DQI	Initial QI offset term, calculated at the start of the analysis period or after an overlay.
SNCa	Modified structural number for a pavement with an AC overlay.
Ba	Equilibrium Benkelman beam deflection after an AC overlay (0.01 mm).
QIIA	Predicted QI immediately after an AC overlay.
QIb	QI value immediately before an overlay.
H	Overlay thickness in cm.
CR	Predicted extent of Class 2 or worse cracking at age A, for a pavement with AC surface (original or overlaid) or slurry seal surface (percent of pavement surface area).
DCR	Cracking offset term, calculated to ensure that predicted cracking conforms with the initial value at the start of analysis, or to ensure that CR equals 0 before the onset of cracking.
AICR	Age since the last overlay when cracks first appeared in years.
CRb	Extent of cracking present before overlay or slurry seal (percent of area).
AANC	Average annual traffic in the period between overlaying and appearance of the first crack (ESAL/yr).
RA	Predicted extent of ravelling at age A for a surface treated pavement (percent of surface area).
AIR	Age of surface treatment when ravelling appeared in years.
CF	Construction quality indicator for surface treatments. Here it is assumed that CF equals 1 for a single-surface treatment; CF equals 0 for a double-surface treatment.
AAHV	Average annual heavy vehicle traffic in the period between surface treatment and the onset of ravelling (100,000 ESAL/yr).

The Maintenance and Design System: A Management Aid for Unpaved Road Networks

A. T. VISSER AND P. C. CURTAYNE

The Maintenance and Design System (MDS) is a model that was developed to determine the effects of alternative maintenance budgets on the vehicle operating costs of a network of unpaved roads. It also is used to identify those roads for which an upgrade to a bituminous standard would be economically justified. It can be used in the framework of a management system to assess a desirable level of funding and the way resources should be allocated. It also indicates the distribution of work needed over the network in physical terms. This application is illustrated by means of a case study in which assumptions inherent in the model are indicated and recommendations are made for further research. Although a need clearly exists for improving the accuracy and scope of the MDS, the fact that it provides an orderly framework for collecting and evaluating the characteristics and needs of unpaved networks is in itself significant. Discrepancies between the system's outputs and practice can be corrected with experience for each region in which it is applied. Maintenance operations can then be effectively controlled and budget requests can routinely be supported on economic grounds.

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In many countries the majority of low-volume roads are unpaved and account for substantial proportions of the maintenance budget. The financial and operational management of this maintenance has traditionally been informal, and has largely been based on historical precedent. The lack of quantitative expressions that relate maintenance needs to local circumstances meant that managers had to rely on the experience and judgment of regional operators to apply appropriate maintenance routines. Decisions to pave gravel roads have similarly often been ad hoc and based on a general traffic volume criterion or a political objective.

The use of the Maintenance and Design System (MDS) model has proved to be a valuable aid in assessing the level and distribution of maintenance needs of unpaved road networks and in programming projects to upgrade roads to a paved standard (*1, 2*). This model is based on relationships that describe the behavior of unpaved roads that were derived from the results of the Brazil study (*3*). Although the results of the model are not necessarily particularly accurate for individual roads, if it is used within the framework of a management system the following important questions can be formally addressed:

- What would the optimum level of maintenance expenditure be for the network?
- What would be the economic consequences of a marginal increase or decrease in the current budget?
- What is the most suitable distribution of available funds among the various regions?
- What provision should be made for regraveling?
- What would be expected to be an appropriate motor grader complement?
- What would be the most advisable upgrading program under the current physical and economic conditions?

An overview is first given of the structure of the MDS. The management system's application and the way these questions are addressed are then illustrated by way of a case study. Finally, the status of the MDS and further research requirements are discussed.

OVERVIEW OF THE MAINTENANCE AND DESIGN SYSTEM

The MDS is composed of a suite of programs that are based on a set of prediction relations that were principally based on the Brazil study (*3, 4*). The development of the MDS has been fully described previously; only a brief outline of the nature of the prediction relations and the way they are used in the assessment models is given.

Prediction Relations

The following three types of relations are used:

- The physical aspects and performance of unpaved roads,
- Vehicle operating costs as a function of road roughness and geometry, and
- The rate of deterioration of paved roads.

A number of empirical relations were derived from observations of 46 unpaved road sections during the Brazil study (*3, 4*). These relations are summarized in the following table, in which the various parameters governing the performance of these roads are shown to have been related to a series of independent variables. Although these relations are still weakly defined in many respects, they represent a significant improvement in quantifying unpaved road behavior.

