Comparison of the Impact of Various Unpaved Road Performance Models on Management Decisions

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Over the last 5 years, maintenance management systems for unpaved roads, such as the Maintenance and Design System and Highway Design and Maintenance System, have become increasingly available. Detailed data requirements have, however, deterred many potential users from implementing these systems, especially for low-volume roads. Furthermore, these systems are based on deterioration relationships obtained from a study in Brazil, and the applicability to other areas has not been confirmed. Therefore, local relationships with good predictability and low data requirements needed to be developed. During a recent study in southern Africa, a new set of relationships was developed for the prediction of roughness deterioration and gravel loss for low-volume unpaved roads over time. These relationships are much simpler than the previous ones, thus fulfilling local needs. The new relationships were compared with the existing models. The effects of the different models on management decisions about annual gravel replacement were examined by comparing the results of each model as it evaluated a typical unpaved road network. The blading frequency was evaluated by the blading cost and total cost, including vehicle operating costs. On the basis of these findings, conclusions about the potential necessity for upgrading can be drawn. Road authorities worldwide must consider the applicability of models developed in one environment to other environments and the potential impact on management decisions.

The necessity for improved management of road maintenance is becoming increasingly important as road networks become larger and funding is reduced in real terms. Although this is a worldwide problem, it is probably more significant in developing areas, where unacceptably rough unpaved roads result in very high vehicle operating costs. Major drains on the economy often result from increased consumption of fuel, tires, and spare parts, which are generally imported. Valuable foreign exchange can be saved by providing adequate roads. In many developing countries, spare parts are often almost impossible to obtain, and failure of an essential component that cannot readily be replaced may render an important vehicle inoperable for an indefinite period.

During the past decade, a number of maintenance management systems have been developed. The Maintenance and Design System, MDS (*1,2*), was developed from data obtained in Brazil, and the Highway Design and Maintenance System, HDM-III, (*3*) was developed by the World Bank on the basis of data collected from a number of countries. The Road Transport Investment Model, RTIM2 (*4*), was developed by the Transport and Road Research Laboratory (United Kingdom) and is based on deterioration models developed mainly in east and west Africa.

The impact of a previously presented set of models (*5*) developed in southern Africa has been evaluated. These models predict roughness deterioration and gravel loss over time. The input requirements of the different sets of models were compared. The impact that replacing the Brazilian models in the MDS with the new models would have on management decisions such as budget requirements for regraveling, routine grader blading, and upgrading, was determined.

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DESCRIPTION OF NEW MODELS

The new models were developed from data collected during the monitoring of 110 sections of road in the Transvaal province of South Africa and Namibia over a period of more than 3 years. A factorial experiment, including a wide range of traffic, climatic, and material properties, has been described fully by Paige-Green (*6*). The background and methods were summarized at the 4th International Conference on Low-Volume Roads (*7*). The development of the set of models has been discussed previously (*5*), but subsequent analysis indicated that particle size distribution and its method of calculation affected the regression model. The particle size distributions were standardized, assuming a maximum size of 37.5 mm (*8*), and the models were reevaluated. Although the statistics and variables in the model did not change significantly, minor changes to the coefficients were necessary.

Gravel Loss Prediction

The best model for the prediction of gravel loss developed during the southern African unpaved roads study (*6*) was as follows:

$$\begin{aligned} \mathrm{GL} = {} & D[\mathrm{ADT}(0.059 + 0.0027N - 0.0006\ \mathrm{P26}) \\ & - 0.367(\mathrm{N}) - 0.0014(\mathrm{PF}) + 0.0474(\mathrm{P26})] \end{aligned} \tag{1}$$

[r^2 = 0.84; root mean square error (RMSE) = 5.3; n = 703; and F = 619] where

- GL = gravel thickness loss (mm);
- D = time period under consideration in hundreds of days (days/100);
- ADT = average daily traffic in both directions;
- N = Weinert N-value (9), which ranges from 1 in wet areas to more than 10 in arid areas and incorporates annual rainfall;
- PF = plastic limit × percentage passing 0.075-mm sieve; and
- P26 = percentage passing 26.5-mm sieve.

