Technical Options for Road Maintenance in Developing Countries and the Economic Consequences

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The basic issues concerning road maintenance are addressed: (a) selection of cost-effective maintenance policies, (b) effect of budget constraints on maintenance priorities, (c) relationship between initial pavement design strength and subsequent maintenance, and (d) economic traffic thresholds for paving gravel roads. The analysis is based on life-cycle cost simulation produced by the latest version of the World Bank's Highway Design and Maintenance Model (HDM-III), which evolved from an extensive program of empirical research conducted over more than 15 years.

Competing demands for resources require that developing countries search for the most economical design of highways and maintenance programs, taking into account not only the costs of government but also the larger costs of vehicle ownership and operation borne by road users. Under budget constraints, it becomes imperative to develop a system for assessing the priorities for the entire budget for the roads sector (capital and recurrent), which gives rise to a series of questions:

- How much should be spent on road maintenance and when should paved roads or unpaved roads be rehabilitated and maintained? Which maintenance measures have the highest payoff under varying circumstances?
- Can future maintenance requirements be reduced by building or restoring roads to higher standards today? Under what circumstances is this an economical strategy?
- How do budgetary and other constraints affect these choices? If restoring a deteriorated network implies acting on a core network and deferring or abandoning action on the rest of the network, what course should be chosen? What should receive higher priority: preventive maintenance on roads that are in fair condition or restoration of roads that are already in poor condition?
- What are the consequences of deferring maintenance on part or all of the network?
- Given the unsatisfactory state of road networks in most developing countries and the multitude of constraints to be overcome, what overall strategy should be adopted? Does it vary much from case to case?

Providing economic answers to these questions requires the ability to predict total transport costs—construction, reconstruction, maintenance, and road user costs—over the life cycle of the roads under various road design and maintenance strategies. The empirical knowledge concerning the underlying physical and economic relationships, particularly the road deterioration, user costs, and maintenance effects, has been too limited to lend much credibility to such modeling efforts.

Faced with this problem the World Bank in 1971 initiated what ultimately became an international collaborative program of primary data collection and research, first in Kenya and later, on a larger scale, in Brazil and India. The support for this effort came from the United Nations Development Program, the World Bank, and the governments of India, Kenya, Brazil, Sweden, Australia, and the United Kingdom. With participation by a number of research institutions, more than $20 million was spent for data collection and analysis to provide rigorous quantification of key relationships. Although gaps remain, basic relationships *(1, 2)* have now been statistically established for a substantial range of traffic and environmental conditions typical of developing countries. These new empirical relationships have in turn been incorporated into the World Bank's Highway Design and Maintenance Model (HDM-III), which, together with its companion Expenditure Budgeting Model (EBM), provides the capability to simulate and compare many alternative strategies according to standard economic criteria, with and without budget constraints *(3, 4)*.

Among the most important advances from this research program have been the twin abilities to (a) relate vehicle operating costs (VOC) to a measure of road surface condition (namely road roughness) and (b) measure roughness in a rigorous, systematic manner using the International Roughness Index (IRI) *(5, 6)*. As shown in Figure 1, vehicle operating costs constitute a large share (75 to 95 percent) of the total road transport cost, except when traffic volume is extremely low. Thus the effect on total transport cost of even a small percentage change in vehicle operating costs is large relative to the effect of changes in construction and maintenance costs. Before the HDM studies *(1, 7)*, no basic empirical data on the relationship between vehicle operating costs and pavement surface condition were available. Road investment decisions were guided by imprecise and fragmentary estimates of vehicle operation costs related primarily to the type of road (paved, gravel, earth). On the basis of improved estimation of vehicle speeds (in a free-flowing traffic regime) and operating costs as functions of road design characteristics, the HDM research suggests that vehicle operating costs are somewhat less sensitive to changes in road condition than previously estimated *(8)*.

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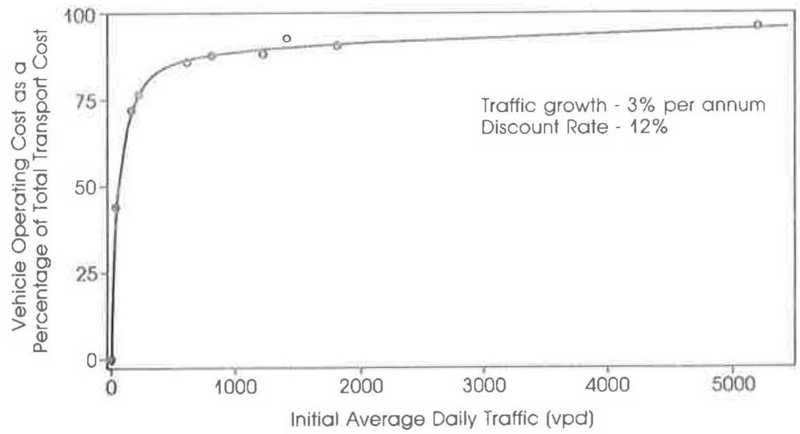


FIGURE 1 Vehicle operating costs as a percentage of total transport cost (construction, maintenance, and vehicle operating costs) for typical cases with optimal road maintenance.

CASE STUDIES

The HDM-III and EBM models were used in a series of case studies *(8)* to simulate the deterioration of roads under alternative maintenance options and to find the best investment and maintenance policies under various constraints. Road types and conditions, traffic, climate, and unit costs in the studies corresponded to those observed in three countries—Mali, Chile, and Costa Rica. Despite the limited inferences possible from the case studies, the consistency of the results permits generalizations for wider application.