Dependent Variables	*Independent Variables*
Roughness	Time
Rut depth	Traffic characteristics
Gravel loss	Material properties
Blading efficiency	Climate
Passability	Topography
Cover thickness	

Another important objective of the Brazil study was to relate the operating costs of various vehicle classes to road roughness (*5*). The applicability of these results to South African conditions is still being investigated, but preliminary adaptations to the Brazil results are currently used to determine the road user costs of predicted levels of roughness.

The need to pave a gravel road is assessed by comparing the total (user and agency) cost of continuing with the unpaved road with the cost of providing a paved road over a given analysis period (*6*). For the purposes of this evaluation, the user and maintenance costs associated with an average rate of deterioration of a light pavement structure are assumed.

MDS Assessment Model

The model operates in the following three steps:

- Ranking of alternative blading strategies on individual uniform sections of road in terms of total cost;
- Optimizing the blading strategy for a network of unpaved roads subject to a budget constraint and other criteria such as the need for certain roads to be passable throughout the year; and
- Determining economic warrants for paving particular roads in terms of traffic volumes.

The structure of the first of these steps is illustrated in Figure 1. The analysis first considers the cost of regraveling and then calculates the cost consequences of different blading strategies. The condition of each pavement is simulated until an equilibrium of costs and road condition is reached under a given strategy. The condition and costs in this stage are taken as representative of the strategy.

The cost arrays generated for each road section are then used in a dynamic programming procedure to assign the optimum blading strategy to each section for a given budget. The advantages of an incremental change in unpaved road maintenance expenditure can be expressed in economic terms by choosing a range of budgets (see Figure 2).

In this representation, the marginal benefit-cost ratio is given as a function of the total maintenance expenditure on blading. The marginal benefit-cost ratio is the ratio of benefits that accrue by way of reduced vehicle operating costs to an incremental maintenance cost. The point at which the ratio passes through unity is the optimum budget. The curve is bounded to the left by the so-called minimum blading budget. This is the least expenditure for which the theoretical requirements of the model can still be met. The theoretical requirements are (a) a relationship that assumes a higher cost of blading with increasing road roughness; and (b) a "balanced" blading policy that requires the roads of the network to be bladed in such a way that the marginal benefit of additional blading on all roads is the same.

It is clearly possible to operate with lower budgets than this minimum, but this would mean that certain roads would be neglected in deference to others.

The economic warrant for upgrading a gravel road is taken to be that traffic volume at which the equivalent uniform annual cost (EUAC) of providing and maintaining a paved road equals the EUAC of the unpaved road over an analysis period, for instance the traffic volume at which:

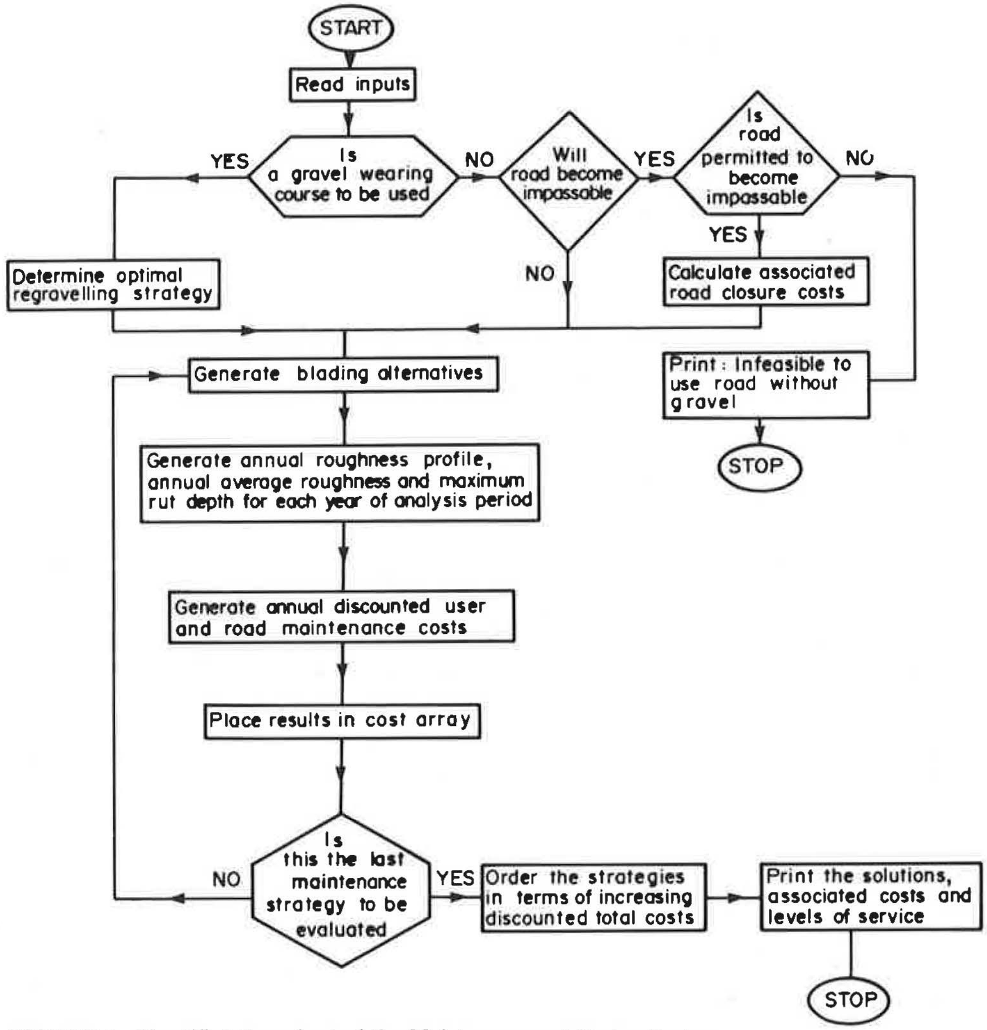

FIGURE 1 **Simplified flow chart of the Maintenance and Design System.**

$$C_p + M_p + U_p = M_u + U_u$$

where

C_p = EUAC of construction cost of paved road,
M_p = EUAC of maintenance cost of paved road,
U_p = EUAC of road user cost on paved road,
M_u = EUAC of maintenance cost of unpaved road, and
U_u = EUAC of road user cost on unpaved road.

The time at which a given road should be considered for paving can be predicted by assuming a traffic growth value.

The MDS can be used to advantage in planning the actions to be taken on an individual road. However, because of the remaining weaknesses in many of the relations and assumptions, the results may easily be overridden by local factors and should therefore be recognized only as a guide. The benefits of the MDS are much more fully realized when it is used in the context of a management system for an unpaved road network in much the same way as pavement management systems at the network level. This is illustrated in the following sections in terms of a summary of a roads needs study of the regional authority of Gazankulu that was performed on behalf of the Department of Transport (*7*).

CONDITIONS IN GAZANKULU

Gazankulu consists of four districts: Giyani, Malamulele, Ritavi, and Mhala. The length of road in each district is given in the following table. The traffic distribution of these roads, which is shown in Figure 3, is predominantly light (62 percent of the network carries less than 200 vpd), but certain gravel roads carry up to 700 vpd. Current development in the region is expected to generate a high traffic growth rate during the first 5 years (19 percent per annum for cars and 16 percent per annum for heavy vehicles). Thereafter, traffic growth is expected to settle down to an annual rate of 2 percent.

District	*Length of Unpaved Roads (km)*
Giyani	445.8
Malamulele	278.9
Ritavi	107.4
Mhala	236.1
Total	1 068.2

Prediction models have thus far only been derived for lateritic and quartzitic materials. In any study, therefore, apart from determining the material properties such as grading and