The t values were 3.72, 6.64, −3.63, −9.72, −4.50, and 17.84 for the respective coefficients. The Brazil study (*1,2*) resulted in a number of gravel-loss prediction models, the following model being the most useful:

$$\mathrm{GL} = D[1.58 + 0.366(G) + 0.083(\mathrm{SV}) - 0.210(\mathrm{PI}) + 0.0132(\mathrm{NC}) + 0.0081(\mathrm{NT}) + 420.45/R] \quad (2)$$

where

- G = absolute value of grade (percent),
- PI = plasticity index (percent),
- SV = percentage of the surfacing material passing the 0.075-mm sieve,
- NC = average daily car and pickup traffic in both directions,
- NT = average daily truck traffic in both directions, and
- R = radius of horizontal curvature (m).

HDM–III uses models developed from the data collected in Brazil to obtain the following gravel-loss prediction equation:

$$\mathrm{MLA} = 3.65[3.46 + 0.246(\mathrm{MMP})(\mathrm{RF}) + (\mathrm{KT})(\mathrm{ADT})] \quad (3)$$

where

- MLA = predicted annual material loss (mm/year),
- MMP = mean monthly precipitation (m),
- RF = road rise plus fall (m/km),
- KT = $\max\{0; [0.022 + 0.969/57{,}300(\mathrm{KCRV}) + 0.00342(\mathrm{MMP})(\mathrm{P75}) - 0.0092(\mathrm{MMP})(\mathrm{PI}) - 0.101(\mathrm{MMP})]\}$, and
- KCRV = curvature (degrees/km).

One of the main advantages of the new model is its simplicity compared to the existing models. Aspects such as the vertical grade and horizontal curvature, which need to be averaged for a road link, are excluded from the new model. No estimate of the rainfall is necessary, and the necessary laboratory testing is minimal. All the parameters required can be easily obtained by relatively unskilled staff in unsophisticated laboratories.

Roughness Deterioration

The best model determined for southern African conditions (*6*) to predict the change in roughness in quartercar index (QI) counts per kilometer was as follows:

$$\ln \mathrm{R} = D[-13.8 + 0.00022(\mathrm{PF}) + 0.064(\mathrm{S1}) + 0.137(\mathrm{P26}) + 0.0003(N)(\mathrm{ADT}) + \mathrm{GM}(6.42 - 0.063\ \mathrm{P26})] \quad (4)$$

($r^2 = 0.22$; $n = 7005$; RMSE $= 0.15$; $F = 288$)

where

- ln R = natural logarithm of change of roughness with time,
- D = number of days since last blading in hundreds (days/100),
- PF = plastic limit × percentage passing 0.075-mm sieve,
- S1 = season dummy variable (1 for dry season, 0 for wet season),
- P26 = percentage passing 26.5-mm sieve,
- N = Weinert N-value,
- ADT = average daily traffic, and
- GM = grading modulus (sum of percentages retained on 2.0-, 0.425-, and 0.075-mm sieves divided by 100).

The t values for the respective coefficients were −14.52, 6.86, 6.75, 14.22, 13.66, 13.72, and −13.29.

If a value of 100 counts/km is predicted for the change in roughness, the actual value will, with 95 percent confidence, lie between 74 and 135 counts/km.

The Brazil study (*1,2*) involved a program of extensive roughness measurements that resulted in the following model for the change in the natural logarithmic value of roughness (LDQ) in terms of the QI value in counts/km:

$$\mathrm{LDQ} = D\{0.4314 - 0.1705(\mathrm{T2}) + 0.001159(\mathrm{NC}) + 0.000895(\mathrm{NT}) - 0.000227(\mathrm{NT})(G) + S[-0.1442 - 0.0198(G) + 0.00621(\mathrm{SV}) - 0.0142(\mathrm{PI}) - 0.000617(\mathrm{NC})]\} \quad (5)$$

where

- T2 = surfacing type dummy variable (1 for clay, 0 for other),
- NC = average daily car and pickup traffic in both directions,
- NT = average daily bus and truck traffic in both directions,
- G = absolute value of vertical grade (percent),
- S = season dummy variable (0 for dry season, 1 for wet season),
- SV = percentage of surfacing material passing the 0.075-mm sieve, and
- PI = plasticity index of surfacing material (percent).

