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Optimization of Roadway Structural Design and Maintenance Strategies with Special Reference to Developing Countries

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The decision to build a bituminous road instead of an unpaved road is often based on preconceived bias, historic preferences, or incomplete analysis. An analysis that uses systems methodology to minimize the total cost, which comprises road construction, maintenance, and user costs, is a just and scientific basis for such decisions. The preferred decision rule is the first-year benefits criterion; i.e., it is advisable to pave the road when the ratio of the net first-year benefits of paving to the difference in construction cost between a paved and unpaved road equals the opportunity cost of capital. For the cost figures and policy constraints adopted, paving becomes an economic proposition at an average daily traffic rate of 575. A reduction of the available maintenance funds to half the optimum has a limited impact on unpaved roads but could have severe implications for paved roads. The major factor that affects warrants for paving is the lower cost of the gravel for unpaved road-wearing courses relative to the cost of materials for paved roads. Dust, accidents, and the depletion of natural resources are factors that cannot yet be included in an economic evaluation, but they should be taken into account together with the results from the economic analysis in a utility analysis.

One of the major problems for developing countries is the development of an adequate road network under conditions of limited available financing. Despite this constraint, frequently the philosophy is to construct paved or black-top roads because this is considered a sign of development. Thus, gravel roads are often not even considered as an alternative, although in many instances they provide the most economical road network, as will be shown. In addition to this problem associated with the development of a road network, two further problems exist in the rational determination of warrants for paving.

1. In certain cases a road authority may use an average daily traffic (ADT) level of 200-250 (such as in South Africa) or even as low as 100 (in Texas) as a fixed warrant for constructing a black-top road. These traffic figures are usually of a historic origin based on experience and availability of funds, and no cognizance is taken of the benefits and cost of paving. As funds become more scarce, the traffic warrants for paving usually increase.
2. Because of limited funds for upgrading gravel roads, some road authorities perform fairly crude economic analyses. In New Zealand (1) the benefit/cost ratio of upgrading, taken over the analysis period, is used as a basis of evaluation. Vehicle operating costs are based on Winfrey (2), and maintenance costs are computed as an annual average. In Spain (3) the increased speed, and thus the greater productivity of trucks, is used as a basis for evaluation.

The World Bank recognized these problems and applied an economic analysis to requests for funds by using the highway design and maintenance standards model (HDM) (4). In HDM the road user cost predictions are based on results obtained in the Kenya study (5), and the paved and unpaved road deterioration relations are based on the American Association of State Highway Officials (AASHO) road test (6) and Kenya results (7). The HDM is a highly sophisticated program that requires a great deal of information to run.

The aim of this paper is to investigate warrants for placing a bituminous surfacing on gravel roads by using a comprehensive economic analysis in a program developed to evaluate the interaction of the different cost components. Obviously, the warrants are linked to the costs of constructing and maintaining both road types and the road user costs associated with the road condition.

The analysis is based on the study executed in Brazil, as a follow-up to the Kenya study, by the Brazilian government and the United Nations Development Program (8,9). This study was designed to extend the results of the Kenya study over a wider range of factors. In the investigation of warrants for paving an unpaved road, it is necessary to know the interaction of pavement construction and maintenance and road user costs for both types of road. A systems approach for the evaluation of unpaved roads was developed by Visser (10) that also contains details of specific computations and a computer program. The results obtained (10) are used as a basis for the arguments in this paper. The paved road deterioration relations used are those presented by Visser and others (11).

In this paper an exposition is given of the method of analysis and factors that influence the costs on unpaved roads so that the factors that have the most influence on the final outcome can be studied in greater detail for the development of warrants. Different methods of conducting an economic analysis are discussed, and warrants for paving are developed for each method. The lack of maintenance funds in developing countries is a factor that needs to be taken into account, and the influence of this on the warrants is investigated. Finally, aspects such as dust, accidents, and the depletion of gravel resources are dealt with.

ANALYSIS OF COSTS ON UNPAVED ROADS

A systems approach was used to develop a methodology (10), termed the maintenance and design system (MDS), to evaluate the interaction of road maintenance and the resultant road condition on road user costs. Road user costs include maintenance, interest, and depreciation, and tire, fuel, and oil costs. The MDS also has the capability of making optimum use of maintenance strategies, in terms of number of bladings per year, and regravelling frequency based on the minimization of the total cost of construction, maintenance, and road user costs over the analysis period. The consequences of road maintenance can thus be determined. All costs are discounted by using a discount rate that is a shadow rate of interest by which future monetary values are expressed in current terms. At present a value of 10 percent is recommended for use in South Africa.