Thirty-one maintenance policy alternatives were tested for paved roads and 10 for unpaved roads. The policies consisted of different maintenance packages (ranging from low-cost pothole patching, through bituminous resealing of the entire surface and more costly asphalt concrete overlaying, to major rehabilitation and reconstruction of the base and the surface) and specifications of the deterioration levels at which they would be applied. As a benchmark against which to measure differences in the costs of other alternatives, a null case was defined that included only the basic routine maintenance activities (drainage clearing, minimal vegetation control, and shoulder repair) that are also included in the other alternatives. Tables 1 and 2 contains a summary of the alternatives; each one is identified by a code (such as AL18), which will be used later in discussing the results. To illustrate, under alternative AL18, 100 percent of potholes would be patched each year, a surface treatment would be applied whenever 25 percent of the area was visibly damaged, and a 40-mm overlay would be applied whenever roughness reached a level of 5 on the IRI scale.

The roads in each country's network were grouped into broadly homogeneous classes according to surface type, condition in the initial year of the study, and traffic volume. For each class, road deterioration and maintenance activity over a 30-year period were simulated under various maintenance alternatives. Road maintenance costs and vehicle operating costs were computed, discounted to the initial year, and subtracted from costs for the null case, giving the net present value for each alternative relative to the null. From these results, the best strategy for different levels of available funds and discount rates was determined for each road class. The results for different road classes were combined with the aid of the EBM to find optimal network strategies, costs, and benefits under conditions of no budget constraint and also under varying levels and time periods of overall budget constraints. The detailed results from the case studies were used to explore cost-effective road investment and maintenance options. The main findings relate to the following factors:

- Selection of cost-effective maintenance policies.
- Optimization of maintenance expenditures under budget constraints.
- Decision criteria for pavement strength.
- Economic traffic thresholds for paving gravel roads.

SELECTION OF COST-EFFECTIVE MAINTENANCE POLICIES

The choice and staging of maintenance operations on paved and unpaved roads are strongly affected by the differences in their deterioration characteristics. On unpaved roads, the linear but rapid path of deterioration requires special attention to routine maintenance, particularly the frequency of blading. The nonlinear deterioration characteristics of paved roads offer more options for the choice and timing of maintenance.

To identify cost-effective road maintenance policies for paved roads, particularly under budget constraints, the trade-off between agency and user costs was examined. To illustrate, Figure 2 shows the results of such an analysis to evaluate maintenance alternatives (identified in this and other graphs by the codes in Tables 1 and 2) for low-volume paved roads in good to fair condition in Mali (average daily traffic of 400 vehicles). The bar chart (Figure 2a) shows the present value, discounted at 12 percent, of the net cost savings relative to the null case. To arrive at net cost savings, the increase in maintenance and construction costs incurred by the road agency is subtracted from the difference in vehicle operating costs. In most cases this yields a positive saving, but alternatives AL15, AL16, and AL17 (involving immediate application of a thick overlay) and alternatives AL20, AL21, and AL22 (involving immediate reconstruction) cost more than the benefits they yield when discounted at 12 percent.

Net present value, discounted at 12 percent, is maximized by strategy AL12 (patching all potholes annually and applying a

TABLE 1 MAINTENANCE POLICY ALTERNATIVES FOR PAVED ROADS

Alternative No.	Patching (percent area of potholes)	Resealing (percent applied to area damaged)	Overlay	Reconstruction
AL00 (Null)	0			
AL01	50			
AL02	100			
AL03	0			REC ST at 8.5 IRI
AL04	50			REC ST at 8.5 IRI
AL05	100			REC ST at 8.5 IRI
AL06	100	ST at 75[a]		
AL07	100	ST at 50		
AL08	100	ST at 25		
AL09	100	ST at 75		REC ST at 8.5 IRI
AL10	100	ST at 50		REC ST at 8.5 IRI
AL11	100	ST at 25		REC ST at 8.5 IRI
AL12	100		40 mm at 5 IRI	
AL13	100		40 mm at 4.2 IRI	
AL14	100		40 mm at 3.5 IRI	
AL15			IMM overlay (80 mm) + AL12	
AL16			IMM overlay (80 mm) + AL13	
AL17			IMM overlay (80 mm) + AL14	
AL18	100	ST at 25	40 mm at 5 IRI	
AL19	100	ST at 50	40 mm at 3.5 IRI	
AL20				IMM REC ST + AL12
AL21				IMM REC ST + AL13
AL22				IMM REC ST + AL14
AL23	0			REC AC at 8.5 IRI
AL24	50			REC AC at 8.5 IRI
AL25	100			REC AC at 8.5 IRI
AL26	100	ST at 75		REC AC at 8.5 IRI
AL27	100	ST at 50		REC AC at 8.5 IRI
AL28	100	ST at 25		REC AC at 8.5 IRI
AL29				IMM REC AC + AL12
AL30				IMM REC AC + AL13
AL31				IMM REC AC + AL14

NOTES: All alternatives include basic routine maintenance such as drainage clearing, minimal vegetation control, repair of shoulders and drains. ST = bituminous surface treatment; AC = asphalt concrete; REC = reconstruction with either ST or AC surface; IMM = immediate (i.e., first year of the analysis period); IRI = International Roughness Index.

[a]Damaged area constitutes the area of pavement surface with specific signs of distress and visible defects.

TABLE 2 MAINTENANCE POLICY ALTERNATIVES FOR UNPAVED ROADS

Alternative No.	Blading Frequency	Spot Regraveling	Gravel Resurfacing
AL00 (Null)	None	None	None
AL01	Once a year	30 percent of material loss	None
AL02	Every 8,000 vehicle passes	30 percent of material loss	None
AL03	Every 6,000 vehicle passes	30 percent of material loss	None
AL04	Every 4,000 vehicle passes	30 percent of material loss	None
AL05	Every 2,000 vehicle passes	30 percent of material loss	None
AL06–AL10	Same as AL01–AL06 in Table 1 but with gravel resurfacing		150 mm whenever thickness < 50 mm

NOTES: All alternatives include basic routine maintenance such as drainage clearing, minimal vegetation control, repair of shoulders and drains.

