Vehicle Operating Costs Under Indian Road and Traffic Conditions

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A research project on road-user costs sponsored jointly by the Government of India and the World Bank has recently been completed in India. As part of this project, an attempt was made to build relationships between vehicle operating-cost components and road, traffic, vehicle, and environmental factors. India presents a wide variety of these conditions. Roads in India are improved in stages in view of the paucity of funds. A major portion of the roads are single-lane, bidirectional, and unpaved. Traffic is heterogeneous in character; it consists of fast-moving as well as animal-drawn vehicles. Climate and topography change across the country. The work was carried out by collecting real-life data on cost of operation of about 1000 vehicles of different types. The results prove that horizontal curvature, vertical profile, pavement roughness, and pavement width are some of the important factors influencing vehicle operating costs. These results are likely to be of great value in evaluating benefits that are possible from highway improvements and in arriving at sound investment decisions. Since the conditions in India are typical of developing countries, the results can be of value to other developing countries.

As part of the development activity in India, vast investments are being made for the improvement of roads. Since the resources are scarce and the demands from the various sectors are heavy, economic appraisal of schemes provides a good basis for investment decisions. A serious handicap in this direction has been the lack of an adequate data base for road-user costs under typical Indian conditions. In order to fill the gap in the process of highway planning in India, the Central Road Research Institute, New Delhi, has recently completed a research project entitled Road User Cost Study, sponsored jointly by the Government of India and the World Bank. As part of the project, research was undertaken on the relationships between the vehicle operating-cost components and road characteristics, traffic factors, and vehicle characteristics. The research was carried out by collecting real-life data on the cost of operation for nearly 1000 vehicles of different types that operate in the different parts of the country. The data were collected over a period of about 18 months. Simultaneously, measurement of the road characteristics on nearly 42 000 km of roads of the various types was completed with the aid of modern instruments. From the data, relationships have been formulated between each of the vehicle operating-cost components and the roadway, traffic, and vehicle factors that govern them.

ROAD AND TRAFFIC CONDITIONS IN INDIA

Since India is predominantly an agrarian and rural-oriented economy, road transport forms a vital sector in planned development. The total length of roads in the country is 1.6 million km, of which only 40 percent are paved (1). The major percentage of roads leading to the villages and small towns are unpaved earth or gravel roads. The country has a large percentage of single-lane bidirectional roads (pavement 3-3.75 m wide). Even on the National Highways, which are the arteries of the nation, the proportion of single-lane pavements is 35 percent (1). Single-lane roads, which permit only one vehicle to use the pavement at a time, result in slowing down of the traffic, hazardous maneuvers, and greater wear and tear on vehicles. A system of staged construction is generally followed in the country, whereby selected single-lane roads are either widened initially to an intermediate width of 5.5 m or widened to the standard 7.0 m.

The number of motor vehicles in India is 3.7 million, which register an annual growth of nearly 10 percent (2). The country produces about 60 000 single-unit trucks annually that have a carrying capacity of 7.5 tonnes. The passenger cars are of small capacity and are also produced in India; annual production is about 40 000 vehicles.

The traffic on Indian roads is heterogeneous in character; it consists of a mixture of motorized vehicles of all types, sizes, and shapes (cars, jeeps, vans, three-wheeled light vehicles, buses, minibuses, trucks, agricultural tractors, semi-truck-trailers, truck-trailers, scooters, motorcycles, mopeds); cycles and cycle rickshaws; and animal-drawn vehicles (bullock carts, camel carts, and horse carts). There is no segregation of vehicles on the roads, with the result that traffic operations are hazardous and slow. Figures 1-6 illustrate the different types of vehicles on the Indian roads and the traffic conditions.

The accident rate in India is alarming. In 1977-1978, 21 300 persons were killed (2). The number killed per 10 000 vehicles is 64, which is very much higher than the rate of 3-7 in developed countries.

ROAD USER COST STUDY IN INDIA

Realizing the growing importance of roads and road transport in India and the serious data gap for effective planning, the Government of India and the World Bank jointly sponsored an ambitious research project entitled Road User Cost Study. This project, which cost nearly $1 million (U.S.), was started in 1978 and was completed in 1982 (3-5). The Central Road Research Institute was the implementing agency.

