issue is the model's shape: the convex shape of the progression curve concerns some, but the shape is virtually linear over the range of interest. The concave exponential model of Visser also has problems of overestimation under low traffic volumes. The most practical solution may be a linear progression model.

Material gradation, maximum particle size, and plasticity have all been shown to affect a road's performance significantly. A well-graded material, with small maximum size (but greater than 15 mm) and slight to moderate plasticity, yields the lowest roughness levels. The rate of roughness progression tends to be highest in dry conditions and is usually slower or sometimes negative (i.e., improving) under light to moderate rainfall. Significant variations in behavior on any given road occur from cycle to cycle of roughness progression and result from the operator's efficiency in the blading operations. These variations cannot be explained in detail by any of the models and must be regarded as stochastic variations.

The rate of gravel loss is influenced primarily by traffic volume, but the Brazil model indicates that small time- and rainfall/gradient-related elements that are independent of traffic also exist. Material, road gradient, and rainfall factors also influence the amount of loss caused by traffic, but only the Brazilian model quantifies the material property effects. Gradient has a generally positive correlation to loss rates, but evidence on rainfall influence is not entirely consistent across different studies and is probably fairly small, as indicated by this analysis of the Brazilian study.

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