40-mm overlay whenever pavement roughness exceeds 5 IRI). But several other alternatives with different combinations of vehicle operating costs and road agency expenditures are almost as good by this measure. This finding is important because it widens the room to maneuver when agencies are subject to budget constraints. For example, the curve in Figure 2b relating agency expenditures to vehicle operating costs for selected alternatives shows that AL05 (pothole patching until roughness reaches an IRI of 8.5, then reconstruction) entails about one-half the road agency expenditure of alternative AL12, whereas vehicle operating costs are higher by about $1.10 for each agency dollar saved—a net loss of only $0.10 per $1.00 of reduction in agency expenditure. If funds are limited, this may be an attractive option.

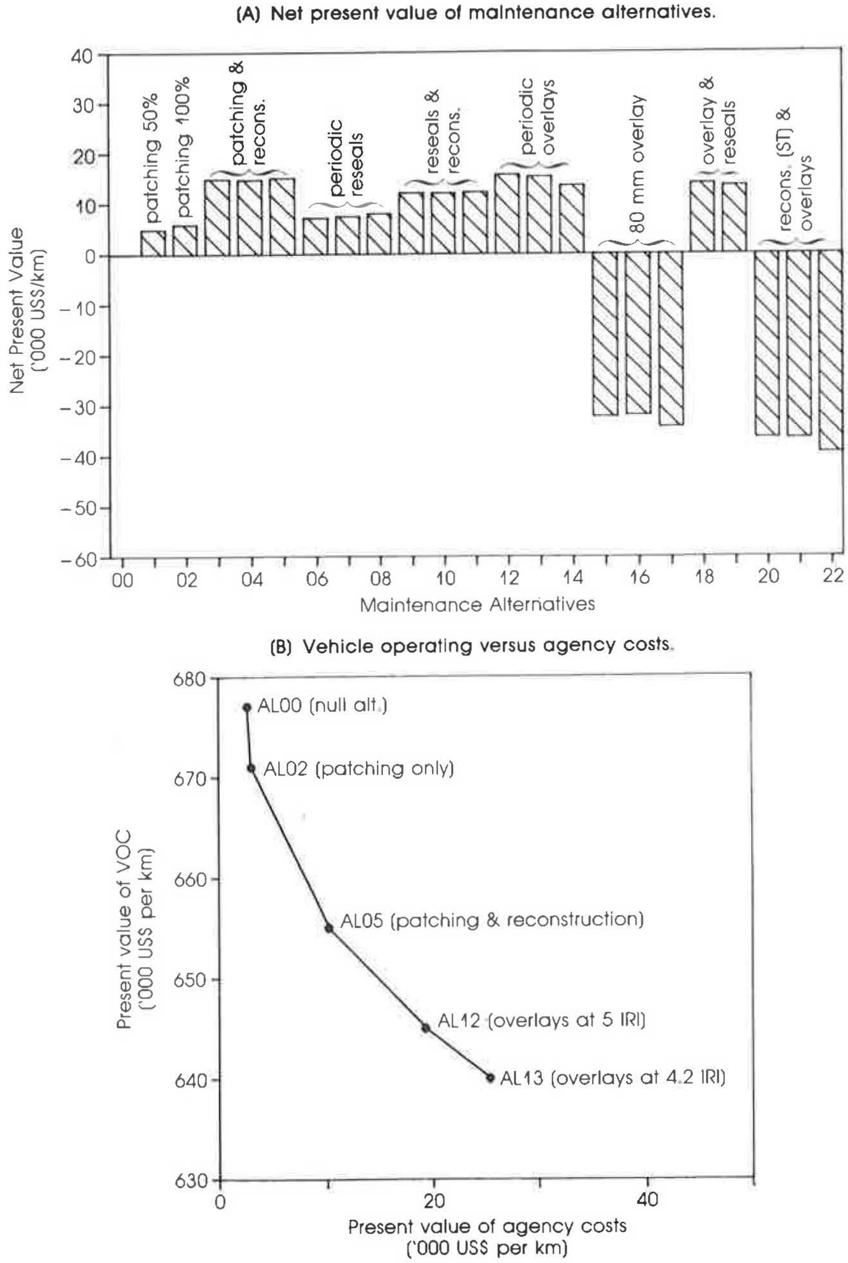


FIGURE 2 Low-volume paved road in good to fair condition (Mali). Analysis of maintenance alternatives.

The net present value of total transport costs for different levels of agency expenditures is shown in Figure 3 for four cases. The most efficient maintenance alternatives lie on the positively sloped segment of the outer boundary—the efficiency frontier. Alternatives represented by points inside the frontier are always inferior to a combination of maintenance options lying on the frontier. For example, in Figure 3a (Mali), alternative AL09 has a net present value of $12,000/km at a present value of agency cost of $15,800/km. A higher net present value should be obtained at the same agency cost by using AL05 on part of the road group and AL12 on the remainder, giving an average result that lies on the line connecting AL05 and AL12 on the graph. In the absence of budget constraints, the alternative that maximizes net present value should be selected.

