ENGINEERING ECONOMICS OF THE MAINTENANCE OF EARTH AND GRAVEL ROADS

Asif Faiz and Edgardo Staffini, The World Bank, Washington, D.C.

This paper presents a methodology for the economic evaluation of maintenance programs for unpaved roads with low traffic volumes (under 250 vpd), a situation commonly encountered in rural areas in developing countries. The technique, drawing heavily on the road deterioration and user cost relationships developed in the IBRD/TRRL Kenya Road Transport Cost Study, involves a dynamic model that relates vehicle operating costs to traffic-induced road deterioration. The proposed methodology requires a two-step procedure: first to determine economically optimal and technically appropriate maintenance strategies; and second to apply these strategies to assess the economic value of the global road maintenance program. The incremental economic analysis used in the methodology permits the differentiation of benefits, in the form of vehicle operating cost savings, between routine and periodic maintenance. The use of the evaluation technique is demonstrated by application to a road maintenance program. Although the proposed method requires the use of multiple regression analysis and elementary calculus, graphical methods can be used as an alternative.

Cost-effective road maintenance practice is becoming a priority objective in most countries of the world since relatively nominal maintenance expenditures (about US$100-1000 per km in case of unpaved roads) can extend the life of existing infrastructure and postpone the need for its renewal. Although the economic value of road maintenance is manifest, its quantification is necessary to determine economically efficient levels of maintenance expenditures. Intensive research by the World Bank over the last decade suggests that the largest benefits of highway maintenance accrue in the form of vehicle operating cost (VOC) savings and that these are often the dominant factor in reaching economically optimal highway maintenance policy choices. In fact, vehicle operating costs on an unpaved road surface in good condition can be about 30-40% lower than if the surface were not adequately maintained.

The traditional approach to quantification of benefits due to good road maintenance takes the form of a static economic model that assumes fixed and often arbitrary levels of VOC under "good" and "poor" road maintenance conditions; the VOC difference comprising the benefits from good maintenance. This subjective method of analysis often results in suboptimal investment decisions relative to the scale and intensity of maintenance operations, such as the frequency of grading operations and the periodicity of gravelling(8).

The proposed method of analyzing road maintenance programs for unpaved roads is based on a dynamic analysis that relates vehicle operating costs to road surface conditions as they are affected by traffic and modified by maintenance operations. Traffic-induced road deterioration is defined in terms of roughness, rut depth, and depth of loose material. The corresponding vehicle speeds and VOC are also estimated as a function of surface condition parameters, because the road geometric and environmental factors influencing VOC remain unchanged under normal maintenance operations.

The Analytical Framework

The mathematical models that relate road surface condition and vehicle operating costs to traffic were developed under the IBRD/TRRL research program in Kenya (2, 3, 5). A review of the background references is necessary for an understanding of the methodology presented in this paper as limitations of space preclude a thorough discussion of these relationships.

Road Deterioration Relationships

Lateritic Gravels Roads

$$R = 3250 + 84\,T - 1.62\,T^2 + 0.016\,T^3 \qquad (1)$$

$$RD = 11 + 0.23\,T - 0.0037T^2 + 0.000073T^3 \qquad (2)$$

$$LD = 1.5 + 14e^{-0.23T} \qquad (3)$$

$$GL_a = 0.94\frac{T_a^2}{T_a^2 + 50}(4.2 + 0.092T_a + 3.5\,R_1{}^2 + 1.88\,VC) \qquad (4)$$

Sand-Clay Earth Roads

$$R = 3250 + 785\,T \qquad (5)$$

$$RD = 14 + 1.2\,T \qquad (6)$$

$$LD = 1.5 + 14e^{-0.23T}\text{; under dry grading with } LD \geq 10.0 \text{ mm.} \qquad (7)$$

$$LD = 1.0\text{; under wet grading} \qquad (8)$$

Tracks

$$R = 3250 + 1255\,T \qquad (9)$$

$$RD = 14 + 1.2\,T \qquad (10)$$

$$LD = 1.5 + 14e^{-0.23T}\text{; with } LD \geq 10.0 \text{ mm.} \qquad (11)$$

where:

R = mean roughness (mm/km)
RD = rut depth (mm)
LD = depth of loose material (mm)
T = cumulative traffic volume in both directions since last grading (thousands of vehicles)
GL_a = annual gravel loss (mm)
T_a = annual traffic volume in both directions (thousands of vehicles)
R_1 = annual rainfall measured in meters
VC = rise and fall, vertical curvature (%)

Vehicle Operating Cost Relationships

In the Kenya Study relationships, if certain physical characteristics of the road (such as geometrics, altitude and moisture regime) are fixed vehicle speeds and consumption of fuel, tires, spare parts, and maintenance labor can be estimated as a function of surface condition descriptors, R, RD, and LD (4). The average road geometric and environmental characteristics assumed in estimating speed and VOC components were: moisture content, 3%; average rise, 30 m/km; average fall, 30 m/km; average horizontal curvature, 175 degrees/km; and average altitude, 375 m. Oil consumption was also estimated from the results of the Kenya Study while for vehicle depreciation and crew costs the method recommended in de Wielle's work (1) was used. Composite VOC, obtained by adding the individual costs of VOC components, were calculated for the four representative vehicles--light goods vehicle (VL), single-unit truck (CMS), medium truck-trailer (CMR) and heavy truck-trailer (CLR)--used in the example demonstrating the application of the proposed analysis method to a road maintenance program. The physical characteristics and costs of these vehicles are shown in Table 1.