The total transportation cost is composed of

1. Cost of initial construction of the facility,
2. Cost of periodic maintenance, and
3. Road-user cost.

The research project recently completed deals with the third component listed above. The Government of India has plans to do further research on the first two components listed above, so that a highway design model can be developed with capabilities for evaluating a number of alternative schemes that have a range of road-design variables, maintenance strategies, and transport options.

The road-user cost itself has three important components:

1. Vehicle operating costs (VOC),
2. Accident costs, and
3. Highway travel-time costs.

We limit this paper to the consideration of VOC in relation to roadway, traffic, vehicle, and environmental factors.

VOC is composed of the following elements: fuel, lubricants, tires, spare parts, labor for maintenance and repairs, depreciation, and fixed costs.

Figure 1. Single-lane road showing crossing between bus and bullock cart.

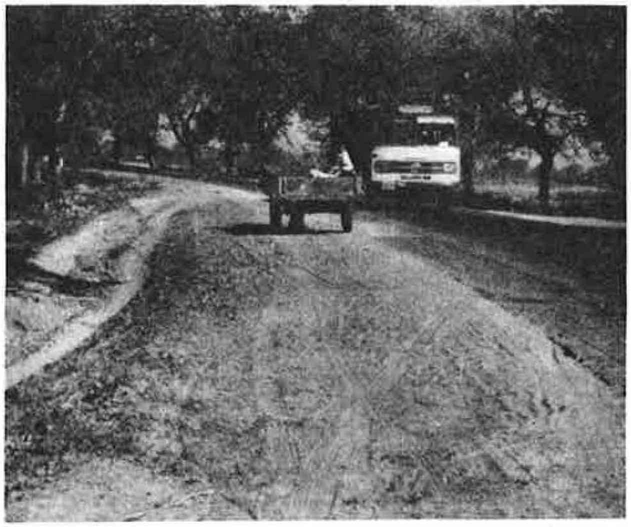


Figure 2. Bullock cart on earthen road in rainy season.

Figure 3. Agricultural tractor-trailer on unpaved road.

Figure 4. Convoy of bullock carts on single-lane road obstructing motor vehicle.

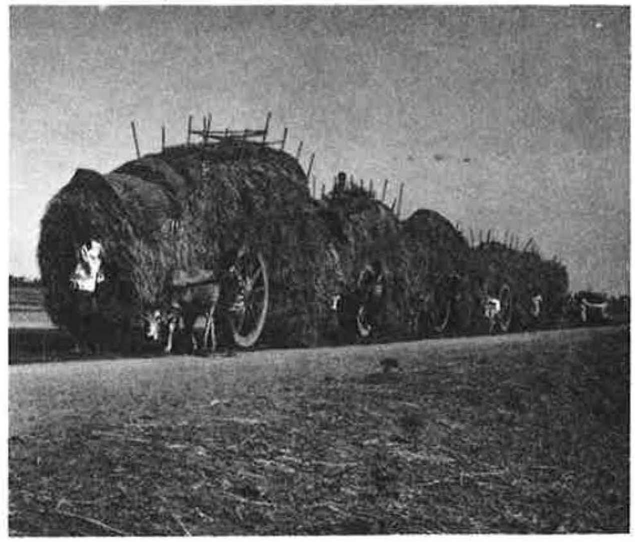
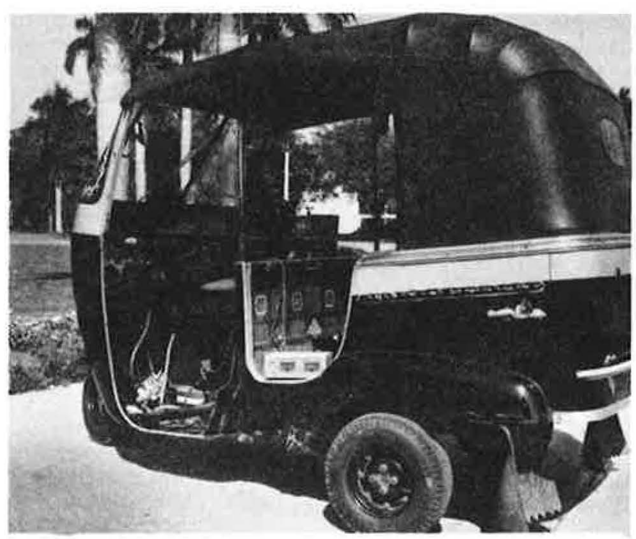


Figure 5. Mixed traffic conditions on typical road passing through a small town.