Visser showed that the main factors that affect the regravelling strategy were traffic-related, namely ADT and the traffic growth rate (10). In addition, the total discounted regravelling cost is affected by the unit cost of gravel, the analysis period, the discount rate, and the salvage value of gravel that remains at the end of the analysis period. Factors such as road geometry and gravel quality have a minor effect. Blading strategy was found to be mainly dependent on ADT (blading frequency was linked to traffic growth) and gravel quality. The total transport cost was consequently found to be mainly influenced by traffic factors, road geometry, analysis period, and discount rate. Gravel quality was important for roads that carry more than 150 vehicles/day. Road geometry becomes important because it has a major effect on vehicle operating costs. The above-mentioned factors that are sensitive to the outcome of the costs on unpaved roads will be treated in greater detail in the development of warrants for paving.

Methods of Economic Analysis

Two criteria that are customarily used in analyses to evaluate the economic feasibility of improvements (4) are the break-even traffic volume and the first-year benefits criterion.

The break-even traffic volume is defined as the base year ADT at which the net present value of paving just equals the costs of leaving the road in the current gravel status. If the base year ADT exceeds the break-even traffic volume, the relevant internal rate of return will be greater than the discount rate used in the net present value computation, and paving is therefore economically justified. This approach assumes that the result over the analysis period is all that needs to be justified, and no consideration is given to the subsidization of losses or smaller benefits that may occur early in the life of the project by profits or larger benefits that may accrue in later years.

The preferred decision rule is the first-year benefits criterion; i.e., the road should be paved when the ratio of the net first-year benefits to the construction cost equals the relevant interest rate or opportunity cost of capital. In a situation where the budget is strictly limited, the relevant interest rate is in fact the return on the marginal highway project that must be foregone. This may be several times the market rate of interest. Road paving projects ordinarily meet the conditions that are needed to ensure that the first-year rule will yield the correct solution.

Information Used in Analysis

The unit costs used in the analysis were those in force in Texas in 1980, shown in Figure 1. Some of the user cost relations (12,13) from the Brazil study were adjusted for use in MDS to reflect vehicle use rates and relative costs of the different components, as suggested by the American Association of State Highway and Transportation Officials (AASHTO) Red Book on user benefit analysis (14). Regravelling and paving unit costs were deduced from contract rates received by the Texas Highway Department in 1980.

The relative proportion of the four vehicle classes shown in Figure 1 was maintained for each of the traffic levels. A good lateritic gravel, whose properties are shown in Figure 1, was used as a wearing course material for the evaluations.

Geometry along a rolling terrain, which is quantified in Figure 1, was selected as a representative geometry for low-volume roads in developing countries.

For the paved road analysis the traffic and road geometry characteristics were maintained as for the unpaved road. A standard pavement structure over the 15 California bearing ratio (CBR) subgrade was selected, which consisted of 150-mm gravel subbase, 150-mm graded crushed stone or gravel base, and a single surface treatment surfacing. According to the draft Technical Recommendations for Highways (TRH) 4 (15), this structure can accommodate up to 3 million equivalent 80-kN axle loads, which is the range normally found on lightly trafficked roads, such as those under consideration.

The deterioration relations that were used in the evaluation of the paved road performance were developed elsewhere (11) and are shown in Figure 2. The change in roughness is determined mainly by repairs that are made to the road, such as the filling of potholes or patching. For the purpose of the exercise, the need for repairs was assumed. Resealing of the road closes the cracks in the road surface and thus retards further deterioration to wider cracks and ultimately reduces or delays the need for repairs, hence the plateau in the curve showing the development of repairs. A reseal, furthermore, does not have the capability of restoring the riding quality, and thus the effect of repairs prior to the reseal remains. The roughness profile is used to compute road user costs on the paved road.

INVESTIGATION OF WARRANTS FOR PAVING

The ensuing discussion is based on the results obtained with the unit costs shown in Figure 1. Different unit costs may lead to different results, although the general conclusions will probably remain similar. The analysis of the unpaved road was based on the premise that the road remains trafficable at all times. This therefore excluded earth roads, which are adequate for traffic volumes only up to about 40 vehicles/day and can be closed during periods of heavy rainfall. Traffic volumes investigated ranged from 50 to 500 vehicles/day.

Break-Even Traffic Volume

The total cost concept, which consists of the sum of the costs of construction, maintenance, and those incurred by the road user, is used. The break-even traffic volume is the volume that prevails in the first analysis year when the total cost on an unpaved road equals the total cost on a paved road. Paved road construction and maintenance costs can vary widely from region to region, and these were therefore kept as a dependent variable in the evaluation; this variable then equals the total discounted cost on the unpaved road minus the discounted user cost on the paved road. The discounted paved road construction and maintenance costs as a function of the ADT during the first analysis year are shown in Figure 3 for different analysis periods.

The paved road construction costs only include the pavement layers above subgrade to make the analysis comparable to that for unpaved roads. A reasonable discounted construction and maintenance cost over 20 years for the selected paved road structure is about $50 000/km based on 1980 contract prices obtained from the Texas Highway Department (10). In Figure 3 the break-even traffic volume is thus 400 vehicles/day for the unit costs employed. The break-even traffic volume for alternative discounted construction and maintenance costs can be read from Figure 2.

