Determining Maintenance and Rehabilitation Programs for Low-Volume Roads Using HDM-III: Case Study from Nepal

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The World Bank's Highway Design and Maintenance Standards Model (HDM-III) has become one of the most common tools in developing countries for establishing maintenance and rehabilitation strategies based on the comparison of both road user and agency costs. However, there are no common methods or guidelines available that outline a methodology for collecting the data necessary to use the model or the best way to apply the model to determine optimum strategies. This paper describes how the model was used in Nepal to define appropriate rehabilitation and maintenance programs for low-volume paved roads. It addresses three distinct areas: data collection, what data are essential for running HDM-III and how they were collected; model calibration, how HDM-III was calibrated to reflect the Nepal vehicle fleet, pavement types, and maintenance practices; model application, how the HDM-III was applied and the output interpreted to obtain meaningful strategies.

Nepal is a mountainous, land-locked country between India and China with a population approaching 20 million. The terrain has inhibited the development of a road network. The country has a total length of only about 8 000 km of roads, of which around 3 000 km have bituminous pavements; traffic levels are generally below 500 vehicles per day (vpd). There is a shortage of social services, in particular health and education; infant mortality is high and life expectancy low. The improvement of social services in isolated areas is made difficult by the lack of road access, and there is constant political pressure to use the limited highways budget to construct new feeder roads. Due to the terrain and unstable geology, road construction and maintenance are expensive, and the emphasis on network expansion has been to the detriment of maintaining the existing primary network.

While all countries must address the problem of allocating limited resources among competing sectors, it is particularly acute in countries like Nepal. The country has large fiscal and foreign trade deficits and is highly dependent on foreign aid to make good the deficiencies. Aid donors require assurance that investments are economically sound and, when considering investment in road rehabilitation and maintenance, some form of benefit-cost analysis must be used to justify each project.

This paper describes the approach used to define a program of pavement rehabilitation and maintenance for 300 km of arterial roads in the central and western regions of the country. The program is being financially supported by the International Development Association.

ANALYSIS METHODOLOGY

In this project a total transport cost (TTC) approach was adopted. The TTC for a road consists of the following components:

- The construction costs incurred at the time the road was built,
- The maintenance and rehabilitation costs, and
- The road user and vehicle operating costs (VOCs).

For each year of the analysis period, the magnitude of each of these cost components was calculated. These costs were then discounted to their present value. Since the roads in this project were already constructed, only rehabilitation and maintenance costs and VOC were included in TTC.

The project that maximizes the benefits to the economy is the one that minimizes discounted TTC. Accordingly, one calculates the discounted TTC for a number of projects with increasing levels of investment by the highway agency. The differences between the discounted TTC of the alternative projects and a base case of minimal investment constitute the net present value (NPV) of the investment. The project that minimizes discounted TTC will be the one that maximizes the NPV.

The TTC approach departs from traditional pavement design and management techniques. Generally the latter are based on engineering considerations and agency costs and do not directly consider the effects of alternative designs and maintenance standards on VOC.

The most widely used tool for estimating the TTC on roads in developing countries is HDM-III (*1*). This model represents the culmination of 18 years of research and contains relationships that predict pavement deterioration, the effects of maintenance, and their impact on VOC.

Research conducted in various countries has demonstrated that road roughness has a significant impact on VOC. HDM-III contains a set of relationships that estimate the various components of VOC, for example, fuel consumption, tire wear, and maintenance, as a function of road roughness. In addition to simulating pavement performance and estimating the effect of pavement condition on VOC, HDM-III carries out the discounting and reporting required to compare the TTC for different investment options.

Road maintenance, such as overlays, reduces the roughness level of the road as well as reduces the future deterioration of the pavement. Both effects have a significant impact on VOC. To illustrate these effects, consider Figure 1, which compares the effects of three different maintenance strategies on a newly constructed pavement:

- Routine maintenance consisting of patching potholes and badly cracked areas;
- Application of a 50-mm overlay when the roughness reaches 4 m/km on the international roughness index (IRI) scale; and
- Application of a 50-mm overlay when the roughness reaches 5 m/km.

As shown in Figure 1, each of the maintenance strategies results in a unique roughness-time profile. A policy of routine maintenance sees the pavement reaching a roughness of more than 12 m/km after 30 years. By comparison, if an overlay is applied whenever the roughness reaches 4 m/km, the result is an average roughness of 3.5 m/km over the period. If the overlay is applied at an intervention of 5 m/km, then the average roughness is 4 m/km.

Since VOCs increase with increasing roughness, the intervention level of 4 m/km will result in a lower VOC than if the 5-m/km intervention were adopted. However, in this example the former policy results in a total of five overlays being required over the 30-year period while the latter would require only four. Thus the policy that gives the lower VOC also results in higher costs to the highway agency. By comparing the discounted TTC over the 30-year period for each policy, one can establish which minimizes the TTC.