Agency expenditures beyond this point (AL05) result in benefits that are less than the increased costs, as reflected by declining net present value. The curve also shows the optimal order of retracting when agency resources are cut. The lower-order options are selected by successively reducing agency expenditures in ascending order of their marginal contribution to net present value. Where traffic is heavier and especially where roads are initially in poor condition (Figures 3b and 3c), the economic loss per dollar saved by the agency is considerably higher and, of course, successive reductions in expenditure have increasingly costly consequences. The steepest slope of the efficiency frontier, indicating the severest penalty, is reached when the only expenditure available for cutting (always excepting minimal routine maintenance) is pavement patching. In none of these choices is agency cost today traded

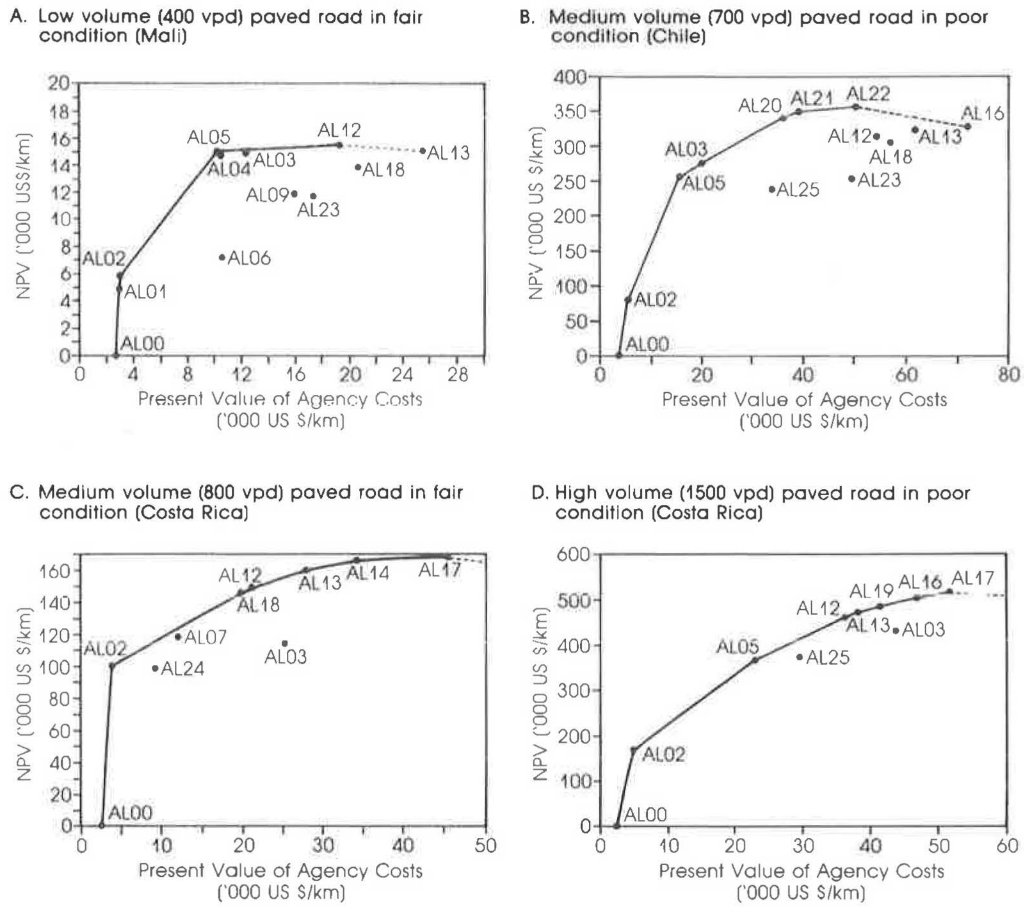


FIGURE 3 Net present value versus agency expenditures for different maintenance strategies.

off against significantly higher expenditures in the future; costs are simply transferred from the agency to the road users.

On unpaved roads, the primary maintenance-related determinant of roughness—and so of the cost of operating vehicles—is the frequency of surface blading. Simulation and costing of the effects of the various maintenance options (Table 1) show that blading costs and vehicle operating costs are closely balanced over a wide range of blading frequencies. Optimal blading frequency is in the range of one blading every 4,000 to 8,000 vehicle passes, which is consistent with generally accepted good practice (e.g., one blading a month at 150 to 200 vehicles a day). Incremental increases in blading frequency within this range result in marginal reductions in user costs that are almost completely offset by corresponding increases in agency cost. Figure 4 shows plots of net present value (NPV) versus blading frequency obtained from the Costa Rica case study.

Even at low traffic levels (25 vehicles a day), the economic returns on blading are substantial. Blading once a year appears to be an acceptable minimum threshold. Although blading once after every 4,000 to 8,000 vehicle passes would be an optimal policy, less frequent blading does not occasion serious economic loss if the road is regraveled at appropriate intervals.

Local conditions will strongly influence the maintenance options for unpaved roads. Extreme combinations of soils and climate (sands in arid climates, heavy clays in wet climates) may justify surfacing earth roads with gravel at an average daily traffic flow of fewer than 50 vehicles to ensure accessibility.

Where capital—especially foreign exchange—is scarce and unskilled labor is available at competitive rates (currently about $5 or less a day), the use of labor-based work methods for spot repairs on gravel roads and of simple drags attached to agricultural tractors or trucks to even out surface corrugations could prolong the time between bladings with mechanical graders. For unpaved roads with very low traffic volumes, increased use of labor for spot repairs could offer a viable alternative to mechanical means of maintenance, with the lower maintenance costs offsetting the somewhat higher vehicle operating costs *(9)*.

OPTIMIZATION OF MAINTENANCE EXPENDITURES UNDER BUDGET CONSTRAINTS

When the maintenance budget for a network is less than that required for the overall optimum, allocations to specific road classes (lengths of road sections grouped together on the basis of similar design, traffic, and condition characteristics and, where appropriate, further stratified by regional, climatic, or other relevant factors) must be reduced from their optimal levels. However, maintenance expenditures should not be reduced uniformly across all road classes. The loss in net present value will be minimized by first reducing allocations to road