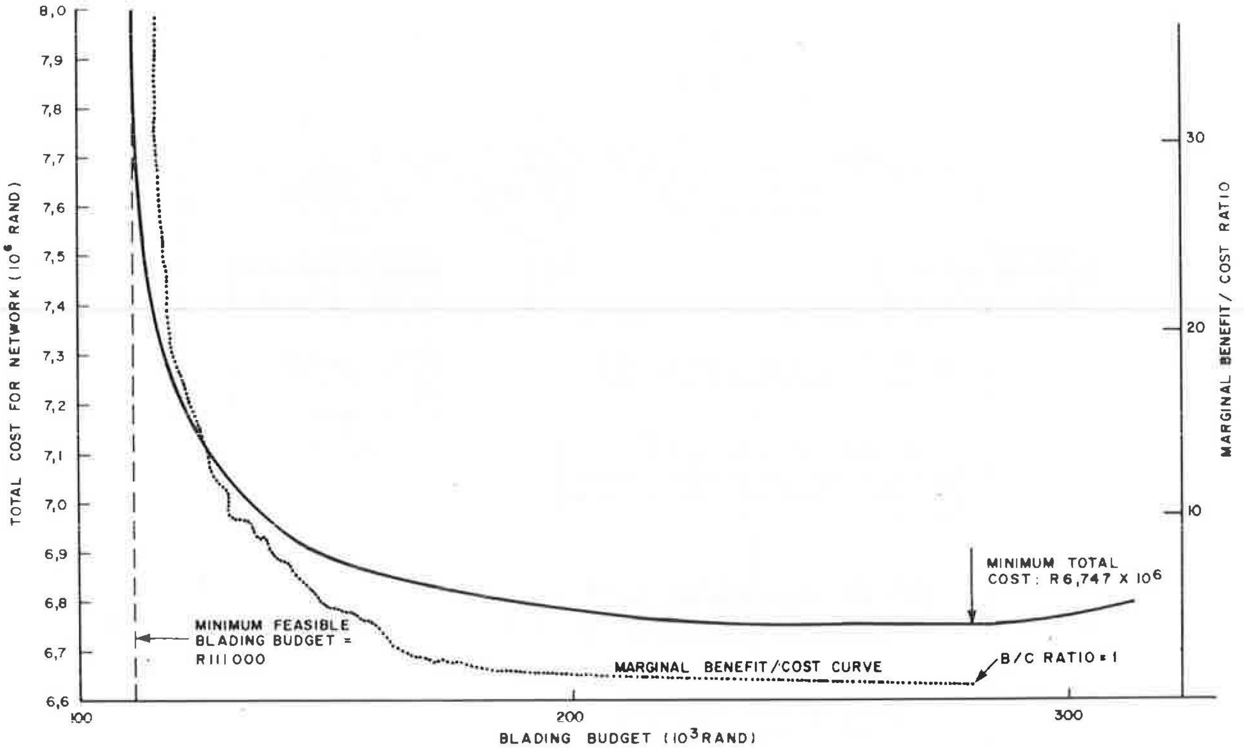

FIGURE 2 Total transport cost as a function of the blading budget for the Bronkhorstspruit network.

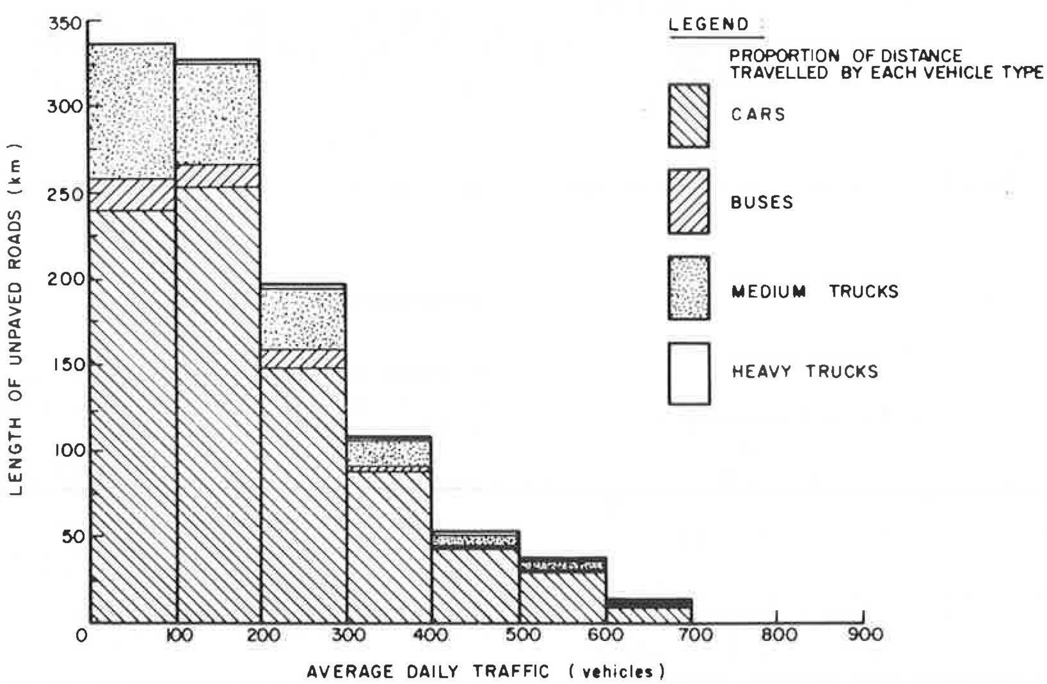

FIGURE 3 Traffic distribution on unpaved roads in Gazankulu in 1984.

CBR, each material has to be classified as either laterite-like or quartzite-like according to the hardness and angularity of the material. In this regard, most of the region uses a quartzite-type material. However, in one district, Mhala, the quartzitic sand available is of such a poor quality that its properties are outside the calibration range of the model and the results for this district are therefore suspect.

The four districts lie mainly in a flat terrain that has an average 214-day dry season. However, some of the roads in the Giyani and Mhala districts are in rolling or mountainous terrain with an average 150-day dry season.

Grader productivity is clearly an important factor in determining the cost of providing a given level of service. The base daily cost of operating a motor-grader was taken as R410, and

250 available working days per operator were assumed. This, however, represents ideal conditions and does not take into account time lost through traveling, servicing, inclement weather, and leave. It is therefore necessary to apply a suitable correction factor, the so-called productivity factor, to represent (a) the proportion of an operator's available working time that is actually used for blading operations, and (b) his working efficiency.