The analysis period must be long enough to cover several pavement maintenance cycles. Although high discount rates reduce the influence of treatments applied

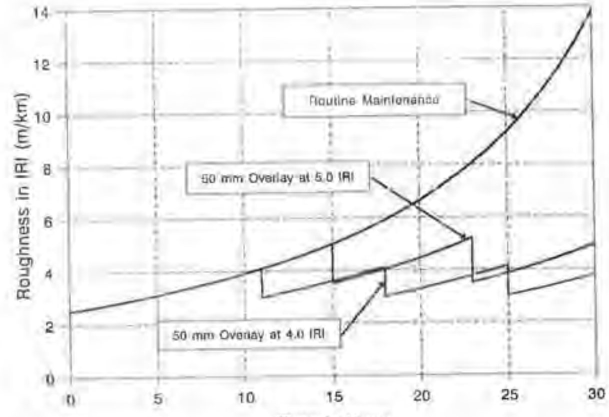

FIGURE 1 **Effect of maintenance on roughness profiles.**

toward the end of the analysis period, the results can be misleading if the analysis period is too short. Therefore, a 30-year analysis period was used in this project, the maximum allowed by the HDM-III model.

DATA COLLECTION

Pavement Data

Pavement Structure

Most of the pavements studied were built using labor-intensive methods and were expected to show great variability in structure and strength. To gain the maximum coverage of data in the time available, Benkelman beam deflection testing was used as the primary measure of pavement strength. Rebound values were recorded at 100-m intervals under a 6.35-ton axle load using the procedures formulated by the U.K. Transport Research Laboratory (TRL) (*2*). The asphaltic layers were thin (mostly less than 20 mm), old, and brittle; thus temperature correction was not applied.

The deflection testing was carried out during the Nepal dry season months of December and January. Correction to some form of annual average was therefore needed for use in the subsequent modeling. A previous study (*3*) had measured deflections at monthly intervals on several road sections in Nepal representing different terrains and subgrade conditions. However, pavement deterioration is not linearly related to deflection and it is not appropriate to use the arithmetic mean. The two HDM-III relationships, those for crack initiation and roughness progression, were considered as a basis for seasonal adjustment. The first of these is a second power relationship between crack initiation period and modified structural number (MSN), while the second is an inverse fifth power relationship between roughness progression and MSN. HDM-III further uses the following conversion from deflection to MSN:

$$MSN = 3.2DEF^{-0.63}$$

Combining the foregoing with the relationship for roughness progression gives the following expression for determining weighted annual deflection:

$$DEF_W = \left(\frac{\Sigma DEF_M^{3.15}}{12}\right)^{0.32}$$

where DEF_W is the weighted annual deflection and DEF_M is the deflection for each month. Using this equation, weighted annual deflection values were derived for each road section.

As expected, many sections showed a high rate of variation in deflection with high and low values of 0.3 and 3 mm. An attempt was made to explain the structural reasons for this variation by measuring layer thickness and properties. This was done using test pits and dynamic cone penetrometer (DCP) tests. A computerized interpretation of the DCP data was applied to convert the penetration rate for each layer to California bearing ratio (CBR) and then to AASHTO strength coefficient. From this the MSN was determined. An analysis of these data showed the following:

- There was no correlation between the MSN determined from the DCP and Benkelman beam rebound.
- More than half the MSN values were higher than those given by the HDM-III expression (above), suggesting that strength coefficients for base and surfacing layers were overestimated in the DCP interpretations.
- There were many cases where low deflections were recorded at points where the DCP showed an apparently extremely weak structure. No explanation could be offered for this phenomenon.

The foregoing illustrates that extreme caution should be exercized when converting deflection data to MSN for use in HDM analyses.

Surface Condition

Surface distress parameters were visually assessed for each 100 m of pavement:

Cracking: all cracks as a percentage of carriageway area, wide cracks (> 3 mm) as a percentage of all cracks;
Raveling: as a percentage of carriageway area;
Bleeding: as a percentage of carriageway area;
Patching: existing, in square meters; required prior to resurfacing, in square meters;
Rut depth: left and right outer wheelpaths where it exceeded 50 mm; and
Edge damage: edge step, left and right edges, in centimeters; edge break, left and right edges, in centimeters.

The most extensive type of distress was cracking. Often, more than 50 percent of cracking was classified as wide, demonstrating the effects of the surfacing age (over 15 years in most cases). Raveling and bleeding were not so widespread. Patching, both existing and required, was also significant. Rutting was not recorded as a common occurrence, suggesting that the pavement structure was better than some of the high deflection measurements would indicate. Edge damage was of minor significance and since most of the carriageways were single lane

(< 4 m wide), this was probably due to the low traffic volumes.

Geometry

A physical inventory recorded the widths of carriageway and shoulders, side drainage, and side slopes. No detailed survey was made of horizontal or vertical alignment as the primary purpose of the study was pavement rehabilitation. Improvements to the alignment were not considered due to the prohibitive cost and low traffic. For input to HDM-III, typical values of curvature and rise and fall were estimated.

Pavement Roughness

Simultaneously with the study, the Nepal Department of Roads (DOR) conducted a roughness survey of the arterial network. This survey was made using a TRL-type bump intergrator mounted in a Land Rover. This was calibrated against the IRI on a number of test sections and the survey data were converted to average values of IRI for each kilometer section.

Traffic Data

The DOR traffic count program had concentrated mainly on high-volume links, and for the low-volume roads in this study 24-hour classified counts were made of 3- to 7-day duration. Daily volumes ranged from 80 to 400 motorized vehicles, excluding motorcycles.

A static axle load survey was also made at three locations to augment existing axle load data. These surveys showed that loaded trucks were predominantly traveling in one direction. Data were converted to equivalent 8.2-ton axles using a fourth power relationship. Buses were found to be fairly constant with an equivalence factor of around 1.2 per vehicle. Loaded trucks had values of up to 8 equivalent single axles (ESA) per vehicle with an average of 3.9. For modeling purposes, loaded and empty trucks were considered separate vehicle groups with a split of 60 percent and 40 percent, respectively.