Figure 6. Three-wheeled auto-rickshaw commonly found on Indian roads.



These elements are influenced by a variety of factors, the more important of which are listed below:

1. Roadway factors
   a. Pavement width
   b. Surface type and roughness
   c. Horizontal curvature
   d. Vertical profile
2. Vehicle factors
   a. Make
   b. Age
   c. Horsepower and engine capacity
   d. Load carried
3. Traffic factors
   a. Speed
   b. Volume of traffic
4. Environmental factors
   a. Altitude
   b. Rainfall and climatic conditions

The objective of the research on VOC was to interrelate each of the VOC components with the above-mentioned factors. In other words, the research project aimed at establishing an accurate statistical relationship between each of the VOC elements and the above-mentioned factors, so that VOC can be predicted for any given combination of roadway, vehicle, traffic, and environmental conditions in India.

METHODOLOGY FOR RESEARCH ON VOC

For determining fuel-consumption relationships, two different approaches were used. The first and the more accurate was to perform controlled experiments on the common makes of vehicles specially procured for the purpose. The second approach was to collect data on fuel consumption of 939 vehicles of different types from a number of operators. The two different approaches were then compared.

For other vehicle operating-cost components such as tire wear, spare-parts consumption, maintenance labor, depreciation, fixed costs, and lubricants, the controlled-experiment approach becomes unmanageable and impractical. The more expedient procedure is to undertake a detailed survey of the cost of operation in real life from a large number of operators, and this approach, known as the user cost survey (UCS) has been tried successfully in Kenya (6) and in Brazil (7).

USER COST SURVEY

Since the relationships are likely to be complex between the VOC components and the factors governing them, the survey had to be carefully structured and adequately planned. The factorial matrix adopted for the survey consisted of the combinations of factors given below:

Factor	No. of Levels	Description of Level
Terrain	3	Level, rolling, or hilly
Horizontal curvature	2	Low or high
Pavement width and type	4	Single-lane unpaved, single-lane paved, two-lane paved, or dual-carriageway paved

Three types of vehicles were included: cars and jeeps, buses, and trucks.

After an intensive search, 939 vehicles belonging to 121 operators were selected for the survey. These were grouped in the following way:

Vehicle	No.
Bus	640
Truck	232
Car	53
Jeep	14
Total	939

Table 1 gives the salient features of some of the typical makes of vehicles included in the survey. Adequate geographic representation across the country was ensured to capture the effect of varying topographical and roadway design features. Tables 2-4 give the representation of the vehicles across the factorial matrix. It will be seen that although some of the cells are unrepresented or underrepresented, the extremes of road conditions are covered by the survey. When the vehicles were selected, it was ensured that only such vehicles were included that had a reasonable expectation of operating on homogeneous routes during the survey period. The data collection on the VOC components from the operators was done for a period ranging from 12 to 24 months. This period was considered necessary since the replacement of tires and major spare parts takes place over a long period of time. Carefully thought out advanced plans were devised, and the field investigators were specially trained to collect accurate and reliable data, after they had gone through the records maintained by the operators and had intensive discussions with them on doubtful items. The information was collected on the various components of VOC such as fuel, lubricants, tires, spare parts, labor for maintenance and repairs, and fixed costs.

Whereas the spare-parts consumption was measured in monetary terms, the rest of the consumption items were measured in physical units. This renders it possible to use the relationships in other countries with similar operating characteristics. In the case of spare parts, inflation was accounted for by bringing all costs to a common reference year of 1978 with the use of price indices.

The number of tires replaced during the survey period included new, retreaded, and used tires. They were brought to a common measure of equivalent tires by applying suitable conversion factors determined from a detailed survey of selected operators.

It will also be necessary to determine the monetary cost of tire replacement, which consists of new, retreaded, and used tires, all of which cost different amounts. A conversion factor of 0.727 has been determined from the data, which can be used thus:

Cost of equivalent new tires = 0.727 x number of equivalent tires as per UCS relationship x cost of new tire.

The data for the entire survey period were averaged to yield the following dependent variables:

1. Fuel consumption (FC) in liters per 100 km;
2. Engine oil consumption (EOL) in liters per 1000 km;
3. Other oil consumption (OL) in liters per 10 000 km;
4. Grease consumption (G) in kilograms per 10 000 km;
5. Spare-parts consumption (SP) in paise per kilometer ($1 U.S. = 9.00 rupees; 1 rupee = 100 paise);
6. Tire life (TL) in kilometers for equivalent new tire;
7. Labor hours (LH) in hours per 1000 km;
8. Labor cost (LC) in paise per kilometer;

9. Speed of vehicles V_B, V_T, V_C, V_J for buses, trucks, cars, and jeeps, respectively, in kilometers per hour; and
10. Use of vehicles (UPD) in kilometers per day.