Often the analysis period used for gravel roads is less than the 20-year period applied to paved roads because of the tremendous uncertainty about traffic volumes on newly developed roads. Because the design life of a paved road is usually about 20 years, the value of the pavement at the end of shorter analysis periods needs to be considered. The salvage value of a paved road is fairly difficult to compute. Two approaches can be used (15):

1. The residual structural salvage value is the saving in cost of constructing a new pavement as opposed to placing an overlay on the existing pavement to bring it to the same condition as the new pavement and to ensure that it can carry the same traffic as the new pavement to the same terminal condition.

2. The salvage value of recycled layers is the difference in cost between furnishing new materials and the cost of taking up and recycling old materials.

Both these salvage value calculations are uncertain, and therefore, for the purpose of the analysis, the outcome will be generalized in terms of relative costs. The salvage value for the gravel roads is taken as the cost of placing the remaining wearing course material. In Figure 3 it is obvious that the

Figure 1. Information used in analysis.

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BASIC DESIGN INFORMATION
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 LENGTH OF THE ANALYSIS PERIOD (YEARS)                              10.0
 LENGTH OF ROAD LINK (KM)                                           10.0
 MINIMUM TIME BETWEEN REGRAVELLINGS (YEARS)                          1.0
 REGRAVELLING STRATEGY                                              SPOT
 SALVAGE VALUE OF GRAVEL SURFACING (PERCENT)                         100
 DISCOUNT RATE OR TIME VALUE OF MONEY (PERCENT)                     10.0
 ROAD WIDTH (M)                                                     10.0
 LENGTH OF DRY SEASON (DAYS)                                         210

TRAFFIC DATA
************

 AVERAGE DAILY CAR TRAFFIC AT START OF AN PERIOD                     300
 AVERAGE DAILY BUS TRAFFIC AT START OF AN.PERIOD                      10
 AVERAGE DAILY MEDIUM TRUCK TRAFFIC AT START OF AN PERD              100
 AVERAGE DAILY HEAVY TRUCK TRAFFIC AT START OF AN PERD                90
 ANNUAL GROWTH RATE OF CAR TRAFFIC (PERCENT)                         5.0
 ANNUAL GROWTH RATE OF BUS AND TRUCK TRAFFIC (PERCENT)               5.0

MATERIAL INFORMATION
********************

 PERCENTAGE OF SURFACING MATERIAL PASSING 0.074 MM SIEVE              15
 PLASTICITY INDEX OF SURFACING MATERIAL (PERCENT)                      5
 SOAKED CBR OF GRAVEL SURFACING (PERCENT)                             80
 SOAKED CBR OF INSITU ROADBED (PERCENT)                               15
 TYPE OF SURFACING TO BE EVALUATED                                  GRAV
 SURFACING MATERIAL TYPE                                            LATR
 IS ROAD WITHOUT SURFACING PERMITTED TO BECOME IMPASSIBLE

CONSTRUCTION INFORMATION
************************

 AVERAGE GRAVEL THICKNESS AT START OF AN.PERIOD (MM)                   0
 MINIMUM ALLOWABLE THICKNESS OF ADDED GRAVEL (MM)                     75
 ROUGHNESS AT START OF ANALYSIS PERIOD (QI*)                          50

COST INFORMATION
****************

 COST OF GRAVEL SPREAD,DLRS/M3                                     12.00
 COST OF MOVING REGRAVELLING EQUIPMENT TO LINK,DLRS                    0
 COST OF NEW CAR,DLRS                                               6500
 COST OF NEW BUS,DLRS                                             135000
 COST OF NEW MEDIUM TRUCK,DLRS                                     19000
 COST OF NEW HEAVY TRUCK,DLRS                                      40000
 COST OF GASOLINE,DLRS PER LITER                                     .28
 COST OF DIESEL FUEL,DLRS PER LITER                                  .27
 COST PER CAR TIRE,DLRS                                               50
 COST PER BUS OR TRUCK TIRE,DLRS                                     250
 DAILY COST TO OPERATE MOTOR-GRADER,DLRS                             200

ROAD GEOMETRY
*************
 PERCENTAGE OF LENGTH OF LINK IN EACH CATEGORY
                               GRADE (PERCENT)
    CURVATURE       *  0-2  *  2-4  *  4-6  *  6-8  *  8-10 *
 TANG AND RAD>400M  *  50.  *  10.  *  10.  *   0.  *   0.  *
 400M>RADIUS>200M   *  10.  *  10.  *  10.  *   0.  *   0.  *
 200M>RADIUS>100M   *   0.  *   0.  *   0.  *   0.  *   0.  *
 RADIUS<100M        *   0.  *   0.  *   0.  *   0.  *   0.  *

PRINTOUT CONTROLS
*****************

 IS PRINTOUT OF REGRAVELLING STRATEGIES REQUIRED                       N
 IS PRINTOUT OF ROUGHNESS STRATEGIES REQUIRED                          Y

COMPUTED INFORMATION
********************

 MINIMUM ALLOWABLE GRAVEL THICKNESS (MM)                              49
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Figure 2. Deterioration relations on selected paved road.