The axle load survey also recorded high average tire pressures with individual values up to 130 psi and over 90 percent at 100 psi or greater. High tire pressures may have a significant effect on the performance of the asphalt surfacings; further research of these effects in developing countries is warranted.

Traffic growth rates were related to projections of growth in gross domestic product (GDP). Using historic traffic and GDP data, an elasticity of 1.5 between traffic and GDP growth was established. The GDP was forecast to grow at approximately 4 percent, which translated into a 6 percent growth in traffic volume, used in all analyses.

VOC Unit Cost Data

HDM-III predicts the amount of resources consumed—fuel, tires, etc.—and then multiplies this consumption by the unit cost of each resource. All unit costs were calculated in economic terms (i.e., net of taxes and duties), using values based on average costs prevailing in 1992.

Workshop Labor Hours

HDM-III predicts the number of vehicle maintenance labor hours. There is some confusion as to the appropriate manner for calculating the cost input into HDM-III. One approach is to use the average wage rate and weight it by an assumed percentage of the work done by skilled, semiskilled, and unskilled labor. However, in Nepal this was not appropriate for two reasons:

- In developing countries, the work is generally performed by more than one person at a time with the semiskilled and unskilled workers assisting the skilled worker. Thus, the wage costs should be combined rather than weighted.
- Using wage costs does not allow for inclusion of overhead costs—buildings, tools, machines, etc. These are significant in relation to labor costs in low-wage countries such as Nepal.

A small study was made involving eight different maintenance activities and 10 garages. The number of hours to perform tasks and the charges for the work, excluding the costs of spare parts, were analyzed. The total time and total cost were used to establish an average overall hourly cost for maintenance labor. The resulting value was approximately three times that which would have arisen had the average wages approach been used.

Replacement Vehicle Prices

HDM-III predicts that spare parts, depreciation, and interest costs are a function of the replacement vehicle price. Capital costs for the representative vehicles were collected from local dealers. For medium trucks, the body price as obtained from local assemblers was included.

Fuel and Oil Prices

The economic costs of fuel is usually obtained by deducting duty and sales taxes from the financial costs. In

Nepal, this approach gave significantly different economic costs for gasoline and diesel, suggesting that there were unaccounted-for transfer payments. Because of this discrepancy, an alternative approach was adopted. Additional margins and estimated costs of refining, transporting, and marketing were added to the cost of a barrel of crude oil to obtain an overall economic cost. This method eliminated any distortions caused by transfer payments and greatly reduced the difference between economic gasoline and diesel costs.

Tire Prices

Both the economic and financial prices of tires differed widely, depending upon the country of origin. This was due to the differing rates of customs duty and sales tax wherein Indian tires attracted approximately 36 percent, while Chinese and Japanese tires approximately 84 percent.

The average economic tire price was obtained from a study covering the representative vehicle classes (passenger car and utility, medium truck, and bus). A sample of 200 tires for each vehicle class was recorded from vehicles stopped at a customs point. The tires on the vehicles were predominantly of Indian origin, although Japanese tires predominated with light vehicles. There were some tires from Malaysia, Indonesia, and Pakistan, but they were rejected as atypical. The data were confirmed by conducting a second survey of Kathmandu tire retailers. The percentage of tire usage by country of origin was multiplied by the cost for each country to calculate an average tire cost.

Travel Time Costs

Passenger travel time costs were not included since (a) time savings in a developing country like Nepal are not significant because actual time savings may not be applied to other productive uses; and (b) the aim of the project was to rank suitable alternative maintenance policies in terms of economic benefit to Nepal. Savings in VOC are a tangible economic benefit and carry considerably more significance than an intangible such as travel time.

Accident Costs

Maintenance treatments may influence accidents but data in this area are lacking. Accordingly, the costs of traffic accidents were not considered in the analysis.

Representative Vehicle Characteristics

The HDM-III VOC calculations require certain vehicle characteristics. Vehicle use is employed to calculate the depreciation and interest costs as well as parts consumption. Vehicle weight influences its speed and its fuel consumption. Vehicle power governs speeds on grades and also influences heavy vehicle fuel consumption.

The characteristics were established using values from several sources (*1,4,5*).

HDM MODEL CALIBRATION

Pavement Deterioration

The pavements were constructed of granular base with hand-laid asphaltic surfacings, mostly penetration macadam or thin premixed asphalt. These surfacing types are not part of the HDM research base, thus adjustment, calibration, and verification of the HDM models were essential.

Roughness Progression

In HDM-III, the linkage between pavement condition and VOC is through roughness. Thus, the prediction of this parameter is critical. The first calibrated roughness measurements were made at the time of the study so there was no historical data base on which to draw. A back analysis was made for a representative section of road with 400 vpd in 1992–1993 and wide ranges of deflection, roughness, and surface distress. This analysis, covering a 20-year period, showed a good agreement with the HDM predictions, assuming the assumptions about past traffic growth and the initial roughness after construction were correct.

The component of the HDM roughness expression that concerns potholing and patching was further verified. For individual road sections, regressions were made between the visual assessment of surface distress and the roughness. The mean coefficients obtained in this way for the effects of potholes and patches were close to those used in HDM.