Table 1. Vehicle characteristics and costs

Vehicle Type	Light Goods Vehicle (VL)	Single Unit Truck (CMS)	Medium Truck-Trailer (CMR)	Heavy Truck-Trailer (CLR)
Physical Characteristics and Utilization				
Brake Horse Power	86	130	160	250
Payload (t)	1	7	14	24
Gross Vehicle Weight (t)	2.5	13	27	38
Fuel Type	Gas.	Diesel	Diesel	Diesel
Annual Operating Hours	800	800	1,200	1,200
Annual Crew Hours	2,000	2,000	2,000	2,000
Annual Kilometerage	25,000	25,000	25,000	35,000
Average Vehicle Life (yr.)	4	6	6	6
Unit Costs (net of taxes)				
New Vehicle (US$/veh.)	5,765	18,185	31,145	49,485
Tires (US$/tire)	69	395	395	395
Maintenance Labor (US$/hr.)	0.40	0.40	0.40	0.40
Crew Cost (US$/hr.)	0.50	0.40	0.40	0.40
Fuel (US$/litre)	0.33	0.30	0.30	0.30
Lub. Oil (US$/litre)	1.40	1.40	1.40	1.40

Unified Road Deterioration and Vehicle Operating Cost Relationships

A review of Kenya Study relationships showed both road surface deterioration parameters (R, RD, LD) and VOC could be reduced to a common denominator--cumulative traffic volume (T), provided that road geometric and environmental parameters remained fixed. This special characteristic of the two relationships was

Table 2. Vehicle operating cost equations

Road Surface and Vehicle Type	VOC Estimation Equation	Maximum T^a	Number of Observations	R^2	Standard Error of Estimate	Upper Bound Limit on VOC (US$ Equivalent)
Laterite[b]						
Light Goods Vehicle	$VOC=213.32+0.0094T^2$	100	19	0.985	1.85	310
Single Unit Truck	$VOC=392.44+0.0216T^2$	100	19	0.991	3.27	610
Medium Truck-trailer	$VOC=692.98+0.0422T^2$	80	19	0.984	8.53	1020
Heavy Truck-trailer	$VOC=861.93+0.0557T^2$	80	19	0.984	10.95	1225
Sand-Clay[c]						
Light Goods Vehicle	$VOC=207.02+12.87T-0.2496T^2$	30	17	0.987	6.72	370
Single Unit Truck	$VOC=385.96+18.56T-0.2660T^2$	30	17	0.994	8.39	710
Medium Truck-trailer	$VOC=676.29+34.73T-0.4365T^2$	30	17	0.994	16.96	1350
Heavy Truck-trailer	$VOC=833.83+51.40T-0.7947T^2$	30	17	0.994	22.49	1675
Track						
Light Goods Vehicle	$VOC=206.86+21.51T-0.8051T^2+0.003T^4$	30	17	0.986	7.42	370
Single Unit Truck	$VOC=384.54+31.04T-1.0593T^2+0.004T^4$	30	17	0.991	10.32	710
Medium Truck-trailer	$VOC=675.07+58.37T-1.9396T^2+0.008T^4$	30	17	0.992	19.23	1350
Heavy Truck-trailer	$VOC=831.15+86.49T-3.0527T^2+0.012T^4$	30	17	0.990	28.99	1675

[a] T=Cumulative traffic volume between gradings in both directions ('000 vehicles).
[b] Applies to gravel roads with at least 2 cm of laterite surface.
[c] Applies to earth roads and gravel roads with less than 2 cm of laterite surface.

Note: VOC = vehicle operating cost (US$/1,000 km)

Table 3. Vehicle operating costs as a function of traffic and road surface characteristics

Road Surface	T	R	RD	LD	VOC Estimate[a]			
					VL	CMS	CMR	CLR
Gravel Road: (Laterite Surface)	0	3250	11.0	15.5	213.32	392.44	692.88	861.93
	1	3332	11.2	11.1	213.33	392.46	693.02	861.98
	10	3944	13.0	2.9	214.27	394.60	697.20	867.49
	20	4410	14.7	1.6	217.09	401.09	709.86	884.20
	30	4744	16.5	1.5	221.81	411.91	730.96	912.30
	50	5400	22.4	1.5	236.89	446.52	798.49	1001.11
	80	7794	43.1	1.5	273.67	530.89	963.09	1218.24
	100	11450	70.0	1.5	307.61	608.76	-	-
Maximum VOC[b]					310.00	610.00	1020.00	1225.00
Earth Road: (Sand-Clay Surface)	0	3250	14.0	15.5	207.20	385.96	676.29	833.82
	1	4035	15.2	11.1	219.64	404.25	710.58	884.78
	5	7175	20.0	10.1	265.08	472.11	839.02	1079.89
	10	11700	26.0	10.0	310.74	544.95	979.92	1304.11
	20	14000	38.0	10.0	364.53	650.73	1196.23	1543.38
	30	14000	50.0	10.0	373.47	706.97	1325.18	1659.38
Maximum VOC[b]					375.00	710.00	1350.00	1675.00
Earth Track:	0	3250	14.0	15.5	206.86	384.54	675.07	831.15
	1	4505	15.2	11.0	227.57	414.52	731.51	914.58
	5	9525	20.0	10.0	294.81	513.53	919.45	1188.03
	10	14000	26.0	10.0	344.45	593.12	1072.97	1402.98
	20	14000	32.0	10.0	360.80	646.98	1197.22	1535.71
	30	14000	50.0	10.0	373.47	706.97	1325.81	1659.38
Maximum VOC[b]					375.00	710.00	1350.00	1675.00