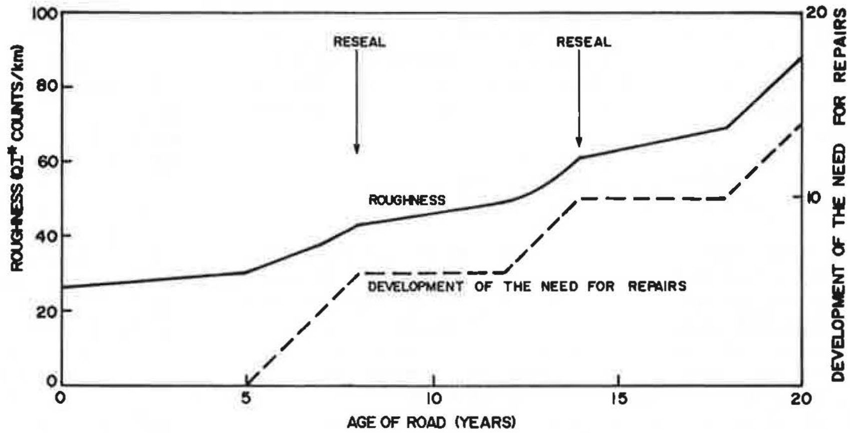
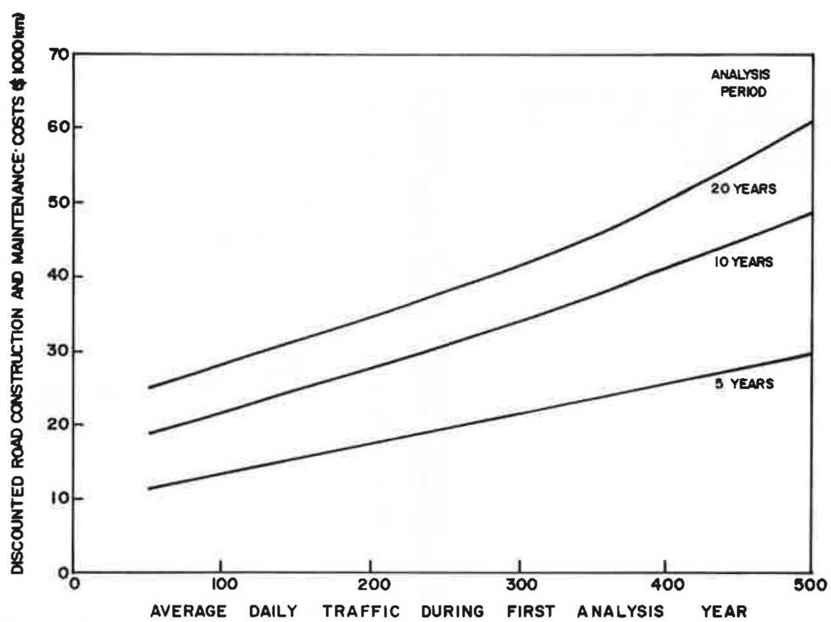


Figure 3. Discounted paved road construction and maintenance cost for a total cost equal to that on unpaved roads.



same break-even traffic volume will be obtained for a shorter analysis period provided that the discounted road construction and maintenance cost minus the discounted salvage value bears some relation to this cost over a 20-year analysis period, shown in Figure 4. The ratios for the 5- and 10-year analysis periods are fairly constant and are approximately 2.0 and 1.25, respectively. Thus, if the computed salvage value is such that the discounted construction and maintenance minus salvage cost over the 5-year period is less than half that of the 20-year period, then the break-even traffic volume will be lower than that computed from the 20-year period. The converse is true if the ratio is greater than half.

Before the decision to use a 20-year or shorter analysis period can be made, the decisionmaker needs to weigh the uncertainty in traffic over a 20-year analysis period against the uncertainties in computing the salvage value at intermediate points in the life of a pavement structure. The use of a 20-year analysis period would be recommended for most cases.

First-Year Benefit Criterion

The road should be paved when the ratio of the net first-year benefits (i.e., savings in road user costs and road maintenance costs) to the additional construction cost of a paved road over an unpaved road equals the relevant interest rate. For the analysis the unpaved road maintenance cost used was that found to give the least total cost. Figure 5 shows the plot of the net first-year benefits as a function of ADT. The ratio of the net first-year benefits to the paved road construction cost of $30 000 and $40 000/km, minus the unpaved road construction cost of $12 000, is also shown. A construction cost of about $40 000/km is approximately equivalent to the discounted construction and maintenance cost of $50 000/km used in the break-even traffic example. The ADT at which a paved road should be constructed for a discount rate of 10 percent is approximately 575 vehicles/day, which is almost 50 percent greater than the break-even traffic volume. This result is similar to that reported by Harral and others (4). It illustrates the extent to which larger benefits later in the life of the pavement subsidize earlier smaller benefits in the break-even traffic volume calculations.