The productivity factor relates actual productivity to the theoretical value used in the MDS. Because a suitable factor for Gazankulu was not available, two values were considered. The first was a high value of 63 percent that was previously found to pertain to an efficiently maintained district elsewhere and the second was a value of 30 percent for comparison.

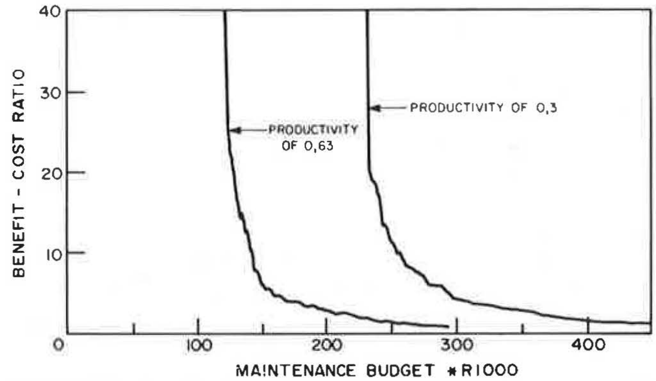

FIGURE 4 Graph of benefit-cost ratio for different grader productivity factors.

RESULTS OF THE BLADING ANALYSIS

The results of the analysis of the blading requirements of the district of Giyani for each productivity factor are shown in Figure 4. An optimum budget of R292 000 is shown in the figure for a factor of 0.63. The minimum balanced budget is R115 000. Although lower levels of funding are possible in practice, they are not feasible under the theoretical "balanced" blading policy.

The desirable level of funding was defined as that which gave a marginal benefit-cost ratio of four, because investments with this return would normally be considered sufficiently economical to attract additional funding if required. In this case the desirable level was R180 000.

The analysis for all four districts using both productivity factors is summarized in Table 1. In each case the associated number of motor-graders is given for each district; because each district has its own complement, the numbers are rounded up to the next integer.

The total desirable budget varies between R501 000 and R830 000, which is roughly in proportion to the indicated productivity. There is, however, a relatively small difference in terms of plant requirements for the two cases. This is mainly because relatively small networks were considered and the predicted figures are rounded up to integers. Nevertheless, for the lower productivity, the number of times each link would be bladed annually would be lower than for a higher productivity. Consequently, the level of service would be lower.

Note that the required number of motor-graders given does not account for down time for servicing, maintenance, and

TABLE 1 SUMMARY OF BLADING BUDGETS

District	Productivity factor	Minimum balanced maintenance budget	Maintenance budget for the marginal benefit-cost ratio of 4	Number of motor-graders required	Optimum maintenance budget	Number of motor-graders required
Giyani	0,63	R115 000	R180 000	1,66 ≈ 2	R 292 000	2,94 ≈ 3
	0,3	R230 000	R300 000	2,72 ≈ 3	R 430 000	4,23 ≈ 5
Malamulele	0,63	R 90 000	R135 000	1,31 ≈ 2	R 184 000	1,80 ≈ 2
	0,3	R180 000	R220 000	1,96 ≈ 2	R 296 000	2,86 ≈ 3
Ritavi	0,63	R 37 000	R 61 000	0,61 ≈ 1	R 96 000	0,97 ≈ 1
	0,3	R 72 000	R100 000	0,88 ≈ 1	R 145 000	1,44 ≈ 2
Mhala	0,63	R 80 000	R125 000	1,23 ≈ 2	R 206 000	2,06 ≈ 3
	0,3	R157 000	R210 000	2,05 ≈ 3	R 300 000	2,99 ≈ 3
Total	0,63	R322 000	R501 000	7	R 778 000	9
	0,3	R639 000	R830 000	9	R1 171 000	13

repairs. This number should therefore be adjusted according to what is considered reasonable for the operating conditions of the region.

Certain external constraints similarly affect productivity, for which adjustments can be made using the productivity factor to give applicable results. The external constraints include the geographic character of the maintenance district; whether blading is executed from a central depot or decentralized; and the availability of a plant.

For a given budget and productivity factor, the number of times per year each link should be bladed, as well as the interval between bladings in the wet and dry seasons, respectively, are computed. An example of an output of these calculations is given in Figure 5. Such outputs provide a convenient basis for planning and controlling blading schedules.

RESULTS OF THE REGRAVELING ANALYSIS

Regraveling is the most expensive maintenance activity on unpaved roads. Adequate provision must be made for it in the budget if the roads are to be kept serviceable at a reasonable cost. The MDS predicts the annual loss and its replacement cost for each link in the network. In this study, a unit cost of R6.00/ m^3 for regraveling, including transportation, placement, and compaction, was used. The results for the four districts are summarized in Table 2, in which the total annual loss for the region is given as 167 000 m^3 with a replacement cost of R1.0 million.