[a] Vehicle operating cost estimate (US$/1000 km).
[b] Maximum VOC corresponds to an average speed of 10-15 km/hr.

used to formulate a unified relationship that would permit direct VOC estimation as a function of cumulative traffic volume (T), bypassing all intermediate steps requiring estimation of vehicle speed and VOC components as a function of surface condition parameters. The unified VOC estimation equations were obtained by regressing composite VOC with cumulative traffic (T), for three road surface types (Table 2). The interaction among cumulative traffic, road surface condition variables and the related VOC is shown in Table 3.

Estimation of Benefits due to Reduced Vehicle Operating Costs

With the use of VOC equations shown in Table 2, savings in vehicle operating costs during a given time period (normally one year for purposes of discounting) can be estimated directly as follows:

1. Calculate an average VOC equation by weighting the VOC equations for different vehicles by their respective percentages in the traffic distribution.
2. Use the average VOC equation to:
(a) sum the operating costs of vehicles accumulated between gradings during one year, for a given maintenance strategy (e.g. 2 gradings per year and other required routine maintenance);
(b) sum the operating costs of vehicles accumulated between gradings during one year, for an alternate maintenance strategy (e.g. regravelling, 2 gradings per year and other required routine maintenance).
3. Determine incremental benefits (VOC savings) due to the alternate maintenance strategy as the difference between the summed VOC for the two maintenance strategies.

Mathematically, this can be expressed as:

$$\text{VOC Savings} = \int f(T)_1 dT - \int f(T)_2 dT \qquad (12)$$

where: $f(T)_1$ = VOC equation corresponding to maintenance strategy 1
$f(T)_2$ = VOC equation corresponding to alternate maintenance strategy 2

This procedure simplifies the calculation of benefits and does not require discrete addition of vehicle operating costs. For example, VOC benefits from two gradings per year, as compared to one grading per year on a sand-clay earth road, for a traffic stream containing only light vehicles (VL) can be expressed as:

$$B = 1000\int_0^X (207.02 + 12.87T - 0.2496T^2)dT$$

$$- 2(1000)\int_0^{x/2}(207.02 + 12.87T - 0.2496T^2)dT$$

$$= 1000\left(12.8T\left(\frac{x^2}{2} - \frac{x^2}{4}\right) - 0.2496\left(\frac{x^3}{3} - \frac{x^3}{12}\right)\right) \quad (13)$$

where: x = accumulated number of vehicles per year in thousands
B = VOC savings in US$/1000 km.

Application to Economic Analysis of a Maintenance Program

The foregoing analytical procedure was applied to evaluate the economic value of a maintenance program for a network of 5,300 km of unpaved roads and tracks in West Africa. The area covered by the maintenance program is characterized by a dry climate with an average rainfall of about 1,100 mm per year. The average altitude is about 375 m with a flat to rolling terrain. As deposits of good lateritic gravels are not plentiful, a mechanically stabilised sand-clay mixture has been used as the wearing course on some unpaved roads.

The Maintenance Program

The maintenance program was designed to cover both routine and periodic maintenance (regravelling) activities. Fully mechanized routine maintenance operations consisted of grading, compacting, and dragging with tractor-drawn tires. Other operations such as filling potholes, clearing ditches and culverts, vegetation control, and spot regravelling were placed under the responsibility of road gangs. Each gang consisted of 25 laborers under the direction of a sector chief with responsibility for a road maintenance sector covering 100-200 km.

The physical requirements for the maintenance program included provision of equipment plus an initial stock of spare parts, workshop equipment, construction of equipment sheds, improvements to the workshops, construction of spare parts store, offices for equipment inventory control and inspection, and buildings to serve as administrative centers for the road sectors. To meet the requirements for mechanics, operators, and other skilled staff, a comprehensive training program including technical assistance and equipment for a training center was instituted. Senior administrative and technical staff needs were met by provision of a technical assistance team, whose functions included training of local staff and development of the necessary capability for equipment maintenance, and planning and execution of road maintenance works.

