Optimum Maintenance Standards for Roads in Developing Countries

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Economic appraisal models, such as the World Bank's Highway Design and Maintenance Standards Model (HDM-III) and the Road Transport Investment Model (RTIM2) developed by the Transport and Road Research Laboratory in the United Kingdom, are often used to determine optimum maintenance standards that result in minimum life-cycle costs. A simplified method of using concepts built into these models is described that can be used to determine optimum maintenance standards for roads in developing countries. The theory used in developing a graphical method of determining optimum maintenance standards is presented in this paper. This is defined as the maintenance interval required to achieve minimum life-cycle costs. The method uses charts initially derived from results of analyses conducted using either HDM-III or RTIM2. The maintenance intervals obtained from the charts have been compared with a range of maintenance standards modeled using both HDM-III and RTIM2. The results of the comparisons confirm that the graphical method gives optimum maintenance intervals with the minimum life-cycle costs. It is suggested that the method could be applied in developing countries in situations in which expert knowledge of HDM-III or RTIM2 is not locally available.

Road project appraisal models such as the World Bank's Highway Design and Maintenance Standards model (HDM-III) (*1*) and the Road Transport Investment Model (RTIM2) (*2*) developed by the Transport and Road Research Laboratory (TRRL) in the United Kingdom, have been used extensively to conduct economic appraisals of road projects in developing countries. The models calculate annual cost matrices made up of costs of construction, maintenance, vehicle operation, travel time, and other associated costs or benefits. The complexity and level of detail required to run these models often limit their use to engineers and economists with expert knowledge of the relationships built into the models as well as familiarity with computers. This level of expertise is sometimes not readily available in developing countries, and therefore simplified methods of using concepts built into the model are necessary.

HDM-III and RTIM2 are often used to determine maintenance and rehabilitation standards for roads in developing countries. This typically requires a number of discrete maintenance standards to be compared in order to select the alternative with the minimum total life-cycle cost. The previously mentioned procedure can be simplified to obtain a good estimate of optimum road maintenance standards applicable under a given set of circumstances. The procedure described in this paper is based on the comparison of costs of maintenance and rehabilitation with road user costs incurred on a road before maintenance in order to determine the optimum maintenance standard. This is defined as the maintenance interval or frequency that results in the minimum life-cycle cost. The word maintenance is used throughout this paper to include rehabilitation.

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RELATIONSHIP BETWEEN VOC AND ROAD ROUGHNESS

The relationships used in both HDM-III and RTIM2 were derived from pavement and traffic studies conducted in Brazil, India, Kenya, and the Caribbean. In all these studies, vehicle operating cost (VOC) relationships were derived from measured consumption of fuel, lubricating oil, tires and spare parts, as well as vehicle maintenance labor, crew wages, vehicle depreciation, overheads and interest on capital. A detailed examination of these relationships shows that they depend largely on road roughness. The VOC incurred on a road with fixed geometric and traffic characteristics is primarily a function of the pavement condition measured in terms of roughness. This relationship is illustrated in Figure 1 for five vehicle types derived using HDM-III. An average weighted VOC can be derived from this to represent the average cost per vehicle-kilometer incurred on a road, taking into account the traffic composition, as illustrated in Figure 2. The value of the weighted VOC depends on the geometric characteristics of the road as well as the traffic composition, and increases with road roughness. A good estimate of the total VOC incurred on a road with similar geometric and traffic characteristics can be obtained by multiplying the annual number of vehicles by the weighted VOC obtained from Figure 2 at the average annual roughness.

The horizontal roughness axis in Figure 2 can be replaced by a cumulative traffic axis or a time axis to represent the number of vehicles using the road over a period of time at the corresponding roughness level, as illustrated in Figure 3. The difference between the shapes of the weighted VOC curves in Figures 2 and 3 is caused by a nonlinear roughness progression with time and traffic loading. If the roughness progression rate remained constant, the shapes of the two curves in Figures 2 and 3 would be the same. Also shown in Figure 3 is the weighted VOC line for a 10 percent discount rate derived by applying discount factors to the weighted VOC in the corresponding years.

CUMULATIVE VOC PENALTIES

The total VOC incurred per kilometer at any point in time because of increase in road roughness can be estimated from