The model used in HDM–III was developed to constrain the tendency of these models to overestimate roughness at high levels under infrequent maintenance. The rate of roughness progression is decreased as roughness tends towards the maximum for a particular material. The result of this exercise was the following, somewhat complex, model:

$$\mathrm{QI}(\mathrm{TG}_2) = \mathrm{QIMAX}_j - b[\mathrm{QIMAX}_j - \mathrm{QI}(\mathrm{TG}_1)] \quad (6)$$

where

$QI(TG_1)$ = roughness at time TG_1 (QI counts/km);
$QI(TG_2)$ = roughness at time TG_2 (QI counts/km);
TG_1, TG_2 = time elapsed since last grading (days);
$b = \exp[c(TG_2 - TG_1)]$, $0 < b < 1$;
$c = -0.001[0.461 + 0.174\ ADL + 0.0114\ ADH - 0.0287(ADT)(MMP)]$; and
$QIMAX_j = \max[279 - 421(0.05 - MGD_j) + 0.22C - 9.93(RF)(MMP); 150]$ (for Section j)

where

ADL = average daily light vehicle traffic (<3500 kg) in both directions;
ADH = average daily heavy vehicle traffic (≥3500 kg) in both directions;
ADT = average daily vehicular traffic in both directions;
MMP = mean monthly precipitation (m/month);
RF = average rise and fall of the road (m/km);
C = degree of horizontal curvature (degrees/km);
MGD_j = material gradation dust ratio defined as $MGD_j = 1$ if $P425_j = 0$, and $MGD_j = P075_j/P425_j$ if $P425_j > 0$;
$P075_j$ = percent passing 0.075-mm sieve for Section j; and
$P425_j$ = percent passing 0.425-mm sieve for Section j.

In order to constrain the prediction model at high roughness values, the maximum value of the roughness is artificially limited to a QI of 150 counts/km. This value appears to be too low for the average unpaved road in rural and developing areas in southern Africa, although it may be defined as an acceptable limit before blading is necessary.

Roughness After Blading

The change in roughness needs to be related to a datum for use in a maintenance management system. For this purpose, a model to predict the roughness after blading (the starting point of roughness progression after each maintenance operation) was developed. The following model was the best obtained for southern African conditions (*6*):

$$LRA = 1.07 + 0.699(LRB) + 0.0004(ADT) - 0.13(DR) + 0.0019(LMS) \quad (7)$$

($r^2 = 0.62$; $n = 1601$; RMSE = 0.28; $F = 650$)

where

LRA = natural logarithm of roughness after blading (QI counts/km),
LRB = natural logarithm of roughness before blading (QI counts/km),
ADT = average daily traffic in both directions,
DR = dust ratio (ratio of percentage passing 0.075- and 0.425-mm sieves), and
LMS = laboratory-determined maximum size (mm), not greater than 75 mm.

The t values for the respective coefficients were 14.98, 45.99, 4.51, −2.67, and 3.23. The Brazilian model (*1,2*) for the roughness after blading is as follows:

$$LRA = 1.4035 - 0.0239(W) - 0.0048(SV) + 0.01694(PI) + 0.6307(LRB) + 0.1499(T1) + 0.3096(T2) + 0.00020(NT) + 0.2056(BS) - 0.01183(PI)(BS) \quad (8)$$

where

LRA = natural logarithm of roughness after blading,
LRB = natural logarithm of roughness before blading,
W = road width (m),
T1 = surfacing type dummy variable (1 if surfacing type is quartzite, 0 if other), and
BS = season during which blading occurred (0 if dry season, 1 if wet season).