Although the first-year benefit criterion is the preferred one, care should be taken in its application. A cheap paved road structure may be designed that may last a very short period and then require extensive maintenance and even rehabilitation. Stage construction may be considered to fall into this category. In such a case the discounted rehabilitation cost or cost of excessive maintenance that occurs after the first year should be added to the construction cost to give a more realistic assessment.

IMPACT OF REDUCED MAINTENANCE FUNDS ON THE WARRANTS

One of the major concerns about the establishment of a road infrastucture is the effect that a reduction of the maintenance budget could have on the optimally selected pavement design. Frequently the construction of roads in developing countries is financed by international loans or grants; however, maintenance is funded by the government from internal sources through the treasury department. A reduction in funds available to the treasury frequently results in a cut in the maintenance budget. The influence of such a cut on the warrants for paving thus needs to be investigated.

The unpaved road analysis was constrained to provide access throughout the year. A cut in the maintenance budget could therefore not affect the regravelling strategy, and its result would only influence routine blading. Within the policy constraints evaluated, a complete cut in the funds available for maintenance is infeasible, because the road would become impassible within one to two years, depending on the traffic. The influence of reducing by half the funds available for blading on the discounted paved road costs is illustrated in Figure 6. The break-even traffic approach is used because road engineers are better able to relate to costs than to benefits or discount rates. To convert to the first-year benefit rule, the break-even traffic volume should be increased by half; for example, an ADT of 400 becomes 600 for the first-year benefit rule. The reduction of available routine

Figure 4. Ratio of discounted maintenance and construction cost of 20-year analysis period relative to other analysis periods to give same break-even traffic volume.

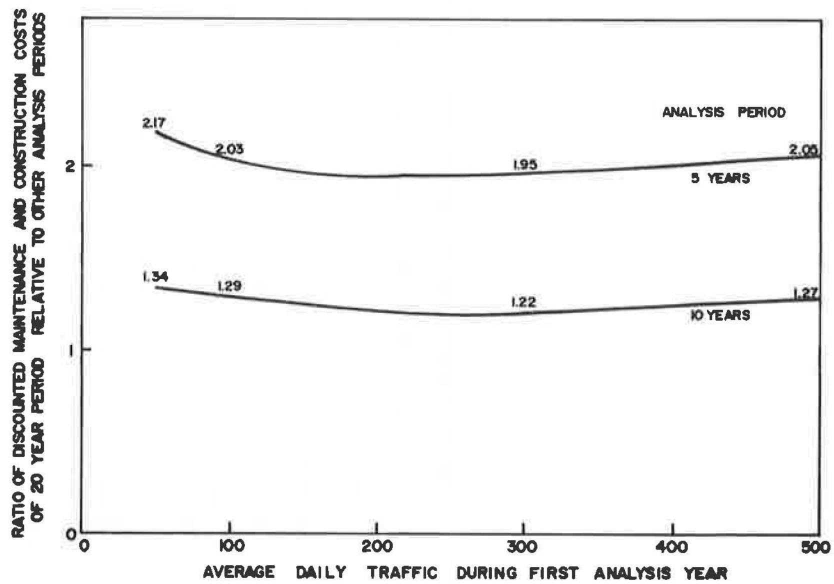
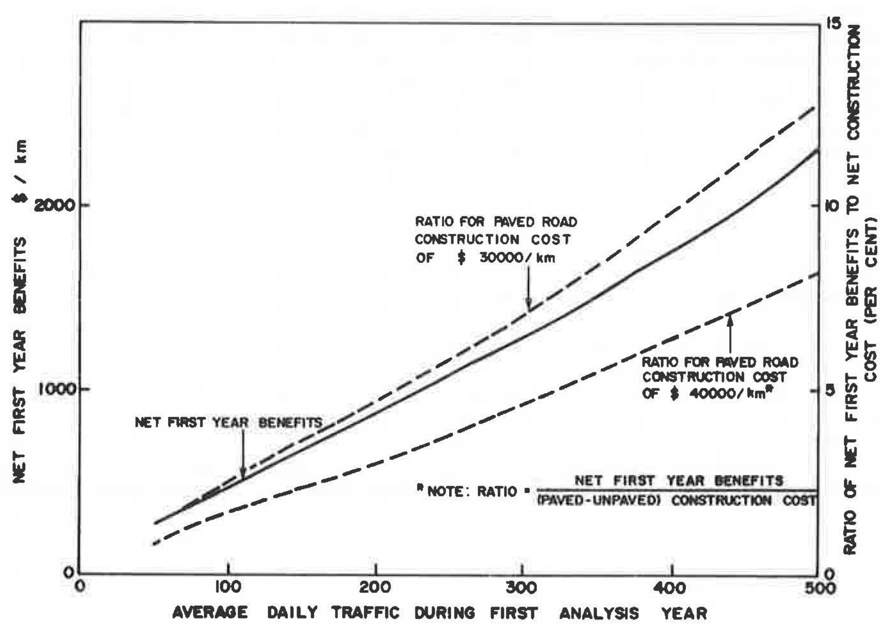