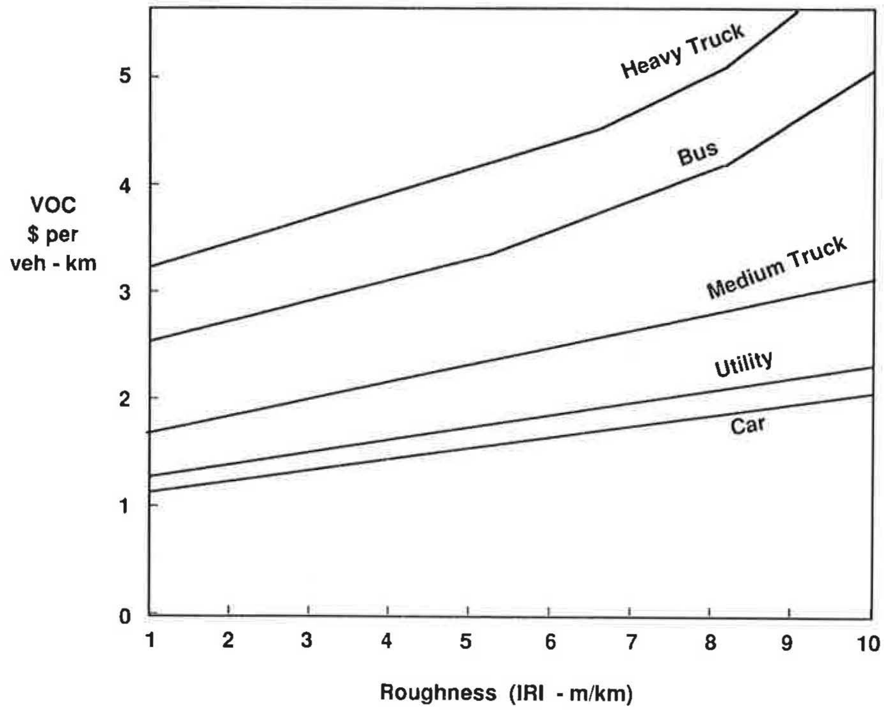

FIGURE 1 Effect of road roughness on vehicle operating costs.

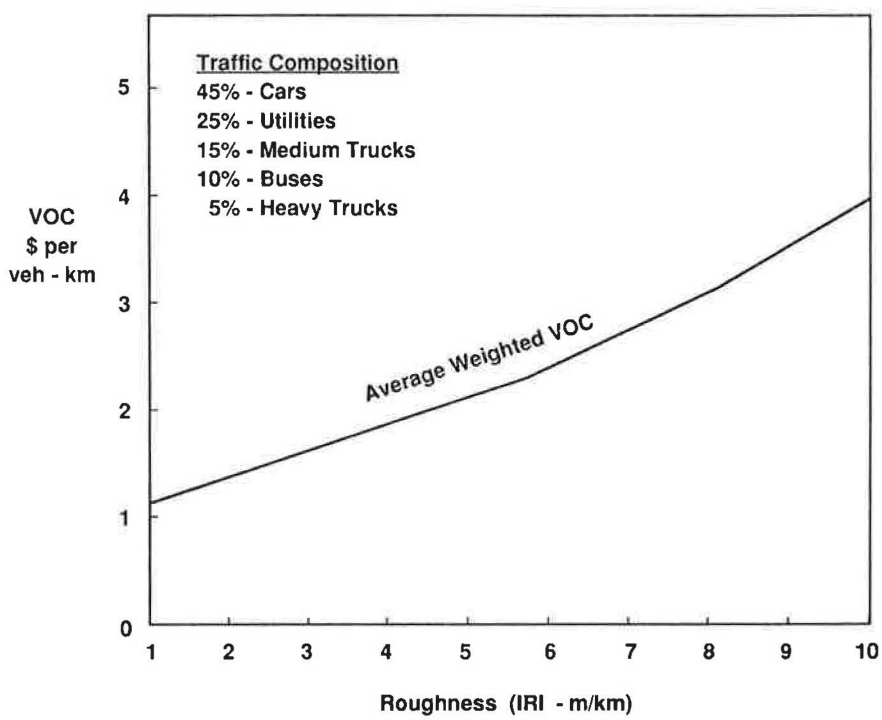

FIGURE 2 Variation in the weighted average VOC with roughness.

the area under the weighted VOC curve in Figure 3. This can be obtained either by mathematical integration, if the equation of the curve is known, or by graphical integration. The shaded area between the weighted VOC curve and a horizontal line drawn from the initial weighted VOC represents penalties incurred by vehicles operating at road condition worse than the initial roughness. This constitutes VOC penalties incurred by road users caused by failure to keep road roughness at the level immediately after construction. The optimum time for maintenance depends on the unit cost of maintenance and the rate at which these VOC penalties increase. The cumulative VOC penalties, when plotted against