MEASUREMENT OF ROUTE CHARACTERISTICS

Since VOC data have to be related ultimately to the route characteristics, it is necessary to evolve a quick and reasonably accurate method of measuring the important route characteristics. A variety of roadway factors influence VOC, but the following important ones were considered: horizontal curvature, vertical profile, roughness, and pavement width.

The vehicles included in the survey were associated with nearly 42 000 km of routes spread over different parts of the country and having a variety of characteristics. The measurement of the characteristics by conventional surveying methods would have been time consuming and was ruled out. A system of route-characteristic measurement from an instrumented moving car was selected (8).

The instrumentation consisted of a distance-measuring device, a gyroscope for measuring horizontal curvature, a pendulum-type gradometer, and a car-mounted roughness integrator.

Table 1. Salient features of some typical UCS vehicles.

Vehicle Category	Model	British Horsepower	Engine Capacity (cc)	Unladen Weight (tonnes)	Gross Laden Weight (tonnes)	No. of Axles
Car	Ambassador	50	1489	1.2	1.5	2
Jeep	Mahindra	75	2350	0.6	1.2	2
Bus	Tata 1210	112	4788	7.0	11.0	2
Bus	Ashok Leyland Comet	110	6075	7.0	11.0	2
Truck	Tata 1210	112	4788	6.0	13.5	2
Truck	Ashok Leyland Comet	110	6075	6.0	13.5	2
Truck	Tata 1516	145	5675	9.0	24.0	3
Truck	Ashok Leyland Taurus	125	6735	7.0	18.5	2

Table 2. Representation of buses across factorial matrix.

	Plain Terrain[a]		Rolling Terrain[a]		Hilly Terrain[a]		
	Curvature (degrees/km)						
Pavement Width and Type	0-50	>50	0-100	>100	0-200	>200	Total
Single lane unpaved (up to 5.0 m wide, roughness >8000 mm/km)	11	17	10	25	-	9	72
Single lane paved (up to 5.0 m wide, roughness <8000 mm/km)	36	67	9	115	-	21	248
Intermediate lane paved (up to 5.0-6.0 m wide, all roughnesses)	48	35	7	70	-	-	160
Double lane paved (>6.0 m wide, all roughnesses)	90	42	4	23	-	1	160
Total	185	161	30	233	-	31	640

[a]Terrain defined as follows: plain = rise + fall = 0-15 m/km; rolling = rise + fall = 15-30 m/km; hilly = rise + fall = >30 m/km.

Table 3. Representation of trucks across factorial matrix.

	Plain Terrain[a]		Rolling Terrain[a]		Hilly Terrain[a]		
	Curvature (degrees/km)						
Pavement Width and Type	0-50	>50	0-100	>100	0-200	>200	Total
Single lane unpaved (up to 5.0 m wide, roughness >8000 mm/km)	6	10	-	-	-	14	30
Single lane paved (up to 5.0 m wide, roughness <8000 mm/km)	5	11	-	1	-	3	20
Intermediate lane paved (up to 5.0-6.0 m wide, all roughnesses)	5	6	3	10	-	-	24
Double lane paved (>6.0 m wide, all roughnesses)	93	28	9	28	-	-	158
Total	109	55	12	39		17	232

[a]Terrain defined as follows: plain = rise + fall = 0-15 m/km; rolling = rise + fall = 15-30 m/km; hilly = rise + fall = >30 m/km.

Table 4. Representation of cars and jeeps across factorial matrix.

	Plain Terrain[a]		Rolling Terrain[a]		Hilly Terrain[a]		
	Curvature (degrees/km)						
Pavement Width and Type	0-50	>50	0-100	>100	0-200	>200	Total
Single lane unpaved (up to 5.0 m wide, roughness >8000 mm/km)	-	-	-	-	-	2	2
Single lane paved (up to 5.0 m wide, roughness <8000 mm/km)	-	11	-	1	-	2	14
Intermediate lane paved (up to 5.0-6.0 m wide, all roughnesses)	-	4	-	2	-	1	7
Double lane paved (>6.0 m wide, all roughnesses)	34	4	-	5	-	1	44
Total	34	19		8		6	67

[a]Terrain defined as follows: plain = rise + fall = 0-15 m/km; rolling = rise + fall = 15-30 m/km; hilly = rise + fall = >30 m/km.