Figure 5. Results of computations according to first-year benefit criterion.



maintenance funds by half has a minimal influence on the warrants for paving. This is because the routine maintenance cost is a relatively small part of the total cost, and the slope of the total cost curve in the proximity of the least total cost blading frequency is flat. However, for one or two bladings per year, the curve is very steep, as was shown earlier (10).

The likelihood of a cut in the routine maintenance budget will also affect the paved road alternative. The filling of potholes and repairs usually have a high priority, and therefore, a cut in the budget would probably result in the deferment of a reseal. In Figure 2, if the reseal due after eight years is deferred and the need for repairs continues at the same rate, then an expensive rehabilitation or overlay may be necessary after about 12 years. A paved road may therefore be more sensitive to reductions in the maintenance budget than unpaved roads under the system of constraints analyzed.

In cases of extensive cutbacks of the maintenance funds, the system of constraints under which the road system is maintained may be altered. Passability throughout the year may be eliminated, and this would then have the effect of a reduced regravelling expenditure, since the reversion of a gravel road to an earth road would be feasible. Figure 7 illustrates the relative cost components of the total cost. In those cases in which the road is permitted to revert to an earth road, a careful economic analysis is necessary to evaluate the impacts of the reduced regravelling expenditure on additional road maintenance and delay costs. Such an approach would probably not be economically feasible, and an analysis could provide data to back up technical arguments.

EFFECTS OF REGRAVELLING COSTS ON WARRANTS FOR PAVING

At the optimal blading frequency the average road roughness of an unpaved road is similar to the average roughness of a paved road during its service

Figure 6. Discounted paved road construction and maintenance costs for different unpaved road blading budgets.

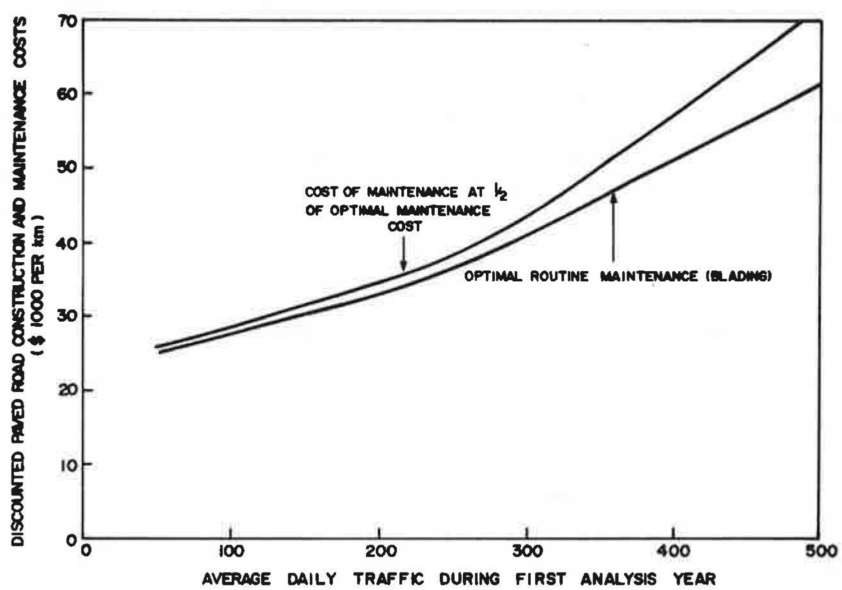


Figure 7. Illustration of relative costs on unpaved roads.