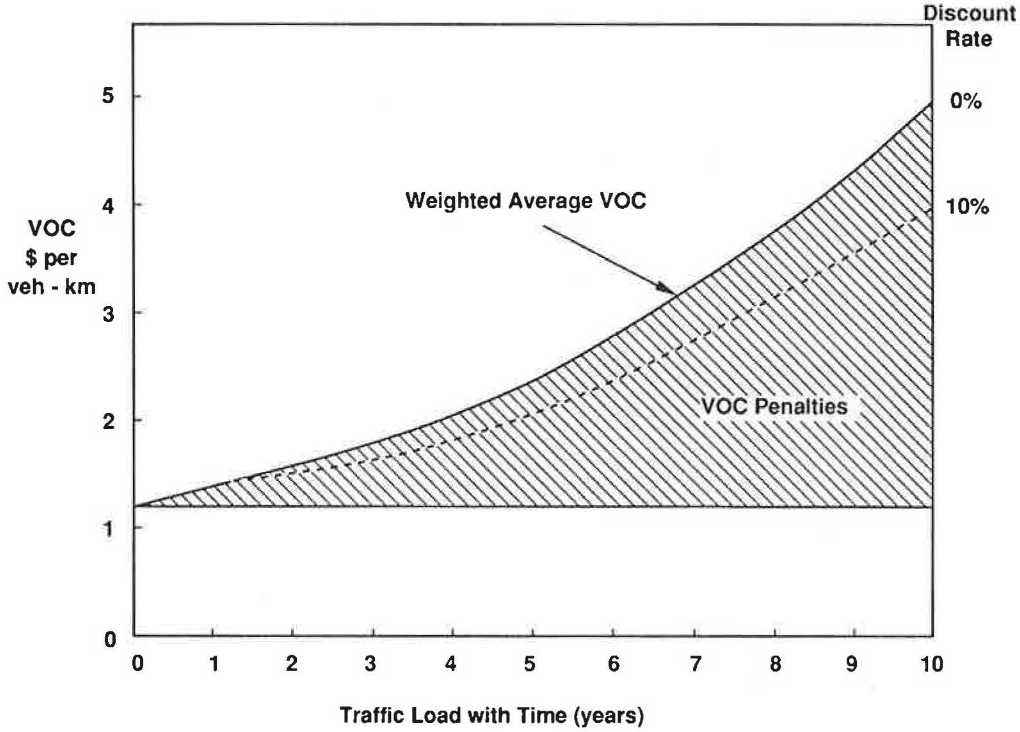

FIGURE 3 Increase in VOC penalties with traffic and time.

traffic loading with time, increase exponentially, indicating large cost penalties to road users when maintenance is delayed (see Figure 4). The optimum maintenance interval therefore depends on the rate of increase in VOC penalties and on the cost of maintenance or rehabilitation. When maintenance is applied, the benefits to road users will be equivalent to the VOC penalties that would otherwise have been incurred.

EFFECT OF MAINTENANCE ON ROUGHNESS

The shaded area in Figure 3 represents VOC penalties resulting from failure to control the increase in road roughness. This assumes that any maintenance applied will reduce roughness to the level immediately after construction. This in practice only applies when a pavement is reconstructed. Main-

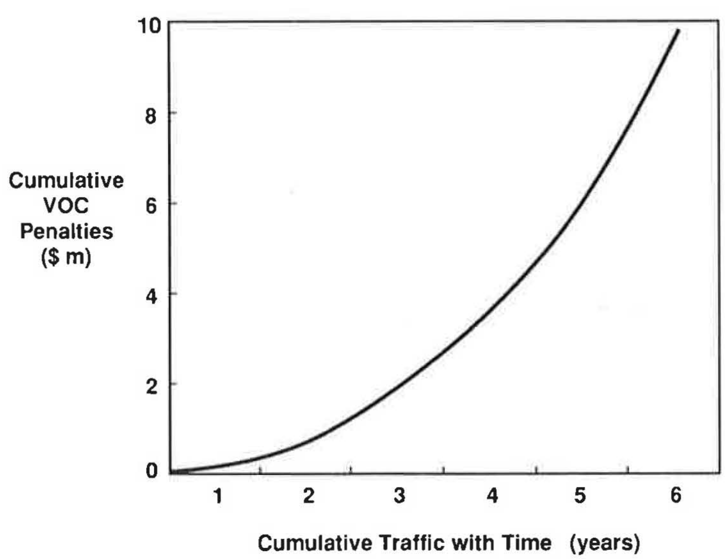

FIGURE 4 Cumulative increase in VOC penalties with traffic and time.

tenance treatments will usually reduce roughness levels by varying amounts depending on the effectiveness of the treatment. This implies that the VOC penalty area is not bounded on the lower side by a horizontal line starting at the initial weighted VOC. An inclined line, representing the VOC at roughness levels immediately after maintenance, marks the lower boundary. The VOC penalty area therefore depends on the efficiency of a maintenance treatment in reducing roughness. For example, in HDM-III, the effectiveness of an overlay in reducing roughness depends on its thickness. Thin overlays have less effect on roughness reduction than thick overlays, hence the benefits derived from a thin overlay will be less. The lower boundaries to the VOC penalty areas for 40-mm and 80-mm overlays and a horizontal line for reconstruction are shown in Figure 5.

VOC PENALTIES ON UNPAVED ROADS

The VOC penalties incurred on unpaved roads also depend on the efficiency of gravel road maintenance activities in reducing roughness. In HDM-III, the roughness immediately after grading (or blading) varies initially but attains a steady state after a few cycles. This steady-state roughness level can be used to determine the lower boundary to the VOC penalty area, as shown in Figure 6. It is therefore assumed in this paper that the lower boundary to the VOC penalty area for unpaved roads is given by the VOC at the average roughness after grading.