In other studies in South Africa, it was found that gravel loss predictions in data of the Brazil study agree well with actual values. However, the accuracy of the values for the poor, sandy materials found on some of the Gazankulu roads is unknown and will have to be monitored. It has also been found that road authorities tend to use additional gravel (up to 50 percent) to make minor improvements to roads when regraveling; a suitable allowance for this should therefore be made in the budget.

TABLE 2 SUMMARY OF THE PREDICTED ANNUAL GRAVEL LOSS

District	Annual Gravel Loss (mη)	Replacement Cost (R)
Giyani	67 900	407 400
Malamulele	36 400	218 400
Ritavi	13 700	82 200
Mhala	48 500	291 000
Total	166 500	999 000

BLADING FREQUENCIES FOR A GIVEN MAINTENANCE BUDGET

GAZANKULU-MALAMULELE

BLADING BUDGET = R220 000

ROAD	LINK	LENGTH (KM)	NO. OF BLADINGS PER YEAR	FREQUENCY DRY SEASON (DAYS)	FREQUENCY WET SEASON (DAYS)
D202	D203-D204	5,5	9	35	50
D202	D204-D205	7,6	6	53	75
D202	D205-D207	6,9	6	53	75
D203	G1-17-D202	2,2	7	53	50
D204	AD202-G1-17	3,6	9	35	50
D204	G1-17-1	1,0	9	35	50
....	....	...	...	....	....
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D216	D214-D215	5,9	9	35	50
D217	AD214-D213	4,9	6	53	75
G1-12	D213-G1-13	13,0	8	42	50

NUMBER OF GRADERS REQUIRED FOR DISTRICT = 1,96

FIGURE 5 Recommended number of bladings for roads in Malamulele for blading budget of R220 000 at lower productivity.

RESULTS OF THE UPGRADING ANALYSIS

As explained earlier, the economic warrant for upgrading a gravel road to a paved standard is that traffic volume for which the discounted maintenance, construction, and user costs of providing and using a paved road are equal to the cost of maintaining and using it in its unpaved state. This is defined as the "break-even traffic volume," T_0. The year in which paving should take place is determined by comparing T_0 with the traffic volume predicted for each successive year. Note that the cost of paving does not include geometric or drainage improvements. For budgeting purposes, these will have to be added according to what improvements are likely to be done.

The upgrading requirements of the Gazankulu network were evaluated for a 10-yr planning horizon. Two values of paved road construction and maintenance costs were considered for a 20-yr design period, namely R60 000/km and R100 000/km, to test the sensitivity of the results to actual local costs. These costs exclude major geometric or drainage improvements. It was further assumed that the productivity factor is 0.63; the actual maintenance budget is two-thirds of the optimum; and the discount rate is 8 percent.

The results are summarized in Figure 6, which shows for each construction cost the length of road currently eligible for upgrading and the length becoming eligible in each successive year. These lengths are converted to upgrading costs on the right-hand axis. A budget profile is suggested in Figure 7, for each construction cost, that would eliminate the backlog of upgrading work by 1990 and would thereafter accommodate newly eligible projects. These results indicate that up to 1990 an average of between R3.4 and R4.8 million, depending on construction costs, should be provided for upgrading annually.

In the earlier analysis, T_0 was derived by directly comparing road user costs with those of the road authority. However, in the blading analysis it was suggested that the authority might select a budget level at which the marginal benefit-cost ratio is four. This is equivalent to choosing an optimum budget in which benefits are assumed to have one-quarter of their nominal value; for instance, they are rated a quarter as important as authority costs. To make the warrants analysis compatible with this, it was repeated with road user costs taken at a quarter of their actual value. Because benefit values are greatly reduced, the length to be upgraded is greatly reduced. A comparison of budget profiles is shown in Figure 8 for the two