Sequential Economic Evaluation Procedure

The evaluation of the maintenance program followed a sequential procedure involving classification of roads included in the maintenance program, determination of appropriate maintenance strategies and the overall economic assessment of the maintenance program. After the road network was categorized broadly according to its engineering and traffic characteristics, an appropriate maintenance strategy was determined for each road surface type by calculating the incremental VOC savings associated with the improved maintenance operations. This was followed by determination of overall economic benefits (VOC savings), which were then compared with maintenance costs to evaluate the economic returns for the routine and periodic maintenance components of the maintenance program.

Table 4. Classification of road network for economic analysis of the maintenance program

Network Category	Length (km)	Base ADT (vpd)	Distribution of Traffic %VL	%CMS	%CMR	%CLR
Gravel Roads[a]	395	48	45	15	25	15
Gravel Roads	79	38	45	15	25	15
Gravel Roads	276	15	45	15	25	15
Earth Roads[b]	63	40	45	15	25	15
Earth Roads	181	34	45	30	0	25
Earth Roads	175	17	45	30	0	25
Earth Roads	49	34	45	15	25	15
Earth Roads	150	17	45	15	25	15
Earth Roads	259	10	45	30	0	25
Major Tracks[c]	99	29	45	15	25	15
Major Tracks	846	17	45	15	25	15
Major Tracks	72	13	45	55	0	0
Minor Tracks	1544	5	45	55	0	0
Minor Tracks	1130	7	45	15	25	15
TOTAL	5318					

[a] All gravel roads have a wearing course of lateritic gravels.

[b] All earth roads have a wearing course of a mechanically stabilized sand-clay mix.

[c] Most tracks follow the natural ground profile and may have a few drainage structures.

Classification of the Road Network

The unpaved road network of about 5,300 km, varied from all-weather gravel (laterite-surfaced) roads to tracks. The base-level average daily traffic (ADT) on the network ranged from about 50 vpd on the laterite-surfaced roads to less than 10 vpd on the tracks. As the road network had not been functionally classified, it was categorized according to its engineering and traffic characteristics (Table 4). An average traffic growth rate of 3% per annum was assumed over the analysis period.

Determination of Maintenance Strategies

Maintenance policies for unpaved roads included drainage and vegetation control, dragging (with rubber tires), emergency repairs resulting from washouts and weak spots, grading, and resurfacing with gravel. As no definite, quantified models are available to evaluate benefits from four of the basic routine maintenance operations--drainage clearance, vegetation control, shoulder maintenance and surface dragging--it was assumed that a certain level of expenditures for these routine items was required as part of the overall maintenance policies. For grading and gravelling, which consituted the major maintenance operations it was necessary to determine: (i) appropriate grading strategies for various classes of roads included in the maintenance program; and (ii) the traffic level at which surfacing with gravel would be economically justified.

Grading Frequency

The effect of more frequent grading is to improve the condition of the road surface and thereby lower vehicle operating costs. The vehicle operating costs corresponding to various grading frequencies for a given type of road surface were obtained by

$$\Sigma VOC = N \int_0^{x/N} f(T)_w \, dT \tag{14}$$

where:

ΣVOC = cumulative vehicle operating costs in one year corresponding to a grading frequency, N/year (US$/km);

x = cumulative number of vehicles during one year in thousands;

N = grading frequency (number of bladings/year); and

$f(T)_w$ = average VOC equation obtained by their respective share in the traffic stream.

The incremental benefits (reductions in vehicle operating costs) due to additional grading were obtained as:

$$\Delta VOC = \Sigma VOC_N - \Sigma VOC_{N+1} \tag{15}$$

where:

ΔVOC = Incremental reduction in vehicle operating costs (US$/km)

ΣVOC_N = Cumulative VOC per annum for a grading frequency, N/year (US$/year)

ΣVOC_{N+1} =Cumulative VOC per annum for a grading frequency N+1/year (US$/year).

By equating the incremental benefits associated with progressively increasing grading frequencies with the incremental unit cost of grading (US$80/km); optimal grading frequencies were established for various

Table 5. Effect of grading frequency on vehicle operating costs for lateritic gravel roads

Grading Frequency (number/year)	Cumulative Vehicle Operating Costs, ΣVOC (US$/year)	Incremental Reduction in VOC, ΔVOC (US$/year)
ADT = 10 vpd		
1	1,670.00	-
2	1,669.60	0.40
ADT = 30 vpd		
1	5,020.04	-
2	5,011.38	8.66
ADT = 50 vpd		
1	8,400.98	-
2	8,360.85	40.13
ADT = 70 vpd		
1	11,833.29	-
2	11,723.17	110.12
3	11,702.78	20.39
ADT = 90 vpd		
1	15,377.50	-
2	15,103.47	274.03
3	15,058.09	45.38
ADT = 120 vpd		
1	20,774.76	-
2	20,219.14	555.62
3	20,116.25	102.89
4	20,080.24	36.02
ADT = 150 vpd		
1	26,489.33	-
2	25,404.15	1,085.18
3	25,203.19	200.96
4	25,132.86	70.33
ADT = 200 vpd		
1	36,819.60	-
2	34,247.33	2,572.27
3	33,768.93	478.40
4	33,604.26	164.67
5	33,522.09	80.17
ADT = 250 vpd		
1	48,436.01	-
2	43,412.04	5,023.97
3	42,481.67	930.37
4	42,156.04	325.63
5	42,005.32	150.72
6	41,923.45	81.87
7	41,872.82	50.63