DERIVATION OF OPTIMUM MAINTENANCE INTERVALS

The optimum maintenance interval is defined as the cumulative number of vehicle passes after which a maintenance activity should be applied so that the total cost of maintenance plus VOC is a minimum. Shown in Figure 7 is the relationship between VOC penalties and cumulative traffic on a road that is maintained or rehabilitated after T vehicle passes. Because the vertical axis in Figure 7 represents total costs per kilometer, the unit cost of maintenance carried out after every T vehicle passes can be added, as illustrated. The relationship between maintenance frequency and the cumulative increase in VOC penalties depicted in Figure 7 forms the basis of the method presented in this paper for estimating optimum maintenance intervals. The optimum maintenance interval can be determined by varying the traffic interval T so that repeated maintenance applications will result in the minimum total of VOC penalties plus maintenance cost after several cycles.

A total cost line drawn from the origin to point A in Figure 7 represents the average rate of increase in the total of VOC penalties plus maintenance cost. The optimum maintenance interval must necessarily have the minimum total of VOC penalties plus maintenance cost over an extended period of analysis. This implies that the total cost line for the optimum maintenance interval must have the minimum gradient. This can be obtained by drawing a tangent to the cumulative VOC penalty curve from an off-set point on the vertical cost axis equivalent to the cost of maintenance or rehabilitation. The optimum maintenance interval is given by the point of inter-

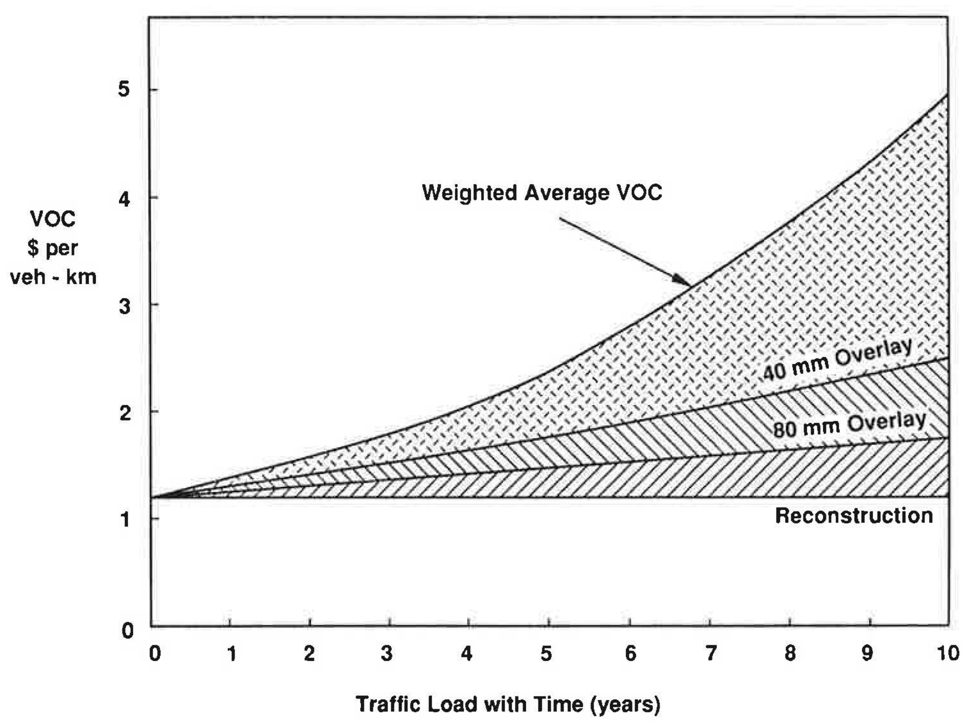

FIGURE 5 Changes to VOC penalty area caused by maintenance efficiency.

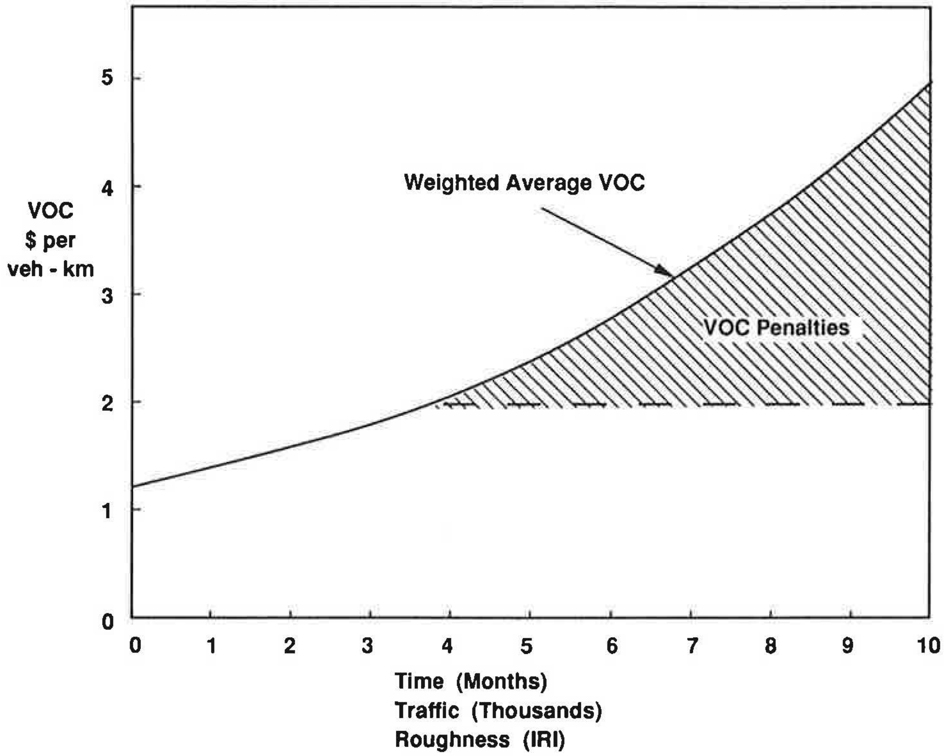

FIGURE 6 VOC penalty area for grading gravel roads.