Given the correlation above, the roughness progression model was not adjusted. However, the upper limit of roughness was raised from 11.5 IRI m/km to 20.0 m/km since the study roads had many values over the HDM default limit.

Crack Progression

The HDM-III research originally developed with two sets of relationships for crack progression; one as a function of time and the other as a function of traffic (*6*). However, the HDM-III model itself contains only the time-based models (*1*). In a previous study in Thailand (*7*), HDM-III was modified to include both types of relationships, the traffic-based relationships being preferred for volumes exceeding 1,000 vpd. Consideration was given to using the traffic-based models in Nepal but they were rejected for the following reasons:

- The roads being studied had volumes below 1,000 vpd, which was the lower limit found suitable for the traffic relationships in Thailand; and
- Anomalies were discovered when applying the traffic-based model for surface-treated pavements.

HDM-III, in its standard form, does not consider the effect of crack reflection on the rate of crack progression although it is allowed for in the crack initiation period. The study investigated thin overlays and surface treatments on heavily cracked existing surfaces as possible treatments. Thus crack reflection effects could not be ignored. An intuitive modification was made to the crack progression models by applying the following factor:

$$ICR = 1 + PCRW/100,$$

where ICR is a multiplicative factor for annual rate of crack progression and $PCRW$ is the percentage area of wide cracking before overlay or reseal.

Rut Depth Progression

HDM-III predicted high values of rut depth progression, particularly for roads with lower values of pavement strength and roughnesses over 10 IRI m/km. This was contrary to the observed conditions so an upper limit of 10 mm was applied to the mean rut depth.

Maintenance Effects

Patching and Surface Dressing

One section had been partially treated with patching and surface treatment immediately prior to the study. The average roughness was 8.1 IRI m/km, and an adjacent untreated section had a roughness of 10.4 m/km, indicating that the roughness reduction from patching and surface treatment was just over 2.0 m/km.

The HDM expression patching and surface treatment effects is

$$DIRI = 0.6 + 0.0066\ DCRX + 0.38\ DAPOT$$

where

$DIRI$ = reduction in roughness (IRI m/km),
$DCRX$ = reduction in percentage area of indexed cracking, and
$DAPOT$ = reduction in percentage area of potholes.

On the untreated section, the indexed cracking was 80 percent and potholing 2.5 percent. Applying the foregoing expression gives a reduction in roughness of 2.1 m/km, very close to the observed implied value.

Overlays

Hand-laid surfacings are characterized by short base-length roughness. Thus, thin overlays give a significant reduction in roughness compared with thin overlays on long base-length roughness asphalt roads. A study in Indonesia (8) yielded the following relationship:

$$IRIA = 2.0 + \max[0.0071(IRIB - 2.0)(80 - T), 0]$$

where

$IRIA$ = roughness after overlay (IRI),
$IRIB$ = roughness before overlay (IRI), and
T = overlay thickness (mm).

Data from Nepal suggested that the best achievable roughness on new machine-laid asphalt was 2.5 m/km; thus it was appropriate to replace the constant of 2 with 2.5 in the equation above. The modified model was compared with the pre- and postoverlay roughness for a recently maintained section. The overlay thickness was 30 mm and the average roughness values 10.0 and 5.2 m/km, respectively. This agreed very closely with the modified Indonesian expression that replaced the default expression in HDM-III.

Reconstruction

After full reconstruction of a road, laying a new course of granular base, the posttreatment roughness is expected to be independent of the pretreatment condition. Based on the DOR roughness survey, which covered several recently constructed roads, values of 4.5 m/km for surface treatment and 2.5 m/km for machine-laid asphalt were adopted for postreconstruction roughness.

VOC Model

The proposed screening procedure called for a TTC analysis. Since by far the greatest component of a TTC analysis is the VOCs, it is important that they be appropriate for local conditions. HDM-III contains four distinct sets of VOC—those derived from studies in Brazil, Kenya, the Caribbean, and India. The first stage of the calibration, therefore, consisted of evaluating the various equations and selecting the appropriate equations for use in Nepal. The equations were then tested over the full range of roughness experienced on the project roads to ensure that the predictions were consistent. Since the project was oriented toward maintenance activities, the effects of roughness on VOC was of particular interest.

Selection of Equations

Because of its proximity to India, the HDM-III India equations are the natural choice for use in Nepal. The medium trucks and buses in Nepal are the same as those in India, so the parts and fuel consumption rates should be similar. The repair policies would also be similar since Nepal has a similar economic climate, with inexpensive labor and high import costs. Both the Kenya and Caribbean studies were based on limited data and conditions markedly different from Nepal, leaving the Brazil model as the only alternative to the India model.

The predictions of the India VOC model in HDM-III were compared with truck and bus costs gathered in field surveys (4). The comparison showed the following:

- Good agreement existed between observed tire and oil costs and the India equation predictions.
- India fuel consumption predictions were lower than the actual. The Brazil values were much closer.
- The Brazil model predicted markedly higher parts consumption.
- The weighting of parts to labor costs in the Brazil model appeared to be unreasonable for a country such as Nepal with low labor costs relative to parts.
- Differences between the India and Brazil crew, depreciation, and interest costs were entirely due to the different speeds predicted by the models.