levels of base ADT. Where incremental benefits were larger than US$400/km (the cost of grading with compaction), the grading operation was supplemented with compaction. The incremental (marginal) reduction in VOC with increase in grading frequency for a lateritic gravel surface is shown in Table 5 with levels of base ADT varying from 10-250 vpd. A similar analysis was carried out for earth roads with a sand-clay surface and earth tracks; the results are summarized in Table 6. The optimal grading frequency from an economic standpoint is defined as the breakeven point where incremental reduction in vehicle operating costs due to an additional grading (or grading with compaction) operation is equal to the incremental cost of one grading (or grading with compaction) operation. It was found that at least one grading per year was economically justified on all of the three surfaces whenever the base ADT was more than 5 vpd, when compared with the null alternative (no grading at all). The frequency of grading, however, is a function of surface type and level of traffic; a laterite (gravel) surfaced road requiring a considerably lower frequency of grading than a sand-clay (earth) road or an earth track, for the same level of traffic intensity. The optimal grading frequency on gravel roads was found to be less sensitive to traffic, changing from 1 to 6 gradings/year with ADT varying from 30-250 vpd. For an earth road, the optimum varied from 1 grading/year at an ADT of 10 vpd to about 17 gradings/year for a base ADT of 120 vpd. The optimal grading frequencies obtained by the preceeding analysis were used as benchmarks and, where warranted, modified in the light of local experience and climatic conditions to arrive at operational routine maintenance strategies that maintained an appropriate technical balance between grading frequency and other essential routine maintenance operations, particularly for earth roads. As a result, the grading frequencies for gravel roads were slightly increased while those for earth roads and tracks were reduced (Table 7).

Table 6. Economically optimal frequency of grading operations

Road and Surface Type	ADT (vpd)	Optimal Grading Frequency (Gradings/year)		
		Without Compaction[a]	With Compaction[b]	Total
Gravel Road: (laterite)	10	1	0	1
	30	1	0	1
	50	1	0	1
	70	1	1	2
	90	1-2	1	2-3
	120	1	2	3
	150	1-2	2	3-4
	200	2	3	5
	250	3	3	6
Earth Road: (sand-clay)	10	1	0	1
	30	2	2	4
	50	4	3	7
	70	6	4	10
	90	7	5	12
	120	10	7	17
Track: (earth)	5	1	0	1
	10	2	0	2
	30	4	1	5

[a] Unit Cost of grading = US$80/km

[b] Unit Cost of grading with compaction = US$400/km

Gravelling

Surfacing an earth road with gravel provides a riding surface which can better withstand the deleterious effects of traffic and environment, thereby permitting all-weather usage. The serviceability of the road is considerably enhanced, while routine maintenance requirements become less stringent. In addition, the better surface quality results in lower vehicle operating costs.

In order to determine the breakeven traffic volume at which surfacing an earth road with gravel or resurfacing an existing gravel road would be economically justified, a benefit/cost analysis was carried out comparing the cost of four gravelling alternatives with benefits resulting from differences in VOC on gravel and earth surfaces with base ADT ranging from 30 to 90 vpd. The gravelling alternatives considered were:

Alternative:

- A - 10 cm thickness; 6 m width with 0.5 m shoulders.
- B - 10 cm thickness; 7 m width with 0.5 m shoulders.
- C - 15 cm thickness; 6 m width with 0.5 m shoulders
- D - 15 cm thickness; 7 m width with 0.5 m shoulders.

Routine maintenance strategies shown in Table 7 were assumed for the two surface types as required. Benefits at a given base ADT were then calculated as:

Table 7. Routine maintenance strategies adopted for the maintenance program

Road Type	Gravel Roads					Earth Roads					Tracks		
Base ADT (vpd):	10	30	50	70	90	10	30	50	70	90	5	10	30
Dry Grading (operations/year)	1	2	2	2	2	1	1	1	2	2	1	1	2
Grading with Compaction (operations/year)	-	-	-	-	-	-	1	1	1	2	-	-	-
Spot Repairs (m^3/km)	-	-	-	-	-	-	25	50	50	50	-	-	25
Light Routine Maintenance[a] (km/year/sector)	-	200	150	100	50	-	150	100	50	50	-	-	200
Dragging[b] (No. of operations)	-	20	30	50	90	-	-	-	-	-	-	-	-

[a] Filling potholes, drainage and vegetation control, shoulder maintenance, etc.
[b] With tractor-drawn tires.

$$B_{PV} = \Sigma_{a=1}^{n} \quad N_E \int_0^{x_a/N_E} f(T_E)\ dT - N_G \int_0^{x_a/N_G} f(T_G)\ dT \quad pwf_a(i,n) \qquad (16)$$

where:

B_{PV} = present value of difference in vehicle operating costs between gravel and earth surfaces summed over a period of one regravelling cycle (US$/km);
n = analysis period = regravelling cycle (years);
x_a = cumulative number of vehicles during year "a" in thousands;
N_E = grading frequency for earth surface (number/year);
N_G = grading frequency for gravel surface (number/year);
$f(T_E)$ = average vehicle operating cost equation for earth road;
$f(T_G)$ = average vehicle operating cost equation for gravel road; and
$pwf_a(i,n)$ = present worth factor for period a, discount rate i, and analysis period n.