The distance-measuring device was developed by introducing a miniature Halda gear in the vehicle speedometer cable; this reduced the speed of rotation in the ratio 20:1 in a subsidiary cable at right angles to the speedometer cable. The revolutions of the subsidiary cable are then converted into elastic pulses that activate an electromechanical counter.

The gyroscope is a flight instrument used for navigation of aircraft. One such instrument, operated on 110 V, was mounted in the instrumented car, and the car battery (12 V) supplied the needed power through a static inverter. The instrument records the direction of movement at any time. By noting the reading at the beginning and end of a horizontal curve and the corresponding distance measurements, one can calculate the deviation angle, length of curve, and radius.

The pendulum-type gradometer, designed and supplied by the U.K. Transport and Road Research Laboratory (TRRL), is a simple heavy aluminum alloy pendulum that has a pointer needle at right angles. The needle makes contact at different points on a semicircular arc; the points correspond to the upward or downward gradients. The readings so obtained are recorded by an electromagnetic counter.

Accurate measurement of roughness of the surface was recognized to be the key to the derivation of good VOC relationships. A number of devices are available for this purpose (9-11). The subject of roughness measurements, the need for calibration of the instruments, and the equally pressing need for a universally acceptable measuring scale are engaging the attention of researchers all over the world. The British towed fifth-wheel bump integrator is a standard instrument for roughness measurements and has been used successfully in the Kenya (6) and the Caribbean (12) studies by TRRL. Since sufficient experience existed in the country with the use of this instrument, it was selected as the basic roughness-measuring device. A large roughness-measurement program that uses the towed fifth wheel is slow and unmanageable and is fraught with the danger that the device frequently runs out of calibration. Hence, a simpler device consisting of an axle-mounted integrator unit was used for the large-scale measurements, and the towed fifth wheel was reserved only for setting the standards for calibration. Calibration of the axle-mounted roughness unit was done at frequent intervals on actual road surfaces of varying roughness values against the standard towed fifth-wheel integrator at the same locations. By this means, conversion equations were developed that enabled the roughness measurements with the car to be converted into the standard towed-fifth-wheel values (13). These standard values are used in the analysis.

The UCS routes were conveniently split up into a system of nodes and links, which facilitated the transfer of data into computers for analysis. From the average route characteristics of each link, the average characteristics of routes on which the UCS vehicle operated during the survey period were worked out. These were later used as the dependent variables in the statistical analysis as shown below:

Variable	Unit of Measurement	Symbol
Horizontal curvature	Average accumulated deviation angle of the curves in degrees per kilometer	CV
Vertical profile	Average rise and fall in meters per kilometer	RF
Roughness	British towed-fifth-wheel values in millimeters per kilometer	RG
Pavement width	Average pavement width in meters	W

ADDITIONAL DEPENDENT VARIABLES

In addition to road-geometry variables and roughness, some additional variables were also used in the analysis: gross vehicle weight (GVW) in tonnes, power/weight ratio (PW) in kilowatts per tonne, and number of tires on vehicle (N).

Some vehicles are operated on long-distance hauls and inherently involve long hours of use per day. Others are very poorly used and deployed only for local trips. In order to isolate these features, the following three 0-1 dummy variables were introduced: (a) medium use (MU), 4-12 h/day; (b) low use (LU), less than 4 h/day; and (c) high use (HU), more than 12 h/day.

ANALYSIS OF VOC DATA

Correlation Between Independent Variables

It was seen that the two important geometry variables, curvature (CV) and rise and fall (RF), were highly correlated. The use of both these variables in the analysis was therefore likely to cause trouble. Hence the analysis was done by using one of these variables at a time. The following relationship was derived between the two variables:

$$CV = 1.4011\,RF^{1/2} \qquad (1)$$

where $R^2 = 0.8436$ (R is the correlation coefficient). Pavement width and roughness were also similarly correlated. The two variables were tried together and have been retained only if a satisfactory t-value was obtained for the regression coefficients. Otherwise, a transformation of the variables to the form RF/W was also successful.