There were two possible explanations for the apparent inappropriateness of the India fuel consumption model. First, since few vehicles are driven by owners, drivers have a financial incentive to overreport the actual fuel costs. Second, HDM-III uses an "adjustment factor" to convert the experimentally derived fuel consumption to actual operational values. Factors of 1.15 are used by HDM-III, while the original India study had a factor of 1.31 for trucks (5). A higher factor is justified in Nepal because of the difficulty in maintaining constant driving speeds. On the basis of the analysis in Nepal (4), the India VOC models were adopted with the fuel consumption modeled using a correction factor of 1.5.

Parts Consumption Model

The India HDM-III equations predicted the parts consumption as a function of age and roughness only. This differs from the original models (5), which included other variables, such as gradient and pavement width.

The India parts model for passenger cars was very sensitive to roughness, particularly when the equation was extrapolated over the 9.7 IRI m/km limit observed in the original study. In reviewing this equation, Chesher and Harrison (9) observed that the "roughness coefficient [was] rather poorly determined and no effect for vehicle age [was] detectable."

Chesher and Harrison (9) also compared parts consumption equations for light vehicles from all four user cost studies. The Brazil equations also appear to be highly sensitive to roughness at the higher roughness levels and were thus also unsuitable for use in Nepal. After some investigation, the India model was modified. The tangent at the maximum roughness in the original study (9.7 m/km) was used to extend the roughness range.

For trucks, the parts consumption model in HDM-III as reported by Watanatada et al. (1) is different from the original India equation from the Central Road Research Institute (CRRI) (5), as well as different from the equation reestimated by Chesher and Harrison (9) from the original data. The Chesher and Harrison equation is conceptually much more attractive than the HDM-III equation. It is consistent with the findings of the original India study in that the effects of roughness and geometry on parts consumption are the same as the original CRRI equations. It was also found to give predictions of the correct magnitude for Nepal (4). Accordingly, the Chesher and Harrison equation was adopted in place of the standard HDM-III equation.

The India bus equation predicts a lower roughness effect on parts consumption than the truck equation. This was also observed with the Brazil data, where the buses were less influenced by roughness than trucks (9). The differences between the truck and bus roughness effects are inconsistent in the context of Nepal. The prevailing driving practices are such that buses do not slow down significantly on rough pavements, whereas trucks, because of their high loads, have low, constant speeds. This differs from India where buses slowed down on rough pavements (9). In Nepal, the effect of roughness on bus parts would be equal to or greater than that on truck parts. Furthermore, the bus chassis in Nepal are almost identical to those for trucks, so the costs should be much closer than suggested by the HDM-III equations. Accordingly, the truck roughness coefficient was substituted into the bus parts consumption model.

Labor Hours

The HDM-III India labor hours model predicts that the labor costs are proportional to the parts costs, with bus and truck costs also being influenced by roughness (1). The predicted labor hours are 20 to 60 hours per 1000 km on smooth pavements. At a speed of 50 km/hr, it would take 20 hours to travel 1000 km. Thus, the models predict service times of 1 to 3 hours for each hour of operation. Clearly, the labor models require closer examination.

The equations in HDM-III are not from the original CRRI India study (*5*) but are based on the India data, reanalysed by Watanatada et al. (*1*). The original CRRI research found a reasonable correlation between parts costs and labor costs. Using a value of 2.25 Indian rupees per hour, the labor costs were converted to the number of labor hours (*5*). It appears that this conversion is the source of the error since the CRRI equations predict appropriate labor costs when used with typical input data. Because of the problems with the India labor hours model in HDM-III, the original CRRI equations were incorporated into HDM-III for the project.

Tire Consumption

The HDM-III India passenger car tire consumption model predicts significant increases above 8 IRI m/km. This is due to the nature of the model formulation. At higher roughness, the predictions actually become negative. This model was therefore unsuitable for the rough pavements in Nepal.

At low roughness, the slopes of the Brazil and India passenger car models are virtually identical. As roughness increases, the Brazil model slope is consistent. Thus, the Brazil model was used in place of the anomalous India model. The slopes of the India bus and heavy truck curves are markedly different, with the bus slope showing slightly higher roughness effects at higher roughnesses. These were retained.

Oil Consumption

Oil consumption is a very small component of the total VOCs. The default HDM-III equations were adopted.

Depreciation and Interest Costs

The depreciation and interest costs in HDM-III are calculated as straight-line depreciation over the service life of the vehicle. One can make these costs sensitive to operating conditions by varying the vehicle service life and annual use.

The nature of the terrain and the length of many trips in Nepal are such that travel time savings will seldom translate into additional trips. Furthermore, heavy trucks tend to travel fully loaded in one direction and almost empty in the other. Use is therefore unlikely to be affected by speed changes so the constant annual use method was adopted. The varying service life model in HDM-III has a limited theoretical basis, so a constant service life was adopted. By assuming that the service life and the annual use are constant, the depreciation costs were calculated as straight-line depreciation, unaffected by operating conditions.

Speed Prediction Model

There were essentially two options available for selecting a speed prediction model: the India or the HDM-III Brazil model. The India model was developed from a multiple linear regression of observed speeds, while the Brazil model was based on mechanistic principles and driver behavior.

The India model uses linear coefficients for each of the independent variables. Thus, the derivative of speed with respect to these variables is constant. Consequently, the effect of roughness on speed for a road with high gradients and tight curvature is identical to that on a flat, straight road. Given the extreme differences in the operating conditions on the roads in Nepal, this would lead to unreasonable results.