For this analysis, the average VOC equations for gravel and earth roads are given as:

$$VOC_G = 457.39 + 0.0264T^2 \qquad (17)$$

$$VOC_E = 445.20 + 24.97T - 0.3806T^2 \qquad (18)$$

with 45% VL, 15% CMS, 25% CMR, and 15% CLR with VOC expressed in US$/1000 km. The details of the analysis are presented in Table 8.

The regravelling cycle in years, obtained by dividing the thickness of the gravel surface by the average annual gravel loss, was taken as the analysis period. Discounted VOC savings were obtained as the present value of the difference in vehicle operating costs between gravel and earth surfaces over the analysis period as given by Equation 17. The net present value, then, was given as the difference between VOC savings and the corresponding cost of gravelling. The breakeven ADT for the four gravelling alternatives was taken as the ADT at which the net present value becomes zero. At a discount rate of 12% (assumed to be approximately equal to the opportunity cost of capital), it was shown that regravelling alternative B was economically justified for all roads with a base ADT of at least 47 vpd. Accordingly, 395 km of gravel roads with an average base ADT of 48 vpd (Table 4) were included for gravel surfacing in the maintenance program; the design standards for regravelling comprised a 7m wide running surface, 0.5m wide shoulders, and a 10cm thickness.

Table 8. Benefit cost analysis to determine breakeven ADT for gravelling

Base ADT[a] (vpd)	Average Annual Gravel Loss[b] (cm)	Regravelling Cycle for Gravel Thickness (years)		Cost of Gravelling (US$/km) Alternatives				Present Value of VOC Savings (US$/km) at 12% Discount Rate		Net Present Value (US$/km)			
		10 cm	15 cm	A	B	C	D	A,B	C,D	A	B	C	D
30	0.98	10	15	7,165	8,265	10,745	12,400	3,270	3,960	-3,895	-4,995	-6.785	-8,440
50	1.26	8	12	7,165	8,265	10,745	12,400	8,300	10,390	1,135	35	-355	-2,010
70	1.40	7	11	7,165	8,265	10,745	12,400	9,845	12,860	2,680	1,580	2,115	460
90	1.54	6	10	7,165	8,265	10,745	12,400	10,830	14,950	3,665	2,565	4,205	2,550

Alternative:	A	B	C	D
Breakeven ADT:	43	47	50	58

[a] Traffic growth: 3% per annum.
[b] From equation 4 with R_1 = 1.1 m; VC = 3%.

Economic Evaluation of the Maintenance Program

The economic evaluation of the maintenance program consisted of an engineering-economic assessment of the condition of the road network and the associated vehicle operating costs with and without the maintenance program. Without the maintenance program, it was estimated that effective road maintenance would decrease systematically and eventually cease in about four years. Maintenance output for with and without maintenance program conditions is given in Table 9.

Table 9. Maintenance output with and without maintenance program

	Without Maintenance Program				With Maintenance Program	
	Routine Maintenance					
Year	Gravel Roads (km)	Earth Roads (km)	Tracks (km)	Total (km)	Routine Maintenance[a] (km)	Regravelling (km)
1	474	161	965	1,600	-	-
2	474	161	565	1,200	1,800	100
3	474	161	165	800	5,318	100
4	400	-	-	400	5,318	100
5		-			5,318	95
6		-			5,318	-
7		-			5,318	-
8		-			5,318	-
9		-			3,545	-

[a] Distribution of roads and tracks as shown in Table 4.

The economic rates of return for the maintenance program (separately for routine and periodic maintenance components), were calculated by relating the incremental cost of equipment and other maintenance inputs to the corresponding incremental benefits in the form of reduced vehicle operating costs, resulting from improved road maintenance brought about during the economic life of the equipment.

The incidence and magnitude of vehicle operating costs and related benefits as a function of accumulated number of vehicle passes and level of road maintenance with and without the maintenance program is demonstrated in Figure 1. Although the proposed method of economic analysis requires the use of statistical regression analysis and elementary calculus, to estimate VOC savings, it can be seen from Figure 1, that such VOC estimates can be alternately determined by preparing templates consisting of graphed average VOC curves and then measuring the area under these curves for given maintenance strategies.