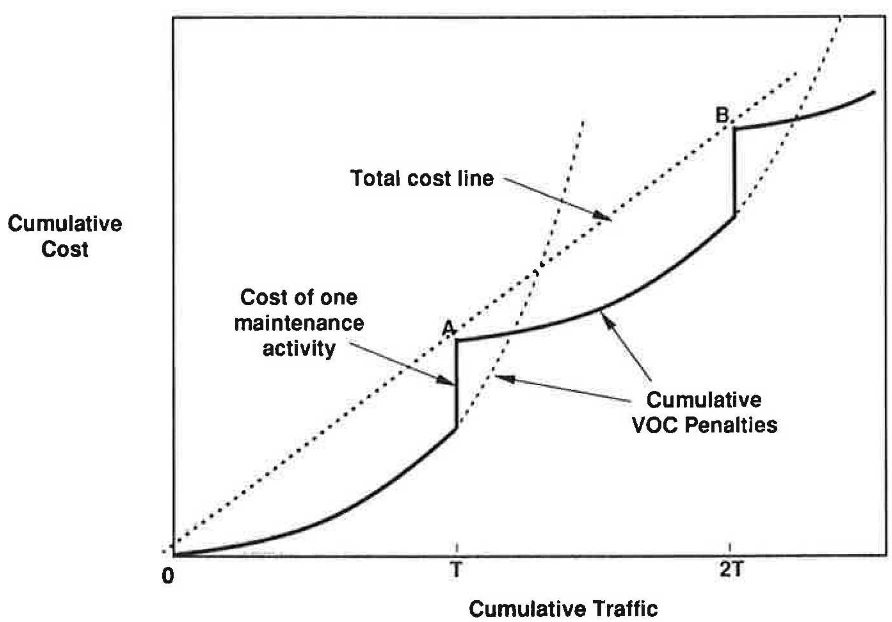

FIGURE 7 Cumulative cost of VOC penalties and maintenance cost.

section between the cumulative VOC penalty curve and a tangent drawn from an off-set point on the negative side of the vertical cost axis equivalent to the cost of maintenance, as illustrated in Figure 8 (*3*).

COMPARISON WITH HDM-III AND RTIM2

The method of deriving optimum maintenance intervals described in this paper has been compared with the results from similar analyses conducted using the two models HDM-III and RTIM2 with data from Costa Rica and Kenya. In each case a range of maintenance intervals, including those obtained using the graphical method, were analyzed using HDM-III or RTIM2. The cumulative increase in VOC penalties derived using HDM-III for a typical gravel road in Costa Rica carrying 100 vehicles/day is shown in Figure 9. For a unit cost of grading of $100 U.S./km, a tangent to the VOC penalty curve gives an optimum grading interval of approximately 2,800 vehicles. The results of comparisons made with a range of other grading intervals obtained from HDM-III for a 10-year analysis period are given in Table 1. It may be seen that the minimum life cycle cost is given by a grading interval of 3,000 vehicles, which is close to the optimum of 2,800 vehicles derived from Figure 9. If the unit cost of grading is doubled to $200 U.S./km, the optimum grading interval would increase to 4,300 vehicles, as shown in Figure 9.

A second analysis was conducted using RTIM2 to determine the optimum overlay interval for the heavily trafficked Nairobi to Mombasa road in Kenya. The VOC penalty curve with the overlay tangent drawn at an off-set cost of Shs 582,000 K./km ($36,500 U.S./km) is shown in Figure 10. This gives an optimum interval of 1.95 million vehicles, or 5.4 million equivalent standard axle loads (ESAL) in both directions for a 50-mm overlay. A series of RTIM2 runs were conducted to test this against a range of selected overlay intervals. A summary of the results is given in Table 2. The results confirm that the overlay interval of 5.4 million ESAL gives the minimum life-cycle cost.

A third analysis was conducted using HDM-III to derive optimum overlay intervals for a typical paved road in Costa Rica. It is shown in Figure 11 that a tangent drawn to the cumulative VOC penalty curve from a unit overlay cost of $40,250 U.S./km gives an optimum overlay interval of 9 million vehicle passes equivalent to 1.26 million ESAL in 6 years. A number of time-scheduled overlay intervals were tested against the optimum derived from Figure 11. A summary of the life-cycle costs calculated over a 25-year analysis period using HDM-III is shown in Table 3. The table contents confirm that overlays applied at an interval of 6 to 7 years give the minimum life-cycle cost.