HDM–III makes use of the following model:

$$QI_{(after)} = QIMIN_j + a(QI_{(before)} - QIMIN_j) \quad (9)$$

where

$QI_{(after)}$ = roughness after blading (QI counts/km),
$QI_{(before)}$ = roughness before blading (QI counts/km),
$a = 0.533 + 0.230\ MGD_j$,
$QIMIN_j = \max\{10; \min[100; 4.69\ D95_j(1 - 2.78\ MG_j)]\}$
$MG_j = \min(MGM_j, 1 - MGM_j, 0.36)$, and
$MGM_j = (MG075_j + MG425_j + MG02_j)/3$

where

$MG075_j = \ln(P075_j/95)/\ln(0.075/D95_j)$ if $D95_j > 0.4$, otherwise 0.3;
$MG425_j = \ln(P425_j/95)/\ln(0.425/D95_j)$ if $D95_j > 1.0$, otherwise 0.3; and
$MG02_j = \ln(P02_j/95)/\ln(2.0/D95_j)$ if $D95_j > 4.0$, otherwise $MG425_j$.

The Brazilian and HDM–III models require significantly more input, and the latter is especially cumbersome for developing areas. However, any of these models in association with the roughness progression models can be used to determine (a) the blading frequency necessary to retain the road roughness between upper and lower limits as required, or (b) economic efficiency by comparing the cost of maintenance with the road-user savings. However, the lower roughness limit is strongly dictated by the particle size distribution and plasticity of the wearing course material. The required roughness after blading may not always be achievable on roads with excessively oversized material or inadequate plasticity (i.e., those highly susceptible to the formation of rhythmic corrugations) through normal maintenance procedures.

Discussion of Results

An analysis of the applicability of the deterioration models for unpaved roads used in the different management systems indicated that the models developed outside southern Africa were not always applicable to southern African conditions (*6*). The average annual gravel losses for the sections monitored during the experiment were predicted as 13.0 and 21.8 mm by the Brazilian and HDM–III models, respectively; the actual measured value was 13.9 mm. The prediction of the average roughness was even further out, being 96.1 and 66.2 QI counts/km for the Brazil and HDM–III models, respectively. The actual average measured value was 80.0 counts/km. The new model predicted values of 13.1 mm and 77.4 QI counts/km for the average annual gravel loss and average roughness. The Brazilian model predicts the annual gravel loss accurately but differs from the roughness prediction considerably, because the maximum size is not taken into account (*10*).

The Brazilian and HDM–III models are fairly complicated, necessitating the determination of a number of geotechnical properties, identification of the material types, and estimation of the average vertical grade (rise and fall) and average degree of road curvature, over the total length of the link. Because these models were developed mainly for use in developing countries, where computing facilities are often rudimentary (even at regional or head offices) and the skill levels of the road personnel may be low, the usefulness of the models, especially in remote areas, is questionable.

A significant aspect of the new models is their simplicity. The data required can be obtained quickly and cheaply using relatively unskilled labor. The models developed in this study eliminated the necessity to identify the material type and to estimate the average grade and curvature for the road link. Simple indicator tests requiring minimal equipment and only basic operator training are required for the input parameters for the model. The predictive capability, however, has not been diminished through this process. In fact, it has generally been improved for local conditions.

MDS

The MDS was originally developed by Visser (*1*) using data collected during the World Bank study in Brazil. The system has subsequently been improved and adapted for use on personal computers. An overview of its operation and use as a management aid has been fully described (*1,10*).

Management personnel generally desire certain information for the routine maintenance and upgrading of an unpaved road network. This information includes the following:

- How much money should be budgeted for regraveling, and what volume of material will be required annually?
- What routine blading budget is required?
- What are the consequences if the required budget cannot be provided?
- How many motor graders are required to perform the maintenance for the selected budget?
- How often should every link be bladed to ensure optimal economic allocation of the maintenance funds?
- Which roads are economically justified to upgrade to bituminous standard, and what funds are required for this?

All of these questions can be answered accurately and efficiently using the MDS.