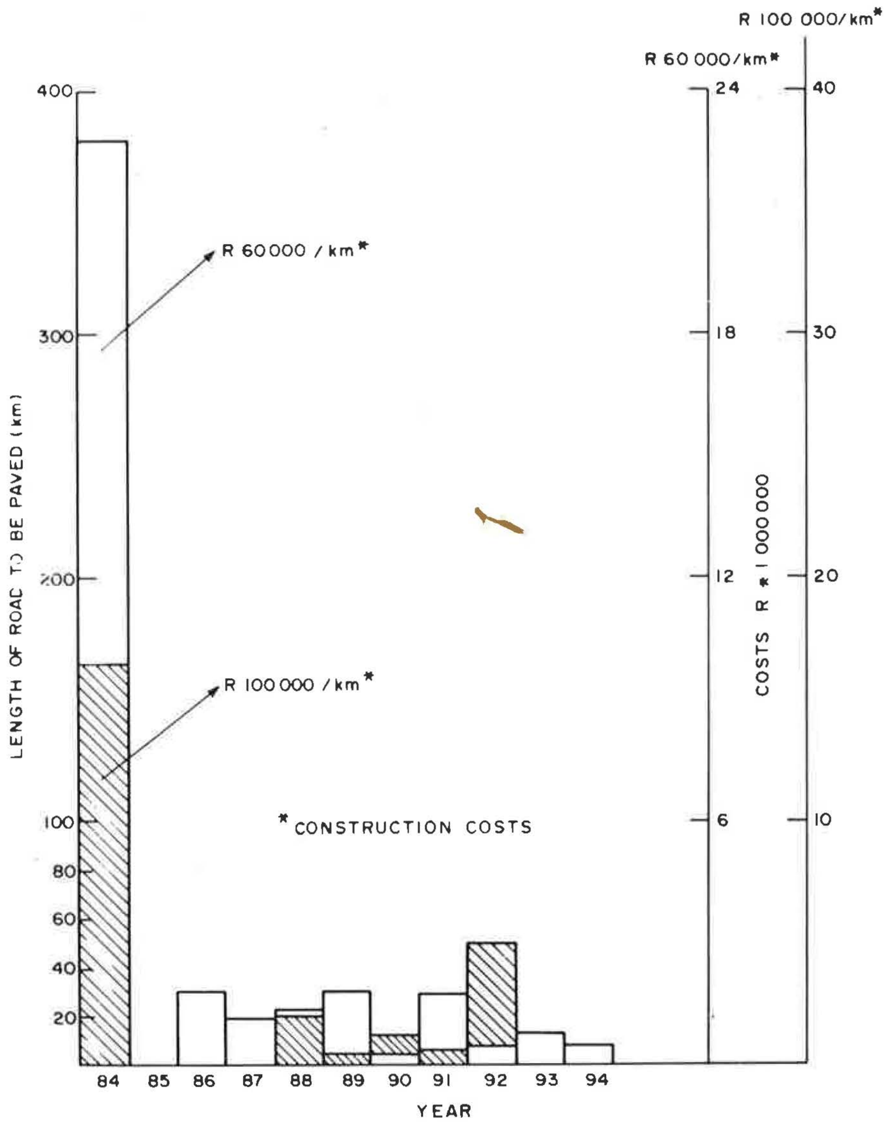

FIGURE 6 Length of roads to be paved each year.

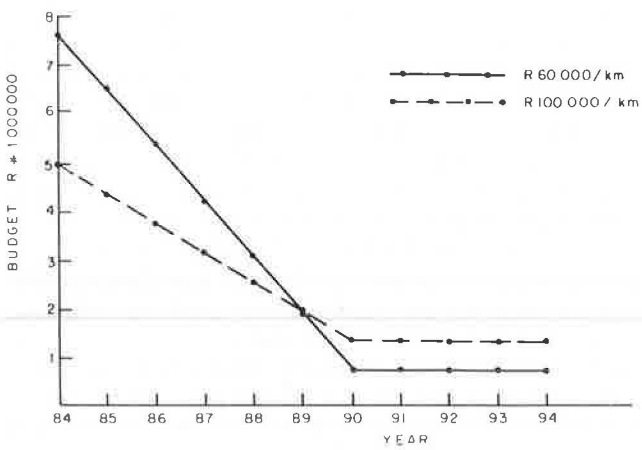

FIGURE 7 Budget profile to eliminate backlog in upgrading work.

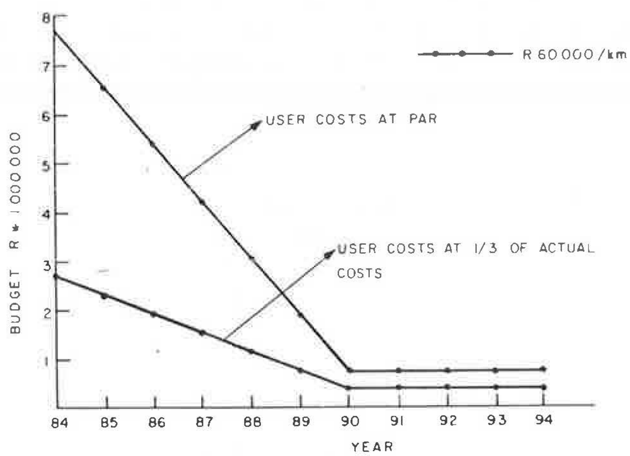

FIGURE 8 Comparison of the budget profiles for reducing the backlog in upgrading works.

cases (for a construction cost of R60 000/km). An average of R1.8 million per annum should be provided up to 1990 for the case of reduced benefit values.