PRACTICAL APPLICATIONS

The simplified method of determining optimum maintenance intervals has been shown to give good estimates of optimum maintenance standards. It can be used relatively easily in situations in which it is not possible to conduct full-scale economic analyses with HDM-III or RTIM2. All that is required are charts of cumulative VOC penalties plotted against traffic, as illustrated in Figures 9 to 11. These can be derived once for groups of roads with similar geometric, environmental, and traffic characteristics, for example one class of roads in a given part of a country.

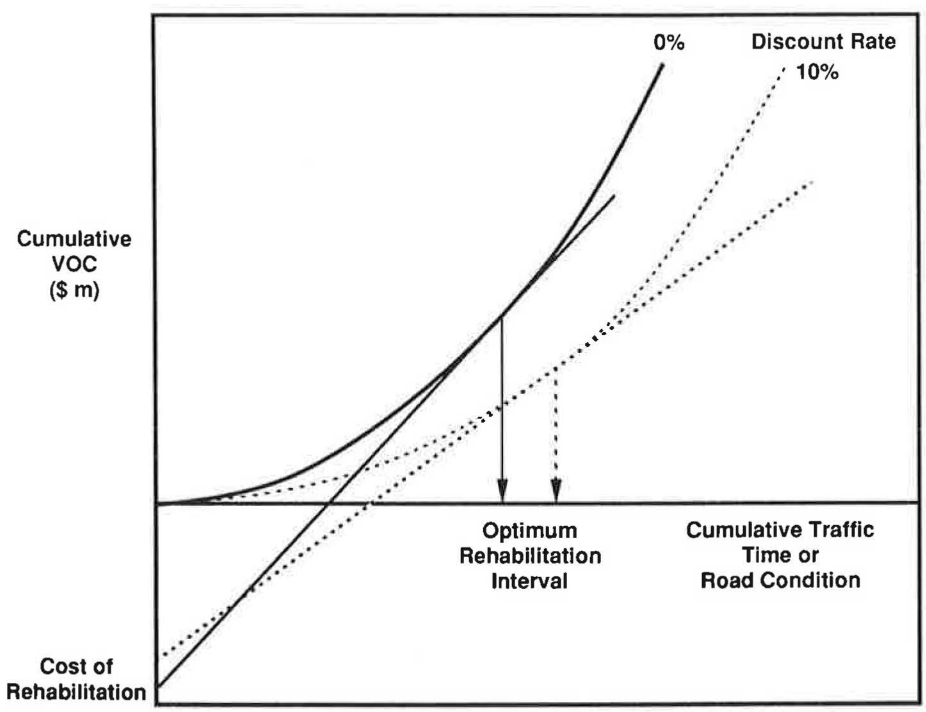

FIGURE 8 Derivation of the optimum maintenance interval.

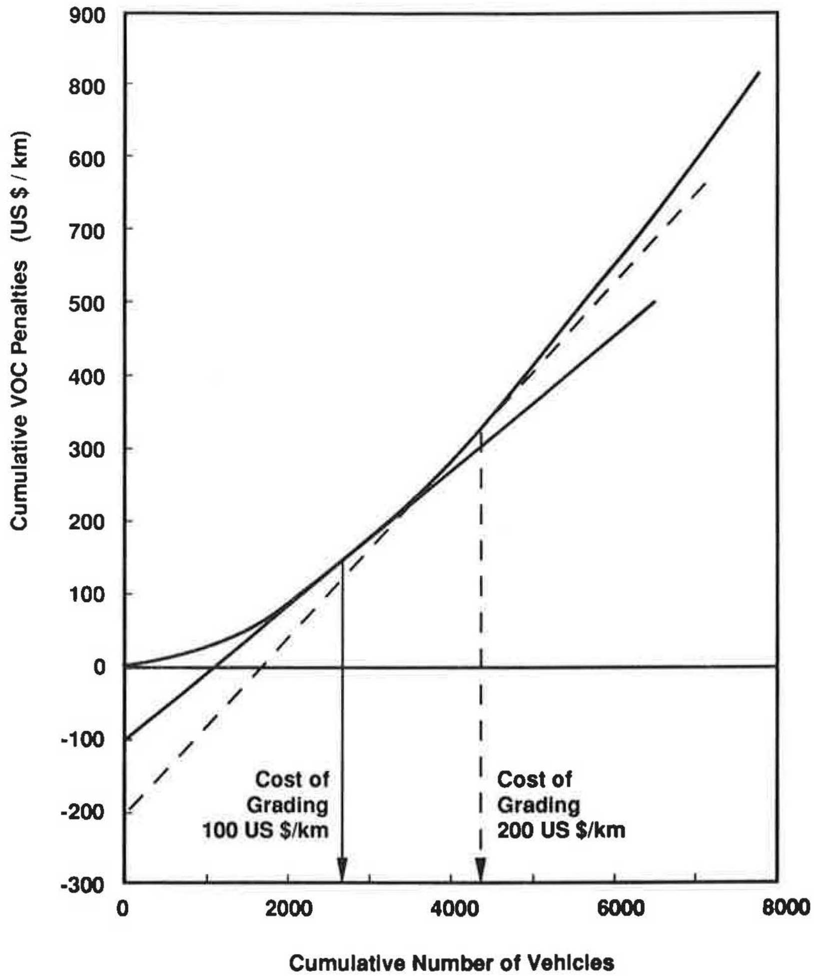

FIGURE 9 Derivation of the optimum grading interval.