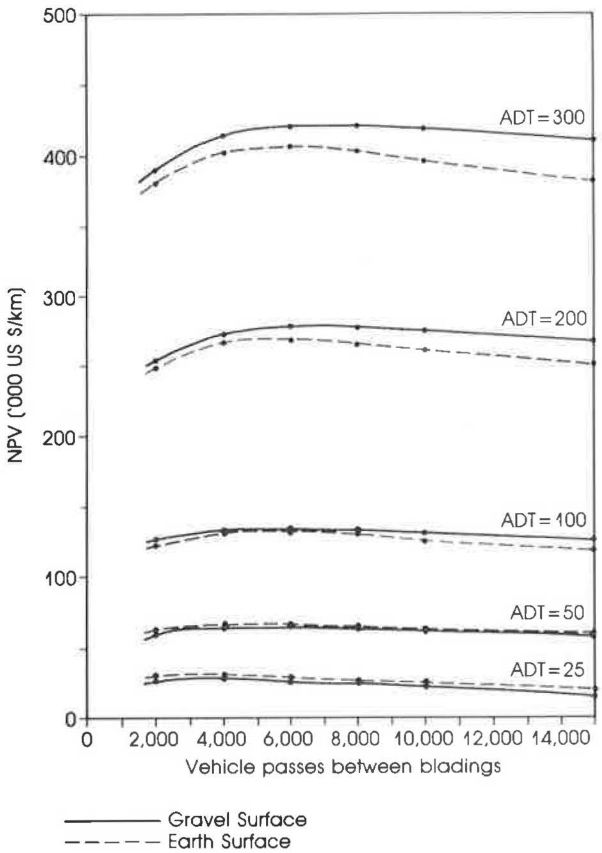


FIGURE 4 NPV versus blading frequency.

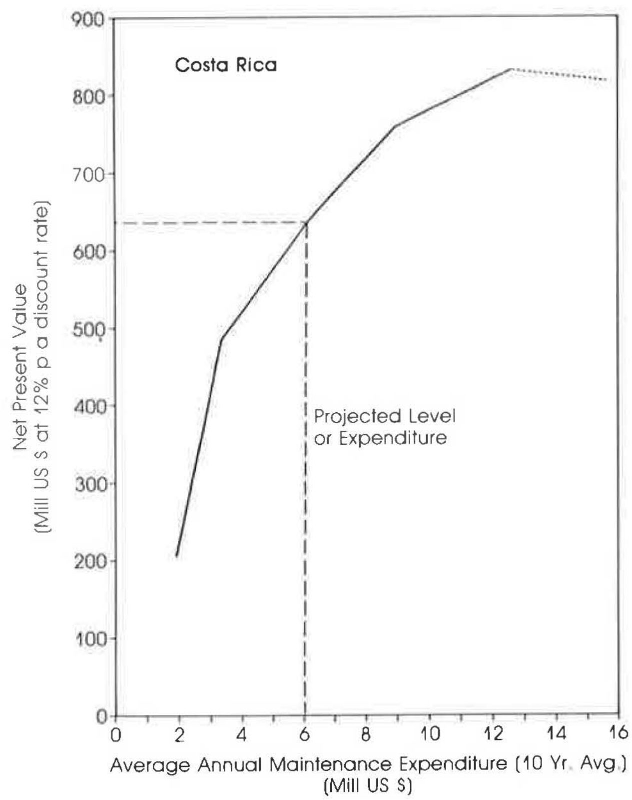


FIGURE 5 Variation of NPV for the entire road networks as a function of average maintenance expenditures.

classes for which the efficiency frontier is least steep. In general, candidates for cutting are high unit-cost maintenance operations on roads with low volumes and good existing surfaces. After the optimal activities have been completely replaced by next best options in a road class, the penalty for further cutbacks will be proportionately greater—the frontier will be steeper—and it may be economical to reduce allocations to some other road classes as well. Roads with high volumes and poor surface conditions suffer the greatest loss in benefit for each dollar of reduction in maintenance outlay, and their allocations should be reduced last.

The effects of reductions in the maintenance budget on the choice of alternatives and on the resulting benefits were examined for the road networks of Costa Rica, Chile, and Mali. In Costa Rica the maximization of total net benefits would require spending an average of $12.5 million/year on maintenance over the first 10 years with $38 million needed in the first year alone to rehabilitate the paved roads in poor condition. Figure 5 shows the maximum net present value of benefits (discounted at 12 percent a year) for the Costa Rican road network under different levels of average annual maintenance expenditures, optimally allocated among different classes of roads. If the budget is raised from the presently planned level of $6 million a year to the optimal level of $12.5 million a year over 25 years (or by $51 million in present value), the attainable net present value (with the best use of the funds in both cases) increases by $200 million, from $635 million to $835 million. The optimal program, even with unlimited funds, would not keep all roads in good condition. In Costa Rica, a high level of maintenance is required to keep two-thirds of the paved roads in good condition with the other one-third to be maintained to lower standards.

For Chile the best maintenance strategy for the road network is similar to that for Costa Rica: two-thirds of paved roads to be kept in good condition while maintaining the rest at lower standards. The optimal program involves immediate major expenditures on the rehabilitation of paved roads and assigns high priority to that activity even if the budget is cut.

In Mali, by contrast, where 84 percent of the paved roads carry fewer than 200 vehicles a day, only patching and basic routine maintenance are economically justified on most roads. The most economical option is indeed to keep only about 1 percent of the paved network in good condition with the rest of the network maintained at considerably reduced standards, mainly by patching and routine maintenance on paved roads and minimal blading on unpaved roads. Even so, about $9 million is required to clear Mali's backlog of economically warranted rehabilitation projects for higher-volume paved roads currently in poor condition. The average annual expenditure required to maintain the combined network of paved and unpaved roads is estimated to be about $6.2 million a year—about twice the current expenditure.

Maintenance activities are often deferred during periods of austerity. For unpaved roads, as long as basic routine maintenance is carried out regularly, the primary effect of deferring blading and, to a lesser extent, regraveling is to increase vehicle operating costs during the deferral period. The effect on subsequent road restoration costs is not large unless the road is allowed to become virtually impassable so that it has to be reconstructed, generally on a new alignment. For paved roads, both effects can be important: vehicle operating costs increase during the deferral period, and the cost of later pavement rehabilitation can increase substantially, depending on the stage in the deterioration process when deferral occurs. On newly constructed or rehabilitated pavements with light traffic loading, the effect of deferring maintenance (other than basic activities such as drainage) for 1 to 5 years is negligible. Once pavement condition becomes fair or poor, the impact is large.