Analysis

For a satisfactory explanation of the effect of a number of variables on a dependent variable, the multiple linear regression technique is well known. A large number of equations were tried, and those that are presented here are the best.

A feature of the Indian study was that a variety of vehicle operators--government, private, large fleet owners, medium fleet owners, and small fleet owners--were covered by the UCS. It was thought likely that each category of operator had its own maintenance policies, which were reflected in VOC. In order to isolate such effects, 0-1 dummy variables were introduced as follows:

Variable	Symbol
Government operator	G
Private operator	P
Government undertaking with high intensity of maintenance	GH
Government undertaking with average intensity of maintenance	GA
Private undertaking with high intensity of maintenance	PH
Private undertaking with average intensity of maintenance	PA

In the equations given in the subsequent paragraphs, t-values are indicated in parentheses, * denotes significant at 5 percent level, and ** denotes significant at 1 percent level. The R^2-value is the square of the multiple regression coefficient.

Fuel-Consumption Relationships

The UCS data yielded directly the relationships given below:

Car:

$$FC = -13.81 + 0.036\,69RF + 0.000\,342\,3RG + (621.3^{*}/V) + 0.005\,005V^{2**} \qquad R^2 = 0.177 \qquad (2)$$

(-1.54) (1.17) (1.66) (2.60) (3.06)

Jeep:

$$FC = -10.91 + 0.088\,23RF + 0.000\,591\,8RG + (432.3^{**}/V) + 0.005\,312V^{2**} \qquad R^2 = 0.919 \qquad (3)$$

(-2.20) (0.75) (0.57) (3.46) (6.34)

Bus:

$$FC = \text{intercept} + 0.001\,023LK^{**} + 0.091\,77RF^{**} + (469.7^{**}/V) + 0.006\,243V^{2**} + 0.5563GVW^{**} \qquad R^2 = 0.709 \qquad (4)$$

(2.57) (5.18) (9.21) (10.23) (6.52)

Value of intercept varies from operator to operator; for a typical operator it has a value of -5.85.

Truck:

$$FC = 7.170 - 0.9202PW^{**} + 0.1432RF^{**} - 0.3889W + (567.1^{**}/V) + 0.007\,868V^{2**} \qquad R^2 = 0.526 \qquad (5)$$

(1.68) (-5.65) (4.68) (-1.82) (6.24) (9.67)

A comparison of the fuel-consumption values predicted from Equations 2-5 with the actual consumption on UCS vehicles was made. It was observed that the actual fuel consumption was related to the experimental values as follows:

1. Jeeps: actual value = 1.53 x experimental value,
2. Cars: actual value = 1.64 x experimental value,
3. Buses: actual value = 1.28 x experimental value, and
4. Trucks: actual value = 1.31 x experimental value.

The higher fuel consumption in actual practice is due to the frequent deceleration and acceleration, stop-and-go motion, travel at speeds other than steady state, idle consumption at forced stops, etc., in short, the driver behavior. However, the results demonstrate that a good deal of savings in fuel consumption can be brought about by improving the road and bettering the traffic-flow conditions.

Lubricants

The consumption of lubricants (engine oil, other oils, and grease) is a small portion of VOC and is not easily amenable to accurate analysis in terms of road and vehicle characteristics. All the same, some interesting results for buses and trucks presented below demonstrate how the road and vehicle characteristics affect these items of cost.

Bus:

$$EOL = \text{intercept} + 0.001\,777LK^{**} + 0.012\,71RF + 0.000\,671\,3(RG^{**}/W) + 0.1614(OHF)^{*} \qquad R^2 = 0.484 \qquad (6)$$

(6.87) (1.25) (5.38) (2.01)

Value of intercept varies from operator to operator; a typical value is 1.52.

Truck:

$$EOL = 2.4816 + 0.0601RF^{**} + 0.0004(RG^{*}/W) \qquad R^2 = 0.241 \qquad (7)$$

(4.77) (2.00)

Bus:

$$OL = \text{intercept} + 0.004\,066LK^{**} + 0.002\,889RF^{*} + 0.000\,821\,7/RG^{**} - 0.3295W \qquad R^2 = 0.400 \qquad (8)$$

(6.25) (2.13) (5.32) (-1.38)

Value of intercept varies from operator to operator; a typical value is 2.79.