SUMMARY OF RESULTS

The results of the analysis of the needs of the unpaved roads of the Gazankulu region are summarized in Table 3. There is a wide variation in total fund requirements depending on whether a high marginal benefit-cost ratio or an optimum economic solution is chosen. However, there is only a small difference in the grader complement. In order to define overall needs, however, the grader complement should be adjusted for down time, work on paved and tertiary roads, and maintenance arrangements.

DISCUSSION OF RESULTS

Despite uncertainties about some of the relations in the model and the assumptions inherent in the procedures, the use of the MDS in the network analysis has been found to be a significant advance in the management of unpaved roads.

TABLE 3 ESTIMATED TOTAL COSTS FOR GRADER PRODUCTIVITY FACTOR OF 0.63

	Marginal Benefit-Cost Ratio of 4	Optimum Economic Solution
Blading costs	R 500 000	R 780 000
Regraveling costs		
Replacement	R1 000 000	R1 000 000
Betterment	R 500 000	R 500 000
Upgrading costs (R60 000/km)	R1 800 000	R4 800 000
Total	R3 800 000	R7 080 000
Grader Complement	7	9

In the first place, it provides a good idea of the maintenance requirements of an authority in terms of plant, blading operations, regraveling, and upgrading. In addition, an indication is given of the economic implications of operating at budget levels different from that shown to be desirable. This type of information is particularly useful when funding is negotiated with an external agency.

Once the basic work has been done, divergencies of predicted values from the case in practice can be determined. These can arise from managerial problems, technical problems, or situations in the field to which the parameters in the model are not applicable. Problems can thereby be identified and rectified as far as possible and adjustments can be made to the model to reflect local conditions more accurately. The "calibrated" model can then be used in that region as an important management tool. For example, it can be used to regularly reassess funding and resource needs; plan and control maintenance operations; and program upgrading projects and justify them in economic terms when they are in competition with other capital works.

Nevertheless, there is still much room for development in many aspects of the model to greatly improve its value in general applications.

The relation between vehicle operating costs and road roughness is largely based on results from the Brazil study, although it was adjusted to some extent to reflect South African prices. It has been found, however, that the Brazil results are by no means definitive and are not easily transferrable to other socioeconomic environments (*8*). The sensitivity of the results of the model to this relation makes it essential to further investigate the calibration of the relation to reflect local conditions.

Even if accurate vehicle operating costs were available it might be necessary to review the way in which they are used in the analysis. When there is a shortage of funding, the authority might choose to downgrade road user costs in relation to its own in order to manage its affairs. For example, a gravel road may be maintained if this is cheaper to the authority than constructing a paved road, even if this action is not optimal in regard to total costs.

The relations that describe pavement behavior in the model are consistent with observations in most of the climatic regions in South Africa (*2*). However, these have largely pertained to good materials and have complied only with the large confidence limits of the predictions. Further investigation has found them to be too restricted in terms of both material type and material properties to adequately cater to many cases found in practice. Further work is therefore needed to expand the scope and accuracy of these models. The results of a major experiment of this type will contribute greatly to this requirement (see paper by Paige-Green and Netterberg in this Record).

The minimum balanced blading budget and the shape of the marginal benefit-cost curve in this region are both very sensitive to the relation between blading efficiency and road roughness. More empirical information is required to define this relation correctly. Moreover, the effectiveness of the various blading techniques in use should be investigated.

CONCLUSIONS

The MDS model was developed to determine the blading, regraveling, and upgrading needs of unpaved roads according to economic criteria. Based on empirical relations of unpaved road behavior, this model represents a major advance in the quantitative analysis of unpaved roads.

Used in the context of a management system in the Gazankulu region, the MDS was found to provide valuable, general network-level assessments. These include optimum levels of funding and the economic implications of operating under different financial conditions. Such information can offer an objective basis for negotiations with external funding agencies.

The analysis can also be used internally to good effect to assess the distribution of resources among the various districts, to identify problems by investigating divergencies between predicted and actual conditions, and to plan and control maintenance operations.

Although the results of the MDS were consistent with observations in areas in which good materials are used in most of the climatic regions in Southern Africa, it is clear a great need still exists to improve its accuracy and scope. Areas that need further research include the behavior of a wider range of materials, the relation between vehicle operating costs and road roughness, and the efficiency and effectiveness of various blading techniques.

Despite its shortcomings, the fact that the MDS provides an orderly framework for collecting and evaluating the characteristics and needs of unpaved networks is in itself a significant management benefit. Discrepancies between the system's output and practice can easily be observed and corrected in each region of application. Management of maintenance can then be effectively controlled and budget requests can be routinely supported on economic grounds.

ACKNOWLEDGMENTS

This work forms part of an ongoing project of the National Institute for Transport and Road Research and this paper is published with the permission of the Chief Director.

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