DECISION CRITERIA FOR PAVEMENT STRENGTH

When a new pavement is constructed or an existing one replaced or overlaid, the choice of design strength should take into account the reliability of future maintenance. Low probabilities of adequate maintenance and timely strengthening in the future favor building a strong pavement initially because stronger pavements enjoy a longer grace period during which maintenance needs are minimal. A normal full-strength pavement is defined as one designed on the basis of accepted pavement engineering principles to carry a specific number of cumulative equivalent standard axle loads (ESALs) until an unacceptable level of functional serviceability is reached. To compensate for inadequate maintenance, a higher pavement strength than provided by normal designs may be warranted in certain situations. High probabilities of good maintenance will favor time-staging—that is, economizing on today's pavement and strengthening subsequently as needs emerge. Time-staging at the network level, however, is effective only when the condition of pavements is regularly monitored and evaluated with an appropriate pavement management system. Otherwise it is difficult to predict the critical points in the pavement life when a major maintenance intervention may be needed to prevent premature structural failure.

To justify the time-staging of road construction, a minimum probability of adequate future maintenance is required. To estimate this threshold probability, life-cycle costs for pavements with initial structural strengths ($\overline{SN}$) of 2.0, 3.5, and 5.0 were estimated for a range of traffic volumes and axle loadings in Costa Rica (light) and Mali (heavy). Three of the cases are shown in Figure 6. Each case shows life-cycle costs (at a 12 percent discount) for the first 14 of the 31 maintenance alternatives for paved roads specified in Table 1. In Case A, with average daily traffic (ADT) of only 500 vehicles per day (vpd) and light axle loadings, it would suffice to use a normal design ($\overline{SN}$ = 2.0) commensurate with the estimated ESALs because the life-cycle costs are consistently higher for a higher strength compensating design ($\overline{SN}$ = 3.5) under all maintenance assumptions. But with heavier traffic a different conclusion emerges, as shown by Case C (ADT = 2,500 and heavy axle loading). In this case, a normal full-strength pavement ($\overline{SN}$ = 5) will have a lower life-cycle cost, under almost any assumption about future maintenance, than one with a lower initial strength ($\overline{SN}$ = 3.5), which represents the time-staging option. At or above this combination of traffic and axle loadings it would not pay to consider the time-staging option.

Between these two limits, the decision for or against time-staging of construction is reached by balancing the potential loss if no maintenance will be done against the cost saving from time-staging that would be realized if future maintenance (including strengthening) were performed as desired. In this way a threshold probability of performing good maintenance in the future is obtained, above which the time-staging option could be justified. For Case B in Figure 6, for example, with an ADT of 1,000 vpd and light axle loads, this threshold probability may be derived as follows:

Let

x = probability of optimal maintenance (ALT 14),
$1\text{-}x$ = probability of nil maintenance (ALT 00), and
Dopt = difference in life-cycle costs for initial pavement strength of $\overline{SN}$ 3.5 and $\overline{SN}$ 2.0, under ALT 14.
Dnil = difference in life-cycle costs for initial pavement design strength of $\overline{SN}$ 2.0 and $\overline{SN}$ 3.5, under ALT 00.

Then, from the inequality:

$(Dopt)\ (x) > (Dnil)(1 - x)$
or $(1.27 - 1.23)x > (1.33 - 1.31)(1 - x)$
Therefore, $x > 0.33$

In this case, time-staging of pavement construction should only be considered if there is a one-third or better chance of good maintenance being performed in the future (33 percent threshold probability).

Under funding arrangements that favor construction over maintenance or when external aid agencies are willing to finance construction but not maintenance expenditures, it is often expedient to forego maintenance until it becomes necessary to reconstruct the pavement. ALT 3 in Case B codifies such a maintenance strategy, an option that would also reduce life-cycle costs significantly, if there is fair expectation that funds for reconstruction would be forthcoming when needed. In this case, a less-than-full-strength design could be considered for initial construction, if the probability of obtaining future funds for reconstruction is 45 percent or better.

The data in Table 3 illustrate how the decision may vary in a wider array of cases. Combinations of discount rate, daily traffic, and axle loading are mapped out where the decision for or against time-staging is independent of the degree of uncertainty about future maintenance. In a middle area, however, the reliability of future maintenance matters. Time-staging is thus generally to be preferred if the probability of adequate maintenance in the future exceeds 30 or 75 percent, depending on traffic volumes and light axle loads. At higher discount rates (in this case 24 percent) time-staging tends to be a preferred choice even with high traffic volumes and axle loading and a relatively low probability of future maintenance. When capital is cheap or a greater weight is attached to long-term benefits (an intergenerational issue), stronger initial pavements based on normal design generally dominate (e.g., at a discount rate of 6 percent).