GENERATION OF ROAD NETWORK

To evaluate the effect of the new unpaved road performance models on management decisions, a network of roads had to be selected. One of the criteria for this network was that all the information required for the old and the new performance models had to be available. In many instances, when performance models are applied to a network of roads, estimates of properties that are not very sensitive to the outcomes are made. Consequently, no readily available network of roads contained all the required information. A fictitious network was developed. This network consisted of all the test sections used to develop the new southern African performance models. A random number generator assigned a length to each link. In this way, a network of 2662.3 km comprising 77 links was developed. Traffic ranged from 20 to 333 vpd. The material, traffic, and environmental characteristics used in the analysis were those pertaining to the actual roads studied during the development of the models.

EVALUATION OF THE MODELS' EFFECTS ON MANAGEMENT DECISIONS

The effects of the old and new performance models on management decisions were compared. Gravel loss, maintenance budget, equipment requirements, overall network condition, and upgrading requirements were studied. Analyses were carried out on the original MDS using the Brazilian models (old MDS) and the new southern African models (new MDS).

Gravel Loss

The thickness of gravel lost, calculated according to the old MDS, ranged from 5.0 mm (the minimum permitted) to 27.6 mm; the gravel loss calculated by the new MDS ranged from 5.0 to 22.1 mm. The total volume of regraveling material required was 306 000 m^3 according to the old MDS and 259 000 m^3 by the new MDS. The new MDS thus predicted that 20 percent less material needed to be replaced annually compared to the prediction of the old MDS. By using the new MDS in southern Africa, budget requirements for gravel loss would be reduced by 20 percent. At a gravel cost of R10 per m^3, the savings would be about R0.5 million. This outcome, which is different from that found by calculating the average gravel loss, is the result of the different length and traffic characteristics of the network.

Maintenance Budget Requirements

Total cost comprises the road-user cost and the road maintenance cost. The point where the total cost curve reaches a minimum is the optimum maintenance position. This means that one unit of saving in road-user cost is balanced by one unit of cost to maintain the road. At this point, the marginal benefit-cost (B/C) ratio is 1. By means of the MDS package, the minimum position was calculated for both models. For the old MDS, the optimum maintenance cost (OMC) was R5.62 million and the road-user cost was R74.3 million. For the new MDS, the OMC was R4.76 million and the road-user cost was R70.9 million.

These results corroborate the previous statements about roughness progression. The rate of roughness progression is lower for the new model, which means that the network is in a better condition with less maintenance. Hence, the OMC and road-user cost are lower for the new model.

The aim of maintenance scheduling is to ensure that maintenance is applied in such a manner that the economic advantage is the same on all links. For a few links this can be done manually, but as soon as a network of roads is considered, mathematical optimization techniques have to be applied. In the MDS, dynamic programming techniques were used. The economic advantage, expressed as the marginal *B/C* ratio, was computed for a range of maintenance budgets. The plots for the old and new models are shown in Figure 1. At the OMC, the marginal *B/C* ratio is 1.

Public authorities do not normally obtain sufficient funds for maintenance to be applied at economic optimality. Public expenditure on maintenance generally lies between marginal *B/C* ratios of 3 and 5. For the purpose of this comparison, a marginal *B/C* ratio of 4.0 was selected. The required budgets for blading were R3.521 million for the old MDS and R2.898 million for the new MDS (i.e., a 20 percent savings). In both instances, the inability to supply this budget would result in additional road-user costs of at least R4 for every R1 in maintenance funds not provided. Again, the new MDS resulted in a 20-percent reduction of the predicted budget requirements over those of the old MDS.

Equipment Requirements and Network Condition

Because of the lower budget requirements of the new model, fewer motor graders were required. Using the old MDS, 15 graders were necessary to maintain the network optimally; only 12 were necessary on the basis of the prediction of the new MDS. Even though fewer graders were required, the overall condition predicted by the new MDS was better. The weighted average network roughness for the new MDS was 63.2 QI counts/km, whereas the prediction for the old MDS was 81.5 QI counts/km. Besides the lower predicted budget and equipment requirements and better road condition of the new MDS, significantly lower road-user costs would be incurred by the traveling public.