The HDM-III Brazil speed model overcomes this deficiency. The speed is treated as the minimum of a number of independent "limiting speeds." These are the maximum speeds that a vehicle would travel under a set of operating conditions. A case study of the transfer of the model to India is discussed by Watanatada et al. (*10*), and the parameters from this case study were considered appropriate for Nepal. The Brazil model was therefore adopted with the India parameters.

PAVEMENT ANALYSES

HDM-III was used to determine the optimum pavement maintenance and/or rehabilitation treatments to apply to the road sections under study. This model predicted the discounted TTC associated with each maintenance treatment over the analysis period. By comparing the TTC of different investment options, the treatments that minimize the TTC were established.

Maintenance Strategies

The objective of the analysis was to determine the appropriate treatments to apply to a pavement given its current condition and traffic. The treatment applied today depends upon the future maintenance activities. For example, when there is a high level of future maintenance, a relatively minor treatment may be sufficient today; whereas limited future maintenance may make a much more major treatment appropriate today.

Accordingly, the analysis considered maintenance strategies comprised of two distinct components: a long-term, regular periodic maintenance policy and a series of different immediate treatments to be applied in conjunction with the long-term policy.

Three different long-term strategies reflecting different levels of maintenance funding or commitment were investigated:

- An optimal policy representing a high level of maintenance; patching with combinations of reseals and thin overlays. The reseal and overlay intervention levels were selected on the basis of the results of a very comprehensive analysis undertaken in Thailand by N.D. Lea International Ltd. (*7*) and adapted to Nepal conditions. The policy consisted of
  - –Patching 100 percent of the potholes or cracks in the year in which they arose up to a maximum of 120 m^2/km/year;
  - –A single surface dressing at 30 percent cracked surface area; and
  - –A 30-mm overlay at 6.0 IRI m/km.
- A suboptimal policy
  - –Patching 100 percent of the potholes or cracks in the year in which they arose up to a maximum of 120 m^2/km/year;
  - –A single surface dressing at regular 7 yearly intervals (*11*).
- A minimum policy comprised of routine maintenance only:
  - –Patching 100 percent of the potholes or cracks in the year in which they arose up to a maximum of 120 m^2/km/year.

Seven initial treatment (IT) options were investigated in conjunction with each of the long-term policies. These treatments, and their effects on roughness and pavement MSN are given in Table 1. Since HDM-III does not materially differentiate between a single (SSD) or double surface dressing (DSD) in terms of their impact on pavement deterioration, only an SSD was considered.

The combination of initial treatments and long-term policies resulted in 21 maintenance strategies in the analysis. The base case in the study consisted of an immediate SSD, then patching all potholes and cracks in the year in which they occur.

The unit costs were calculated and expressed as NRs/m^2. Since HDM-III allowed for a single cost per type of treatment (overlay-reseal, etc.) only the different overlay and reconstruction costs were expressed relative to the IT2 and IT5 costs and input to HDM as cost factors.

TABLE 1 Initial Treatments and Their Effects

Treatment	Description	Roughness after Treatment[1]	Change in MSN[2]
IT1	Single surface dressing (SSD)	Predicted	Predicted
IT2	30 mm hot rolled asphalt (HRA)	Predicted	Predicted
IT3	50 mm hot rolled asphalt (HRA)	Predicted	Predicted
IT4	80 mm open graded bitumen macadam + SSD (OG)	Predicted	Predicted
IT5	100 mm granular base + DSD	4.5	0.67
IT6	150 mm granular base + DSD	4.5	0.95
IT7	150 mm granular base + 50 mm AC	2.5	1.52

NOTES: 1/ The roughness was predicted using equation presented earlier.

2/ The change in MSN was predicted from the layer strength coefficients and layer thicknesses. The strength coefficients used were:

Surface dressing	0.20
Hot rolled asphalt	0.30
Macadam/AC	0.35
Granular base	0.14

Analytical Matrix

The sections of roads in the project were very inhomogeneous and therefore did not lend themselves to an analysis with HDM-III as a single link. Thus, the analysis was conducted using a matrix of dummy links defined by pavement strength, roughness, surface distress, and traffic. There were five strengths, 5 roughness levels, and three cracking levels making a total of 75 cells in the matrix. Table 2 lists the ranges adopted for these characteristics.

Interpreting the HDM-III Output

All 21 maintenance strategies could not be handled in a single run since this exceeded the capacity of the HDM-III reporting facility. The analysis was conducted in two stages: stage 1 for the minimum periodic maintenance and stage 2 for the optimal and suboptimal maintenance. The two output files were combined into a single output file containing all strategies.

Two programs were written to extract the required data from the HDM-III output and to manipulate it into the appropriate format. The first read through the HDM-III output and created new files containing the discounted costs. The second read these cost files and calculated the NPV of maintenance, which was defined as

$$NPV = (VOC_{\mathrm{BASE}} - VOC_{\mathrm{ALT}}) - (MAIN_{\mathrm{ALT}} - MAIN_{\mathrm{BASE}})$$

where

NPV = net present value of maintenance,
VOC_{BASE} = total discounted VOC of the base case,
VOC_{ALT} = total discounted VOC of the maintenance alternative,
$MAIN_{\mathrm{BASE}}$ = total discounted maintenance costs of the base case, and
$MAIN_{\mathrm{ALT}}$ = total discounted maintenance costs of the alternative.