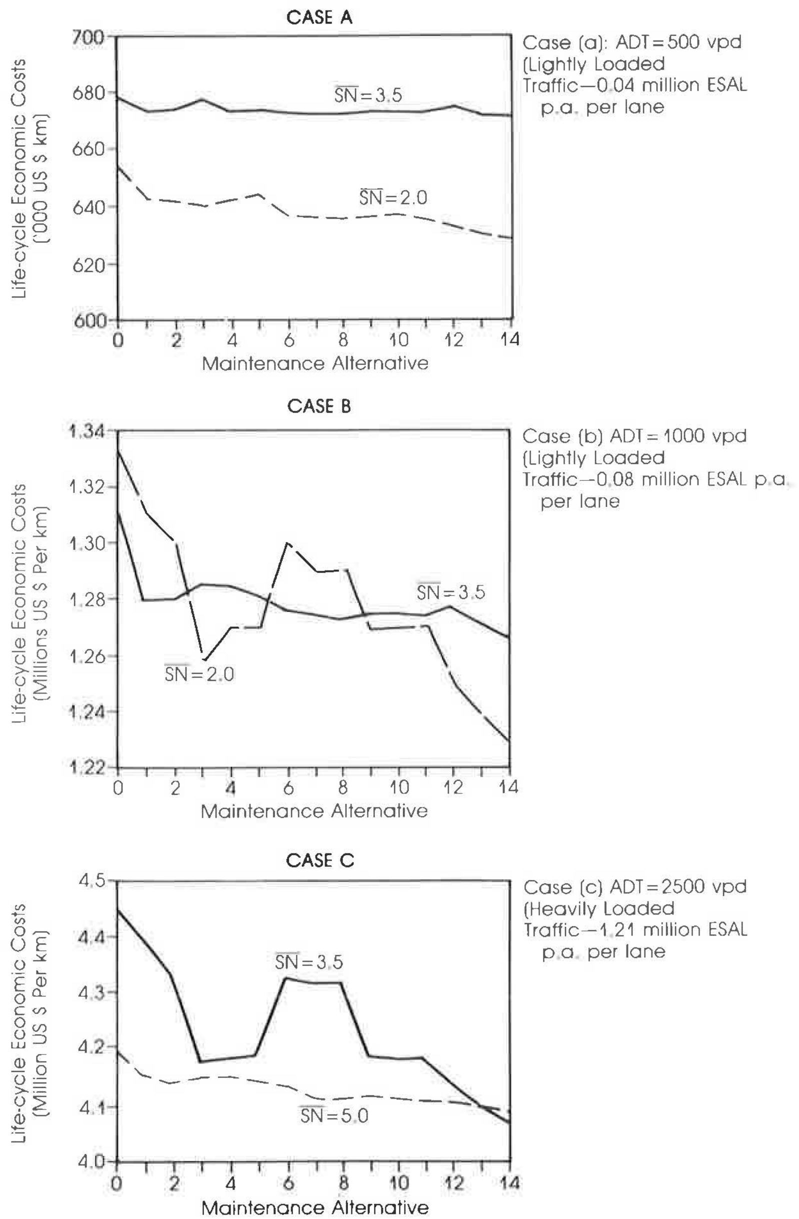


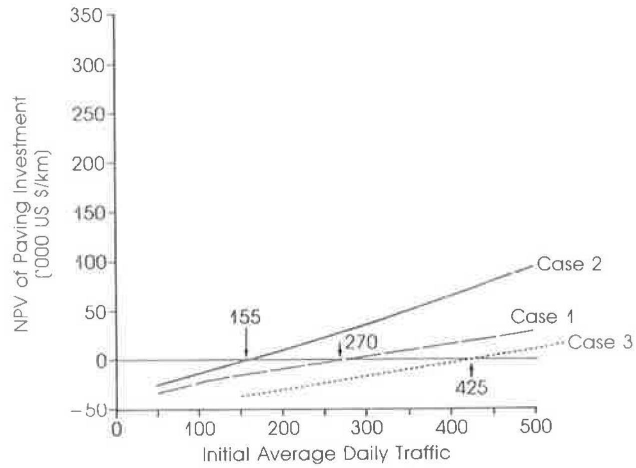
FIGURE 6 Influence of maintenance policies on selection of initial pavement strength (based on present value of life-cycle costs, discounted at 12 percent per annum).

ECONOMIC TRAFFIC THRESHOLDS FOR PAVING GRAVEL ROADS

Even with the best maintenance practice, vehicle operating costs on gravel roads are between 10 and 30 percent higher than on paved roads. In addition, the present value of the cost of routine maintenance and resurfacing is between five and eight times greater for a well-maintained, high-volume gravel road than for a newly built paved road. Paving is therefore indicated when the expected savings in vehicle operating and maintenance costs (relative to a well-maintained gravel road) exceed the present value of the paving cost.

These cost trade-offs now appear to cover a wide range of traffic volumes than had commonly been assumed. Applications of HDM-III in Costa Rica and Mali indicate that the breakeven traffic volume for paving may vary from under 100 vehicles a day to more than 400, depending on the costs of paving, the discount rate, the rate of growth of traffic, and the anticipated quality of future maintenance. Figure 7, based on unit costs and traffic composition typical of Mali, shows the effects of variations in traffic growth rates and paving costs (for a 12 percent discount rate).

Paving thresholds are also sensitive to variations in assumptions about the quality of maintenance. In cases in which experience shows that the probability of adequate future maintenance is low, the traffic threshold for paving is lowered. If there are no budget constraints, an economic case can be made for an all-weather paved road that may remain almost free of major maintenance interventions for 7 to 10 years. When examining total costs, however, more frequent regraveling and grading operations carried out efficiently are likely to prove



Case 1: Base Case, 0% p.a. Traffic Growth Rate, Optimal Maintenance Policies on Paved and Unpaved Roads.
Case 2: As Above, With 6% p.a. Traffic Growth Rate.
Case 3: 0% p.a. Traffic Growth and 50% Increase in Paving Cost.

FIGURE 7 Paving a gravel road at breakeven traffic volumes.