Truck:

$$OL = \text{intercept} + 0.004\,219LK^{*} + 0.000\,264\,6RG + 0.2632GVW^{**} \qquad R^2 = 0.761 \qquad (9)$$

(2.56) (0.79) (3.14)

Value of intercept varies from operator to operator; a typical value is -0.5313.

Bus:

$$G = \text{intercept} + 0.001\,481LK^{**} + 0.033\,76RF^{**} - 0.3634W^{**} \qquad R^2 = 0.489 \qquad (10)$$

(4.27) (2.38) (-4.00)

Value of intercept varies from operator to operator; a typical value is 4.80.

Truck:

$$G = -0.5784 + 0.003\,85CV^{**} + 0.000\,546RG^{**} + 0.1790GVW^{*} \qquad R^2 = 0.262 \qquad (11)$$

(-0.43) (2.78) (3.77) (2.48)

Tires

The equations for tire life are given below:

Car:

$$TL = 47\,340 - 101.8RF - 18.39(RG^{**}/W) \qquad R^2 = 0.558 \qquad (12)$$

(-0.88) (-7.08)

Jeep:

$$TL = 48\,270 - 3.8680RG^{**} \qquad R^2 = 0.536 \qquad (13)$$

(-3.56)

Bus:

$$TL = \text{intercept} - 3.900LK^{**} - 361RF^{**} - 1.227RG^{**} + 911.3W^{*} - 1851VCR \qquad R^2 = 0.621 \qquad (14)$$

(-3.36) (-7.48) (-12.30) (2.13) (-1.34)

Value of intercept varies from operator to operator; a typical value is 35 900.

Truck:

$$TL = 27\,471GA^{**} + 33\,682GH + 31\,680PA^{**} + 38\,053PH^{**} - 275.8RF^{**} - 1.238RG^{**} + 2355W^{**} - 1169(GVW/N) - 3962VCR \qquad R^2 = 0.680 \qquad (15)$$

(-4.42) (-2.61) (3.04) (-0.99) (-1.84)

The equations, which have satisfactory R^2-values, indicate that tire life generally

1. Increases as road width increases,
2. Decreases as roughness increases,
3. Decreases as rise and fall increases,
4. Decreases as the load per tire increases,
5. Decreases as congestion builds up on the road, and
6. Is higher for private operators than for government operators.

The relationships indicate how improving the roads can bring about economy in tire consumption.

Spare Parts

The equations for spare-parts consumption are given below:

Car:

$$SP = \text{intercept} + \underset{(1.71)}{0.0041RG} \quad R^2 = 0.453 \tag{16}$$

Value of intercept varies from operator to operator; a typical value is -11.10.

Jeep:

$$\text{Log}_e SP = 1.069 + \underset{(5.11)}{0.5365\ \text{Log}_e LK^{**}} + \underset{(0.08)}{0.000\,005\,271RG} \quad R^2 = 0.725 \tag{17}$$

Bus:

$$\text{Log}_e SP = \text{intercept} + \underset{(11.37)}{0.2900\ \text{Log}_e LK^{**}} + \underset{(2.70)}{0.000\,466\,6CV^{**}} + \underset{(3.65)}{0.000\,073\,10RG^{**}} + \underset{(1.15)}{0.1100VCR} + \underset{(2.03)}{(1.624^{*}/W)} + \underset{(9.91)}{0.2607OHF^{**}} \quad R^2 = 0.506 \tag{18}$$

Value of intercept varies from operator to operator; a typical value is -0.1947.

Truck:

$$\text{Log}_e SP = -0.8979PA^{**} - 1.3325PH^{**} + 0.0402GA^{**} - 0.5587GH^{**} + \underset{(5.46)}{0.2332\ \text{Log}_e LK^{**}} + \underset{(5.35)}{0.000\,141\,3RG^{**}} + \underset{(2.30)}{(3.4830^{*}/W)} + \underset{(4.22)}{0.0531GVW^{**}} + \underset{(4.50)}{0.276\,20HF^{**}} \quad R^2 = 0.641 \tag{19}$$

The equations indicate that spare-parts consumption generally

1. Increases as roughness increases,
2. Increases as rise and fall or curvature increases,
3. Decreases as pavement width increases,
4. Increases with the age of the vehicle,
5. Increases with the overhauls,
6. Increases as the congestion mounts up,
7. Is higher for the government sector than for the private sector, and
8. Is lower where the operator has a good maintenance policy and adequate maintenance facilities.

The equations underscore the point that road improvements can bring about a good reduction in wear and tear on spare parts.