Having established the NPV, two analyses were undertaken. The first used the NPV to determine the appropriate strategy for each link. The second investigated the timing of the application of the initial treatment.

Selecting Strategies Using NPV

The NPV for each strategy was calculated and the results sorted by increasing NPV. Those strategies with positive NPV were graphed as maintenance costs versus NPV. Figure 2 is an example of such a graph for a hypothetical cell.

The maximum NPV for a given level of maintenance expenditure represents the most cost-effective strategy for that level of expenditure. In Figure 2 these cost-effective strategies are connected by a line to form the "efficiency frontier" (*12*). This represents the most cost-effective series of strategies for the levels of expenditure. Any strategy that falls below the efficiency frontier can, in theory, be replaced by a more beneficial strategy at the same cost. The last strategy on the efficiency frontier (Point 1 in Figure 2) is the strategy that maximizes the NPV and is a high-cost, high-benefit strategy. In practice, one often selects strategies further down the frontier (Points 2 to 4). This is principally done for three reasons:

- Given budget constraints, there is seldom sufficient budget to carry out the high-cost strategies on all links. Network optimization under budget constraints may dictate application of lower-cost, lower-benefit strategies.
- Toward the end of the efficiency frontier, the marginal benefits from increased maintenance standards are often of the same magnitude as the marginal costs. Effectively, this means that the increased maintenance expenditure is of almost equal value to the savings in road users—which is an inefficient use of funds.

TABLE 2 Ranges Adopted for Pavement Characteristics

Pavement Strength				Roughness (IRIm/km)			All Cracking (percent)		
Strength Code	Deflection in mm		MSN	RoughCode	Range	Rep. Value	Crack. Code	Range	Rep. Value
	Range (6.35 t axle)	Rep. Value (8.2 t axle)							
S1	< 0.5	0.4	5.70	R1	4 - 6	5.0			
S2	0.5 - 1.0	1.0	3.20	R2	6 - 8	7.0	C1	< 20	10.0
S3	1.0 - 1.5	1.6	2.40	R3	8 - 10	9.0	C2	20 - 60	50.0
S4	1.5 - 2.0	2.3	1.90	R4	10 - 12	11.0	C3	> 60	90.0
S5	> 2.0	3.2	1.55	R5	> 12	13.0			

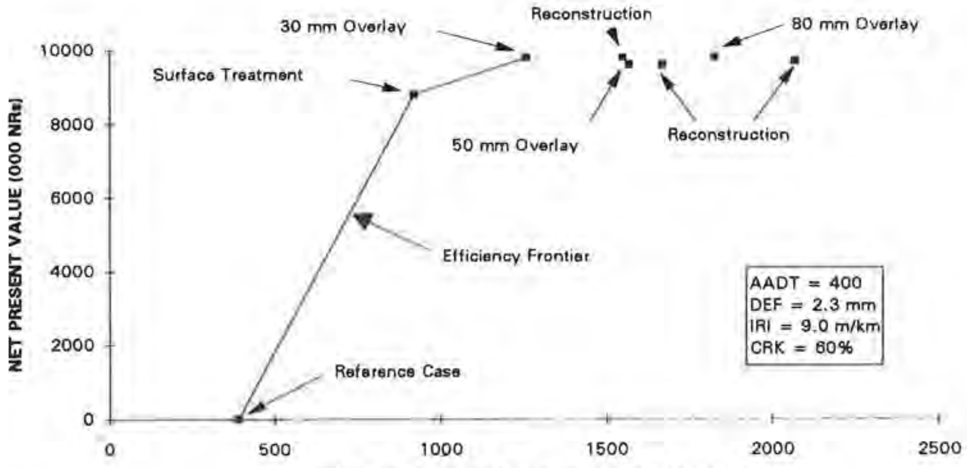

FIGURE 2 Example of efficiency frontier.

- The errors in the VOC predictions are greater than the errors in the maintenance costs, which are usually fairly accurately known. Consequently, it is unwise to adopt marginal projects that may, were the VOCs more accurately quantified, actually be uneconomic.

Accordingly, a cutoff of 2 in the incremental benefit-to-cost ratio was used in selecting cost-effective strategies.

The efficiency frontiers were established for each cell in the matrix. From these, one or more strategies were selected as being appropriate for the cell. In some instances, these were the high-cost, high-benefit strategy, but in others where the benefits were marginal, lower-cost solutions were selected. From these strategies, a single strategy was selected for the link under analysis. The analysis was conducted for both the optimum and sub-optimum long-term periodic maintenance policies.

Treatment Priorities

Having determined the appropriate maintenance strategies for each link, it was necessary to examine the short-term priorities for applying the initial treatments. This allows for the available funds and contracting capacity to be directed toward the links that will yield the greatest benefits from performing maintenance in the short term.

The priorities were established by calculating the TTC of doing the treatment in the first year and the TTC of postponing it by one year. The NPV from postponing the treatment is the difference between these two values, that is,

$$POSTBEN = TTC_2 - TTC_1$$

where

$POSTBEN$ = NPV of not postponing maintenance by one year,
TTC_1 = TTC if the treatment is applied in Year 1, and
TTC_2 = TTC if the treatment is applied in Year 2.

If the difference is positive, there is a benefit from performing the treatment in Year 1; negative if the treatment is postponed.