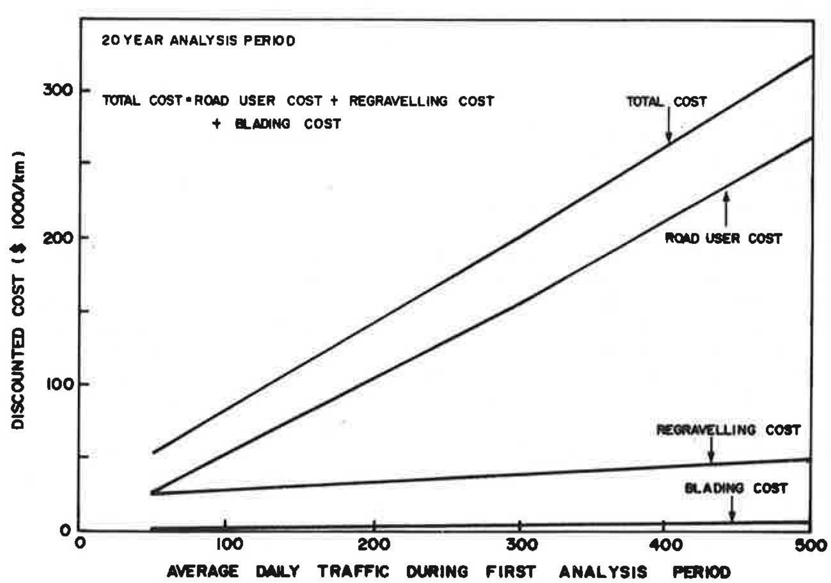
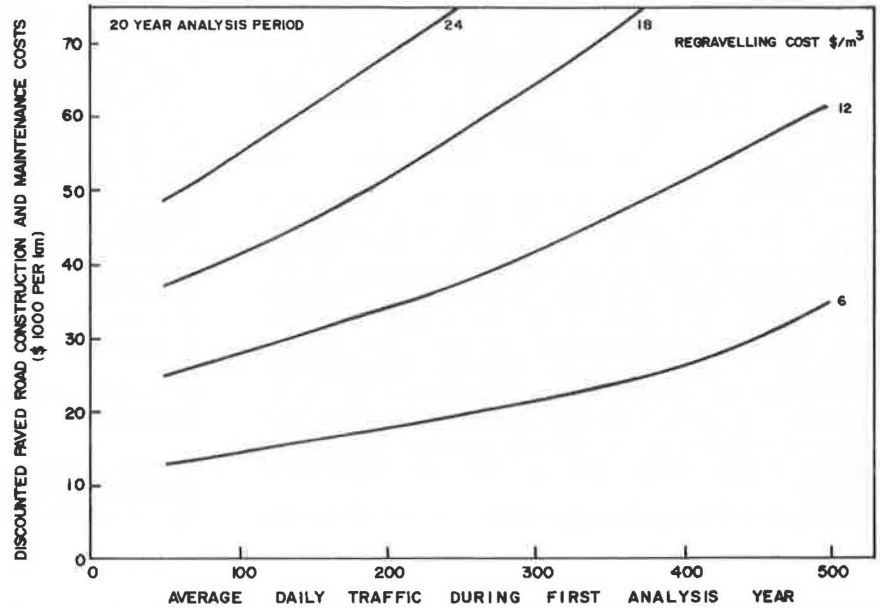


Figure 8. Discounted paved road construction and maintenance cost for different unit costs of gravel.



life based on observations in Brazil (e.g., average roughness of optimal blading for 500 ADT is a QI of 47 for the good laterite gravel over a 20-year analysis period) (10). Consequently, the discounted road user costs during a 20-year period are similar for the two road types, unlike results reported by Winfrey (2). However, over the short term the user costs on a new paved road are lower than on an unpaved road and follow the results presented by Winfrey. Broadly speaking, the main determinant for paving is therefore whether the discounted paved road maintenance and construction cost is less than the discounted regravelling and blading cost. In Figure 7, the regravelling and blading costs are approximately equal to the paved road cost of $50 000/km used previously in the ADT range of 400-500 vehicles/day. The regravelling cost thus has an important impact on the warrants for paving.

The discounted paved road construction and maintenance costs for different unit costs of gravel are shown in Figure 8. In the previous evaluations a regravelling cost of $12/m³ was used. At current transportation costs, if the gravel had to be transported an additional 30 km, then the unit cost would increase from $12 to $18/m³. If the paved road construction cost remained at $50 000/km, then the break-even traffic volume would reduce to about 200 vehicles/day, or about 300 vehicles/day according to the first-year benefit rule. Conversely, if the gravel wearing course material were abundantly available alongside the road, as reflected by a cost of $6/m³, then paving would not be economically desirable until a traffic volume greater than about 600 or more vehicles/day is reached.

The cost of constructing a paved road is usually related to the unit cost of gravel wearing course material, thus a greater unit cost may not necessarily lead to a reduction in the traffic volume for paving because of increased paving costs. In some cases this rule may not hold. In the Orange Free State, in South Africa for example, a decomposed dolerite is frequently used as a gravel wearing course. Depending on the state of decomposition, hard rocks of unweathered parent material about 100-200 mm in diameter are found. The use of this material as a gravel wearing course results in frequent regravelling because the fine material on the surface is abraded away between the rocks to leave a very rough surface. Blading is then ineffective in reducing the roughness. This type of material is adequate for use in a paved road and is frequently abundantly available. Better quality material is often transported over 50 km or more; therefore, the construction cost of a paved road is not linked to the cost of the better quality wearing course gravel material. A similar situation exists in Brazil, where the fine-grained coffee soils in the states of Sao Paulo and Parana become impassible during the rainy season. However, when this material is used in a paved road structure and if they can be kept dry, the road performs adequately.

These results show that it is not feasible to generalize warrants for paving and that every case should be evaluated individually. As a rough guideline, the traffic volume at which paving should occur is about 50 percent higher than the traffic volume at which the paved road construction and maintenance costs over a 20-year period equal the discounted regravelling and blading costs.