Benefit/Cost Analysis of Routine Maintenance

Costs for routine maintenance included (i) capital expenditures for maintenance and workshop equipment, an initial supply of spare parts, buildings, and related technical assistance, and (ii) recurrent maintenance expenditures for fuel, spare parts and labor, incremental to the amount spent without the maintenance program. Using procedures discussed in the preceding sections, benefits were calculated in terms of reduced VOC resulting from improved routine maintenance. The benefits were accumulated over the 14 classified sections and grouped in three categories. The economic life of equipment was estimated to average about 8 years while the salvage value of buildings at the end of the analysis period was estimated at 50% of initial cost. Other than the roads to be regravelled under the maintenance program at the rate of about 100 km per annum during the first four years of the maintenance program, gravel roads with less than 2 cm of laterite surface were treated as earth roads for purposes of the economic analysis of routine maintenance. The results of the benefit/cost analysis are presented in Table 10. The economic rate of return for routine maintenance operations under the maintenance program was estimated at 74%

Figure 1: ECONOMIC BENEFITS FROM MAINTENANCE

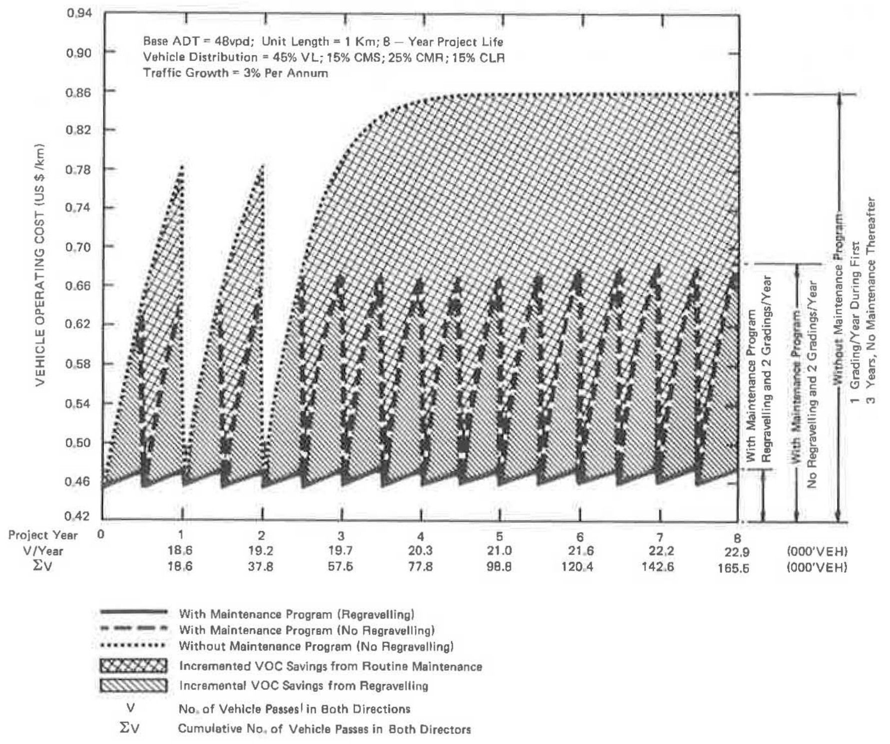

Table 10. Routine maintenance - benefit/cost analysis

	COSTS (US$ million)						BENEFITS (US$ million)			
	Capital Investment			Recurrent Maintenance Costs			Incremental VOC Savings			
Year	Equipment & Spare Parts	Buildings	Technical Assistance	With Project	Without Project	Incremental Costs[a]	Gravel Roads (750 km)	Earth Roads (877 km)	Tracks (3691 km)	Total (5318 km)
1	1.473	0.708	0.621							
2	2.945	1.416	0.621	0.493	0.493	-	0.227	0.231	1.149	1.607
3			0.621	1.479	0.410	1.073	1.116	1.335	4.138	6.589
4				1.479	0.410	1.073	1.098	2.056	4.253	7.407
5				1.479	0.244[a]	1.236	1.079	2.694	4.525	8.298
6				1.479	0.244	1.236	1.351	2.891	4.809	9.050
7				1.479	0.244	1.236	1.831	2.960	4.887	9.678
8				1.479	0.244	1.236	2.869	3.028	4.974	10.871
9				1.479	0.244	1.236	3.232	2.981	5.060	11.270
10		-1.062[b]		1.479	0.244	0.742	2.212	2.120	3.461	7.794

IRR = 74.1%
B/C @ 12% = 3.17

[a] Salaries for permanent road maintenance staff.
[b] Salvage value of buildings.

corresponding to a benefit/cost ratio of 3.17 at a 12% discount rate.

Benefit/Cost Analysis of Periodic Maintenance (Regravelling)

The cost of periodic maintenance included expenditures for equipment and technical assistance, and operational recurrent costs over the 4-year regravelling program. The average regravelling output was estimated at about 100 km per year with a total output of 395 km. A 50% salvage value was applied at the end of the regravelling program, because equipment would have been used for only one-half of its 8-year economic life. Since the regravelling cycle was calculated to be about 8 years, while only about 100 km would be regravelled each year, the residual thickness of the gravel at the end of the analysis period was also assigned a terminal value. The annual gravel loss was estimated to be about 12.6 mm per annum. The benefits from regravelling were taken as the incremental reduction in vehicle operating costs, additional to the reduction effected under routine maintenance, and expressed as:

$$\Delta B = (VOC_2 - VOC_0) - (VOC_1 - VOC_0) \qquad (19)$$

where:

ΔB = Incremental benefits from regravelling (US$ million).