SUMMARY OF PROCEDURE

The procedure for deriving optimum maintenance or rehabilitation intervals may be summarized in the following steps:

1. Divide the country into regions with uniform geographic characteristics based on terrain and environment; for example, mountainous, rolling, or flat area with dry, moderate, or wet climate. In addition, divide the road network according to road classes; for example trunk, primary, secondary, tertiary, and so on. This forms a matrix of road types for which typical maintenance intervals are to be derived.

2. For each combination of geographic region and road class, run HDM-III or RTIM2 to derive VOC/roughness relationships similar to Figure 1 using typical vehicle types found

TABLE 1 Comparison of Unpaved Road Maintenance Intervals

	Costs in thousands of US$ per kilometer over 10 years		
Grading Interval (vehicle passes)	Maintenance Cost	Vehicle Operating Cost	Total Life Cycle Cost
1000	54.6	511.2	565.8
2000	36.7	519.7	556.4
3000	26.7	528.9	555.6
4000	22.0	544.4	566.4
6000	16.8	565.6	572.4
8000	14.7	584.2	598.9
10000	13.2	600.4	613.6
12000	12.2	614.5	626.7
16000	11.0	634.0	645.0

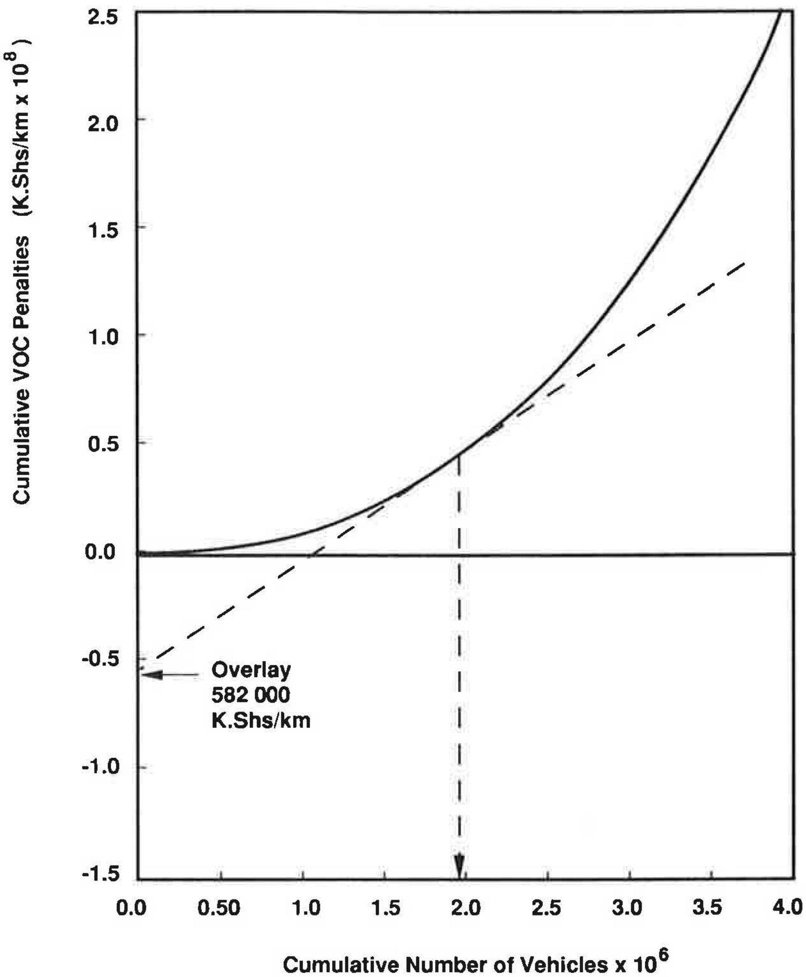

FIGURE 10 Derivation of the optimum overlay interval.

TABLE 2 Comparison of Overlay Intervals Using RTIM2

	Costs in million US$ per kilometer over 15 years		
Overlay Interval (million ESAL)	Maintenance Cost	Vehicle Operating Cost	Total Life Cycle Cost
4.5	0.235	1.759	1.994
5.4	0.219	1.772	1.991
6.0	0.200	1.795	1.995
8.0	0.172	1.838	2.010
10.0	0.145	1.907	2.052

in that part of the road network. The weighted VOC curve may then be derived for the traffic composition observed on individual roads or classes of roads at the discount rate applicable in the country.

3. Superimpose the cumulative traffic using the road at the corresponding roughness level. Determine the lower boundary to the VOC penalty area for the each type of maintenance treatment. The VOC penalty area represents additional costs incurred by road users for operating on roads in suboptimal condition. This is illustrated in Figure 3.