TABLE 3 CRITERIA FOR SELECTING TIME-STAGING OPTIONS FOR PAVEMENT DESIGN (minimum maintenance reliability for time-staging option)

		Discount Rate (%)		
ADT	Axle Loading[a]	6	12	24
300	Light	–[b]	–[b]	–[b]
	Heavy	30	–[b]	–[b]
500	Light	30	–[b]	–[b]
	Heavy	NA[c]	75	–[b]
1,000	Light	95	30	–[b]
	Heavy	NA[c]	80	–[b]
2,000	Light	95	80	15
	Heavy	–[d]	90	15
2,500	Light	–[d]	95	50
	Heavy	–[d]	–[d]	60

NOTES: The economic costs for paving ($1000s/km, 1984) assuming all earthworks and structures already in place were estimated as

$\overline{SN}$	*Costa Rica*	*Mali*
2.0	19.6	27.2
3.5	68.5	59.3
5.0	118.8	129.4

Minimum probability of adequate maintenance in the future; time staging conditional to this minimum level of maintenance reliability; otherwise use normal strength design.

[a]Light axle loading is representative of conditions in Costa Rica (0.05–0.10 million ESAL per year per lane); heavy axle loading is representative of conditions in Mali (1.2 million ESAL per year per lane).

[b]Compensatory design not applicable; low- to medium-strength pavements SN < 3.5) based on normal design, adequate for this level of traffic volume and loading.

[c]NA = time-staging option not applicable; use normal-strength design.

[d]Time-staging not applicable; high strength pavements ($\overline{SN}$ > 4.0) based on normal full-strength design appropriate.

more economical than paving, particularly if the future availability of maintenance funding is uncertain.

Paving gravel roads in arid zones is sometimes suggested as a means to alleviate the discomfort and inconvenience of travel on dusty roads, but it is difficult to quantify these benefits. Common observation suggests that vehicle speeds and passing opportunities on such roads are severely restricted by reduced visibility. The result is a traffic safety hazard similar to fog and congestion akin to that caused by heavily loaded slow-moving vehicles on narrow roads. Insufficient empirical information is available on traffic flow and vehicle operating characteristics in a dusty environment to evaluate the benefits of paving roads in arid or desert areas.

Lower paving thresholds may also be indicated for roads located in river deltas (lower Bangladesh), old lake beds, sandy deserts, and low coastal areas because of the scarcity of gravel deposits and other sources of aggregate. A possible technical alternative to using a gravel surface in these situations is to stabilize in situ soils by using small amounts of a suitable binder (bitumen, cement, lime, or fly ash) and then to protect the stabilized material from weathering and traffic, where necessary, by a light bituminous seal.

CONCLUSIONS

With the empirical knowledge gained in recent years on road deterioration and maintenance together with the methods that have been developed for simulating the processes and evaluating the results of large numbers of alternatives, it is now feasible to compare the economic consequences of different maintenance options in the context of actual conditions and thereby to find the best network-level maintenance policies, particularly under budget constraints.

A study in which these methods and relationships were applied to the road networks of three countries gave quantitative substance to some road investment and maintenance principles already known while showing that others apply only within narrow limits. The principal findings are discussed next.

- Vehicle operating costs (VOC) constitute a very large share (75 to 95 percent) of the total road transport cost, except when the traffic volume is extremely low. Hence, even a small percentage change in VOC is very large relative to changes in construction and maintenance costs. Until recently, basic empirical relationships linking vehicle operating costs to pavement surface condition (roughness) were not available. The past inadequacies in the empirical knowledge of basic road deterioration and VOC relationships may have contributed to premature paving of roads, particularly in low-traffic, high-cost environments and possible structural underdesign of heavily trafficked roads.

• The choice and staging of maintenance operations on paved and unpaved roads are strongly affected by the distinct difference in their deterioration characteristics. On unpaved roads, the rapid but essentially linear path of deterioration with respect to time and traffic requires special attention to routine maintenance actions, particularly the frequency of blading. The nonlinear deterioration characteristics of paved roads allow more room for the choice and timing of maintenance actions and permit trade-offs between agency and user costs, especially under budget constraints. A procedure for identifying cost-effective road maintenance policies based on a trade-off between agency and user costs is provided in this paper.

• When the maintenance budget for a network is less than optimal, maintenance allocations should not be uniformly reduced across the network. In general, the first candidates for cutting should be the high unit-cost maintenance operations on roads with low traffic volumes and good existing surfaces. Roads with very high volumes and poor surface conditions suffer the greatest loss in benefit for each dollar of reduction in maintenance outlay, and their allocations should be reduced last.

• Maintenance activities are often deferred during periods of austerity. For unpaved roads, as long as basic routine maintenance is carried out regularly, the effect of deferral on subsequent road restoration costs is not large unless the road is allowed to become virtually impassable so that it has to be reconstructed, generally on a new alignment. For paved roads, vehicle operating costs increase during the deferral period, and the cost of later pavement rehabilitation can be increased substantially, depending on the stage in the deterioration process when deferral occurs. For pavements in good condition with normal traffic loading, the effect of deferring maintenance (other than basic activities such as drainage) for 1 to 5 years is of no serious consequence. Once pavement condition is in the fair to poor range, the impact is large.

• When a new pavement is constructed or an existing one replaced or overlaid, the choice of design strength should take into account the reliability of future maintenance. Low probabilities of adequate maintenance in the future favor building a strong pavement initially because stronger pavements enjoy a longer grace period during which maintenance needs are minimal. High probabilities of good maintenance will favor time-staging, that is, economizing on today's pavement and strengthening subsequently as needs emerge.

• Even with the best maintenance practice, vehicle operating costs on gravel roads are between 10 and 30 percent higher than on paved roads. Also, the present value of the cost of routine and periodic maintenance is between five and eight times greater for well-maintained, high-volume gravel roads than for newly built paved roads. The breakeven traffic volume for paving, however, varies across a wide range of traffic volumes (4 under 100 to more than 400 vpd), depending on the cost of paving, the discount rate, the rate of traffic growth, and the anticipated quality of future maintenance. Lower traffic thresholds for paving may be indicated in conditions of climatic extremes (e.g., a dusty environment over prolonged periods) or in areas with a scarcity of gravel deposits or other cheap sources of aggregate.

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