VOC_0 = Vechicle operating costs under the null alternative--one grading/year and other routine maintenance operations for initial three years of the program; no maintenance thereafter (US$ million).

VOC_1 = Vehicle operating costs under maintenance alternative '1',--2 gradings/year and other routine maintenance operations over an 8-year period (US$ million).

VOC_2 = Vehicle operating costs under maintenance alternative '2',--regravelling at 100 km/year over 4 years, 2 gradings/year and other routine maintenance over an 8-year period (US$ million).

Then,

$VOC_1 - VOC_0$ = VOC savings under maintenance alternative '1'.

$VOC_2 - VOC_0$ = VOC savings under maintenance alternative '2'.

or,

$$\Delta B = VOC_2 - VOC_1$$

The results of the analysis are presented in Table 11. The incremental rate of return for regravelling operations was estimated at 17%, corresponding to a benefit/cost ratio of 1.26 at a discount rate of 12%.

Sensitivity Analysis

The specific risk elements related to the maintenance program were increase in costs and possible shortfalls in the projected maintenance output. A sensitivity analysis was carried to evaluate the effect of these parameters on the economic return of the maintenance program components (Table 12).

If routine maintenance were confined to the most

Table 11. Regravelling - benefit/cost analysis

	Costs (US$ millions)				Benefits VOC Savings (US$ millions)		
Year	Equipment	Technical Assistance	Recurrent Expenditure	Salvage Value of Remaining Gravel Surface	Alternative 1	Alternative 2	Net Incremental Benefits Alt. 1 - Alt. 2
1	1.832						
2		0.080	0.464		0.683	0.802	0.099
3		0.080	0.464		0.718	1.030	0.312
4		0.080	0.464		0.746	1.280	0.534
5	-0.916	0.080	0.464		0.785	1.611	0.820
6					2.648	3.662	1.014
7					2.694	3.763	1.069
8					2.747	3.881	1.134
9				-0.579	2.798	3.999	1.201

IRR = 17.2%
B/C @ 12% = 1.26

Table 12. Sensitivity analysis

	IRR (%)
A. Routine Maintenance - IRR=74.0%; B/C@12%=3.17	
Effect of Reduced Maintenance Output	
Network Maintenance:	
5,300 km[a]	74.1
3,500 km	63.0
1,800 km	26.6
Effect of Reduced Equipment Utilization	
Economic Life of Equipment:	
8 years[a]	74.1
7 years	73.0
6 years	71.3
Effect of Cost Increases	
Increase in Costs:	
5%	70.3
10%	66.9
15%	63.8
20%	60.8
Effect of Increase in Benefits	
Increases in Benefits:	
5%	77.9
10%	81.8
B. Regravelling - IRR=17.2%; B/C@12%=1.26	
Effect of Reduction in Annual Output of Regravelling	
Kilometers Regravelled per Year:	
100 km[a]	17.2
80 km	12.4
Effect of Increase in Cost of Regravelling	
Increase in Costs:	
5%	16.1
10%	15.0
20%	13.0
Effect of Increase in Benefits from Regravelling	
Increase in Benefits:	
5%	18.4
10%	19.5

[a] As assumed under the maintenance program.

important road links (about 3,500 km of roads and tracks), it would have an economic return of about 63%. If the training program failed to produce sufficient personnel to expand maintenance operations, or if a shortage of recurrent funds limited maintenance to current levels (about 1,800 km), routine maintenance would yield an estimated economic return of about 27%. The economic return for routine maintenance was relatively insensitive to reduced equipment life and the corresponding reduction in maintenance output during the later years of the program, showing only a 3 percentage point drop in the rate of return with equipment life reduced from 8 to 6 years. A 20% increase in costs would lower the economic return to 61% while a 5% increase in benefits, a distinct possibility resulting from a probable traffic growth in excess of the assumed 3% would raise the economic return to 78%.

Relative to regravelling operations, a 20% reduction in the annual regravelling output from 100 km to 80 km would lower the economic return to 15% while a 10% increase in benefits would raise it to 20%.

Conclusions

An attempt has been made in this paper to present an improved economic analysis method for the evaluation of road maintenance programs for unpaved roads. The method employs some of the latest research findings related to traffic-induced deterioration of unpaved roads and its effect on vehicle operating costs. This evaluation technique removes much of the subjectivity from estimation of vehicle operating costs as they are affected by the quality and scale of maintenance operations and provides the analyst a tool for determining economically optimal levels of routine and periodic maintenance. The analysis can be carried out with a portable hand calculator without recourse to expensive and time-consuming computer-based models. Some of the salient conclusions of the maintenance program example described in the paper are:

1. Efficiently executed routine maintenance operations yield a very high economic return and can help to offset the need for early renewal of the road infrastructure.
2. Once an earth road is surfaced with gravel, routine maintenance requirements become less stringent and require a lower frequency of grading operations.
3. The optimal grading frequencies resulting from economic analysis should be used only as guidelines in the design of maintenance programs; where necessary, they should be modified to reflect actual operational conditions.
4. The minimum breakeven ADT at which gravel surfacing of earth roads becomes economically justified varies from about 45-60 vpd, depending upon the design standards used.

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