Upgrading Requirements

The MDS has the capability of determining when it is economically justifiable, in terms of total costs, to upgrade an unpaved road to paved standard. For a given road under consideration, the output is the year when paving is justified, for a range of construction costs. This permits evaluation of the sensitivity of the construction cost.

The same 16 roads were selected for paving by both sets of models during the following 10-year period for the construction costs used. Because of the slower deterioration of the road predicted by the new models, however, the time of paving was generally set a few years later than that of the old models for the higher construction-cost scenarios. This time schedule again represented savings to the road authority.

Discussion of Results

The economic advantages of maintenance management have been shown in a number of countries. However, the economic advantages of using the new models in the MDS for southern African roads are clear. On the network under discussion, annual savings of R1.1 million, made up of R0.5 million for regraveling and R0.6 million for blading, are possible.

Because this savings is on a network of only 2660 km, the potential savings on the numbered unpaved road network of

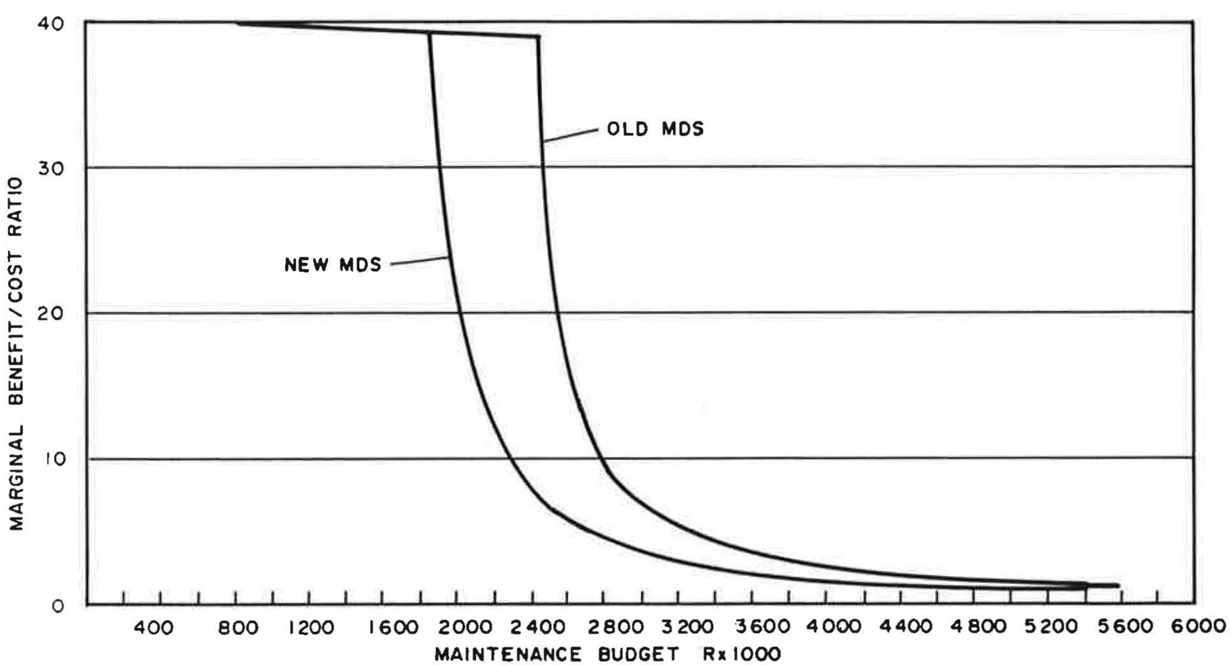

FIGURE 1 Graph for determining the appropriate maintenance budget.

140 000 km are enormous, assuming the network used in this study was a representative sample. The factorial experimental design used to select the original roads should ensure this.

CONCLUSIONS

The new performance-related models developed from southern African roads permit more confidence in the predictions of gravel loss and routine maintenance requirements for unpaved low-volume roads in southern Africa. The predictions also result in significantly lower budget requirements compared to those based on the models developed in Brazil. On a small network, savings of 20 percent, or R1.1 million, can be achieved. This amount alone is equivalent to the cost of the research project. The results of this work also show the danger of using models developed in a different environment.

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