DUST, ACCIDENTS, AND INTANGIBLE INFLUENCES

In the foregoing analysis, quantifiable aspects of construction, maintenance, and user costs were included. However, certain aspects, which may hold important implications, have not been quantified.

Dust

Dust is often considered as a nuisance, but it is difficult to express comfort in monetary terms, because road users are not willing to pay for this sort of comfort. The effect of dust on crops and livestock has been mentioned, but apparently little has been quantified. For example, in cotton-growing areas gravel roads are sometimes paved because the dust affects the cleanliness of the cotton, which may then render it unacceptable. The influence of dust on crops and livestock is an aspect that requires further attention; if the impact is significant, it could greatly reduce the traffic volume at which a road should be paved.

Accidents

Zaniewski and others reached the conclusion that there is no reliable information for making distinctions in accident rates among pavement types and conditions (16). Other researchers (17,18) have shown that accident costs on low-volume roads are an inconsequential part of the total cost of road use. A global estimate of accident rates on two-lane paved and unpaved roads in South Africa showed that the rate for unpaved roads is about 0.63/million vehicle km, which is about four times lower than that for paved roads. This is ascribed to greater concentration by the driver at traffic volumes where traffic interference is minimal. It is thus possible that if a gravel road is paved at low traffic volumes the accident rate would increase, thus reducing the benefits of paving.

Exhaustion of Natural Resources

An aspect of gravel roads that is receiving increasing attention is the depletion of gravel. Initially, the best wearing course gravel is used, and as regravelling becomes necessary, material needs to be obtained from further afield. When the road requires paving, the gravel materials then have to be transported over long distances. This situation ties in with the findings of maintenance personnel, who have shown that the heaviest traffic on gravel roads has often been associated with those roads that have the worst materials.

A utility analysis, which ranks different alternatives in terms of subjectively assigned weights for unquantifiable and quantifiable factors, may be a method in which the depletion of natural resources can be considered. The effect of dust on comfort could then be evaluated in the same manner.

CONCLUSIONS

In the evaluation of warrants the preferred method of analysis, namely the first-year benefit rule, gave traffic volumes for paving that were about 50 percent larger than the break-even traffic volume that is frequently used. For the cost data obtained in Texas, the traffic volume at which a gravel road would be paved was about 575 vehicles/day. This figure is considerably larger than the 100 and 250 vehicles/day figure that is often actually used in different parts of the world. The difference in the predicted volume compared with warrants actually used may be attributable to a heavy weighting being given subconsciously to nonquantifiable aspects such as dust, comfort, and depletion of natural resources. Another factor may be the difficulty of maintaining regular bladings weekly or biweekly over a long period of time.

Based on observations in Brazil, the average roughness of a gravel road that is optimally maintained is similar to that of a paved road during its life. Consequently, road user costs are similar on paved and unpaved roads. The major implication for paving is thus the difference in discounted paved road construction and maintenance cost and the unpaved road regravelling and blading cost. The latter costs are primarily a function of the unit cost of gravel spread and compacted. It follows that each road should be evaluated individually and that generalizations may result in uneconomical practices because of the peculiarities of gravel cost that are usually unique for any particular road.

The impact of aspects such as dust, accidents, and depletion of natural resources has not yet been adequately quantified for inclusion in an economic analysis. These aspects are best evaluated, together with the results from an economic analysis, in a utility analysis.

Under the system of constraints in which the unpaved roads were analyzed, the reduction by half of the funds available for blading, compared with the optimal funding, had a minor effect on the warrant for paving. A complete reduction, however, would result in the road becoming impassable within 1-2 years. These results do not mean that blading funds should be reduced because it is likely that many organizations operate at the reduced budget level. A reduction in maintenance funds appears to have a greater impact on paved roads than on unpaved roads within the system of constraints used. Paving therefore does not seem to be the recommended procedure under conditions of uncertainty with regard to the availability of funds for maintenance.

RECOMMENDATIONS

The paper has illustrated the value of a detailed analysis of both economic and unquantifiable factors. The philosophy and procedure should be applied when decisions have to be made regarding the paving of unpaved roads and in the development of a new infrastructure in regions that were previously economically inactive.

The recommended procedure for determining the traffic level at which an unpaved road should be paved is use of the first-year benefits criterion. A special computer program, MDS, was developed to facilitate determination of the unpaved road design and maintenance strategy with the lowest total cost. The MDS program can be run on a desk-top computer and is thus readily available to most practitioners. An adapted version of this program was used to compute the user costs on paved roads. To run these programs, unit costs of materials and their characteristics, and other costs specific to the region are needed.

Care should be taken in applying the first-year benefits rule to those paved road designs in which the initial construction costs are deferred, such as for stage construction, and it is recommended that later costs of a special nature should be included as discounted construction costs.

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