In applying this technique to the matrix analysis, it was found that the results for the major initial treatments were inconsistent across the various pavement strengths. It was not possible to ascertain the reasons behind this so an alternative approach was used. The TTCs using the treatments were calculated along with those assuming a minimum case of patching potholes only. The incremental NPVs were calculated for each of these cases along with the internal rate of return (IRR). These were found to give consistent results for ranking priorities.

Results of Analysis

A total of 225 graphs were produced in the matrix analysis—one for each combination of traffic volume, strength, roughness, and cracking. After establishing the efficiency frontiers for each cell in the matrix, the appropriate initial treatments were selected.

The results indicated that cracking did not materially influence the results. This is because all the pavements were already cracked and the marginal effects of the different cracking levels were not significant. It was possible to establish the appropriate treatment for each combination of traffic volume, strength, and roughness. These are presented in Table 3 for the optimal long-term periodic maintenance policies. The policies in Table 3 follow a regular pattern across the various pavement strength, roughness, and traffic volume ranges.

The priorities of the treatments were established by calculating the incremental NPV between a base case consisting of patching only and the application of the treatment in Year 1 with optimal and suboptimal long-term periodic maintenance. The IRR for these two scenarios against the base case was also calculated. The results showed that for the 100-vpd road, except at the highest roughness, the incremental NPVs were all negative. This analysis indicated that the treatments should be postponed on these sections. These results were confirmed by the IRR results.

Sensitivity Tests

Sensitivity tests were conducted to investigate the sensitivity of the results to the assumed optimum long-term periodic maintenance strategy. It was found that neither the intervention level (i.e., the roughness at which an overlay is applied) nor the thickness of the overlay affected the results materially. The optimum strategy was not altered and the only detail that varied was the magnitude of the NPV estimates. The results were also not sensitive to small changes in the discount rate.

CONCLUSIONS

The results of applying benefit-cost analyses to the determination of rehabilitation treatments for low-volume roads in Nepal show that very different treatments are appropriate at different traffic volumes:

- At 100 vpd, the only viable treatment is surface treatment unless the roughness is more than 12 IRI m/km when a thin overlay is economic. The results at this low traffic level are insensitive to pavement

TABLE 3 Immediate Treatments by Roughness-Strength-Volume: Optimal Periodic Maintenance

Roughness (IRI m/km)	1993 Traffic Volume (veh/day)	6.35 t Deflection in mm				
		< 0.5	0.5 - 1.0	1.0 - 1.5	1.5 - 2.0	> 2.0
4 - 6	100	SSD	SSD	SSD	SSD	SSD
	300	SSD	SSD	SSD	SSD	SSD
	400	SSD	SSD	SSD	SSD	30 mm OL
6 - 8	100	SSD	SSD	SSD	SSD	SSD
	300	SSD	SSD	SSD	SSD	SSD
	400	SSD	SSD	SSD	SSD	30 mm OL
8 - 10	100	SSD	SSD	SSD	SSD	SSD
	300	30 mm OL	30 mm OL	30 mm OL	30 mm OL	30 mm OL
	400	30 mm OL	30 mm OL	30 mm OL	30 mm OL	30 mm OL
10 - 12	100	SSD	SSD	SSD	SSD	SSD
	300	30 mm OL	30 mm OL	30 mm OL	30 mm OL	30 mm OL
	400	30 mm OL	30 mm OL	30 mm OL	30 mm OL	30 mm OL
> 12	100	30 mm OL	30 mm OL	30 mm OL	30 mm OL	30 mm OL
	300	100 GB+DSD	100 GB+DSD	100 GB+DSD	100 GB+DSD	100 GB+DSD
	400	100 GB+DSD	100 GB+DSD	100 GB+DSD	100 GB+DSD	100 GB+DSD

NOTES:	
SSD	Single surface dressing
30 mm OL	30 mm hot rolled asphalt overlay
100 GB+DSD	100 mm granular base with double surface dressing

strength, surface distress, or the future maintenance policy.

• At 400 vpd, the rehabilitation need is sensitive to pavement strength, roughness, and future maintenance policy. Surface distress is significant only when roughness is low and pavement strength is high. At this volume, varying thicknesses of overlays are recommended when the roughness is greater than 8 m/km if the future maintenance policy includes overlaying. If the future policy comprises only surface treatment, then immediate overlaying is advantageous at a roughness of 4–6 m/km.

It is vital that HDM-III be calibrated to local conditions. This entails collecting not only the basic data needed to run the model but also the data for verifying or adjusting the model relationships. When applied to a study of pavement rehabilitation or maintenance, the most significant expressions are those relating pre- and postoverlay roughness and those relating roughness to vehicle parts consumption. The former is relatively easy to quantify while the latter is more problematic within the time frame of a short study; recourse must be made to data from other studies and countries and to judgment.

If HDM-III were applied without calibration in countries where incomes are low and labor-intensive methods are used for road construction and maintenance, it would likely yield inaccurate results erring on the side of overdesign.

Those interested in a fuller description of the work described here should refer to the original reports (*13,14*).

ACKNOWLEDGMENTS

The work described in this paper was funded by His Majesty's Government of Nepal (HMGN) and the World Bank under a contract with N.D. Lea International Ltd. of Canada and Nepal Engineering Consultancy Services Centre Ltd. of Nepal. The authors would like to acknowledge the assistance of the Department of Roads of HMGN and the other members of the study team. The paper is presented with the permission of the Nepal Department of Roads and N.D. Lea International Ltd.

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