4. Calculate the cumulative increase in VOC penalties with traffic and plot this as shown in Figures 9 to 11 for each type of maintenance treatment. These represent cumulative VOC penalties incurred by road users when the road is not maintained.

5. The unit cost of maintenance or rehabilitation such as an overlay or a reconstruction can then be marked on the vertical cost axis in the negative direction on the corresponding VOC penalty chart. A tangent drawn from this point to the VOC penalty curve gives the optimum maintenance interval in terms of the cumulative number of vehicles, as illustrated in Figures 9 to 11.

6. The maintenance interval can be converted to a roughness intervention level by using observed progression rates,

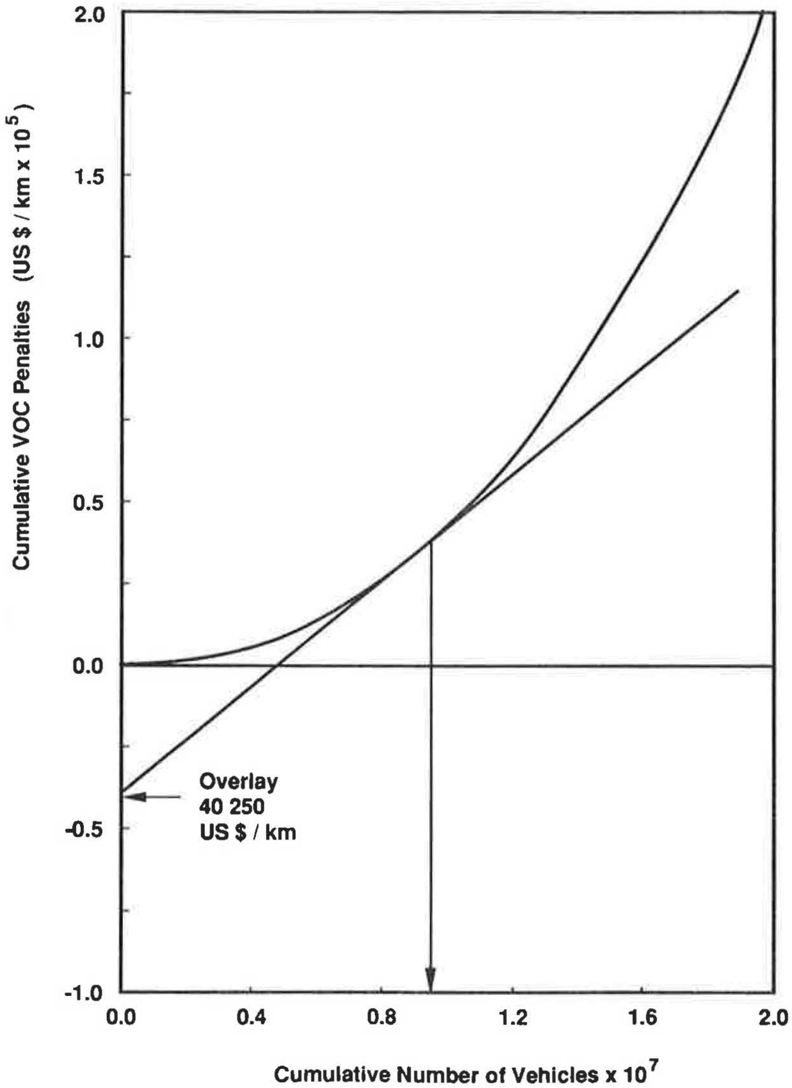

FIGURE 11 Derivation of the optimum overlay interval.

TABLE 3 Comparison of Overlay Intervals Using HDM-III

	Costs in million US$ per kilometer over 15 years		
Overlay Interval (Years)	Maintenance Cost	Vehicle Operating Cost	Total Life Cycle Cost
4	0.220	12.307	12.527
5	0.169	12.349	12.518
6	0.136	12.379	12.515
7	0.112	12.404	12.516
8	0.094	12.429	12.523
9	0.069	12.469	12.538
10	0.052	12.510	12.563

or more simply to a time interval using average daily traffic flows.

CONCLUSIONS

Presented in this paper is a simplified method for determining the optimum interval for maintenance activities on both paved and unpaved roads. It has been shown to give maintenance intervals with the minimum total cost when compared with other maintenance intervals modeled using HDM-III and RTIM2. It should prove particularly useful in developing countries where the lack of adequate computing facilities has often hindered the use of such management tools to plan road maintenance. With the method presented in this paper, the investment programs could be run only a few times to derive weighted VOC/roughness relationships, as shown in Figure 2. Such relationships will generally apply to all roads with similar geometric characteristics within a region or country. Similar figures can also be derived by using tables for calculating VOC published by the TRRL (*4*). A number of VOC penalty charts similar to Figures 9 to 11 may then be derived from the weighted VOC/traffic chart for each type of maintenance treatment and for the combination of road classes and geographic region in a country. Optimum maintenance intervals can then be obtained directly from the charts by applying the tangent method described in this paper with the unit costs of maintenance treatments applicable in each situation.

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