Maintenance and Repairs Labor Cost

The best equations relate the maintenance and repairs labor cost to the spare-parts cost, which can be obtained from known roadway and operating characteristics. The equations are given below:

Car:

$$LC = 0.5498SP \quad R^2 = 0.647 \tag{20}$$

Jeep:

$$LC = 0.3677SP \quad R^2 = 0.774 \tag{21}$$

Bus:

$$LC = 0.4027SP \quad R^2 = 0.513 \tag{22}$$

Truck:

$$LC = 0.3692SP \quad R^2 = 0.837 \tag{23}$$

The above equations have good R^2-values and can be reliably used, since the labor costs are directly related to the spare-parts cost.

Depreciation of Vehicles

One of the important components of VOC is depreciation. Unlike other components of VOC, depreciation is an item difficult to determine, especially in relation to roadway characteristics. Depreciation and use of vehicles are interrelated. In order to simplify the approach, the investigation was carried out in two stages (14):

1. Determination of use rates of vehicles in kilometers per year as a function of road geometry and vehicle speeds and
2. Determination of depreciation rate per year from a survey of prices of second-hand vehicles.

By dividing the depreciation in a given year by the use in kilometers during the year, one arrives at the depreciation cost component per kilometer.

The data for determining the annual rate of depreciation were collected from a large number of second-hand vehicle dealers, financiers, brokers who advance money for purchase of used vehicles, and some selected vehicle operators in the UCS who sold or scrapped their vehicle.

From the data on the initial purchase price, resale price (after adjustment for inflation), and age at resale, it was possible to develop the following equations:

Passenger car:

$$DV = 0.9223^{A} \quad R^2 = 0.9693 \tag{24}$$

Commercial vehicle (bus and truck):

$$DV = 0.8631^{A} \quad R^2 = 0.921 \tag{25}$$

where

DV = depreciated value,
= price of a vehicle at age A years divided by price of a new vehicle, and
A = age (years).

Vehicle Speed

As roads are improved, the vehicles can travel at increased speeds. Greater use per day and per year results. Thus, the annual depreciation cost can be spread over a larger kilometerage. Similarly, the fixed costs and crew costs, which are dependent, can be spread over a large kilometerage.

The analysis of use was accomplished in two stages: (a) establishing an equation relating vehicle speed and road characteristics and (b) building up the use equations by using the predicted speeds from the first equation and other additional variables.

The equations for vehicle speed are given below:

Car:

$$V_C = 55.88 - 0.4969RF^{**} - 0.008\,342(RG^{**}/W) \quad R^2 = 0.709 \qquad (26)$$
$$(41.33)(-7.14) \qquad (-5.33)$$

Jeep:

$$V_J = 52.08 - 0.005\,21CV^{**} \quad R^2 = 0.844 \qquad (27)$$
$$(22.07)(-7.66)$$

Bus:

$$V_B = \text{intercept} - 0.3188RF^{**} - 0.000\,795\,0RG^{**}$$
$$(-9.80) \qquad (-4.17)$$
$$+ 2.080W \quad R^2 = 0.611 \qquad (28)$$
$$(7.12)$$

Value of intercept varies from operator to operator; a typical value is 31.12.

Truck:

$$V_T = 44.78 - 0.3856RF^{**} - 0.002\,87(RG/W) \quad R^2 = 0.482 \qquad (29)$$
$$(63.91)(-7.95) \qquad (-4.67)$$

The equations prove that vehicle speeds are closely related to geometry variables, pavement width, and roughness. Speeds decrease as roughness increases and increase as pavement width increases.

After obtaining the above speed equations in the first stage of regression, the second-stage regression was carried out by using the predicted speeds from these equations and some additional factors in order to arrive at utilization rates. The equations developed are given below:

Car:

$$UPD = -186.34LU^{**} + 14.94MU^{**} + 6.4859VC)^{**} \quad R^2 = 0.627 \qquad (30)$$
$$(4.141)$$

Jeep:

$$UPD = 1.7728V_J \quad R^2 = 0.035 \qquad (31)$$

Bus:

$$UPD = 30.35MU^{**} + 206.75HU^{**} - 113.75LU^{**} + 8.011V_B^{**}$$
$$(15.71)$$
$$+ 10.300HF^{**} - 0.0609LK^{**} \quad R^2 = 0.558 \qquad (32)$$
$$(2.79) \qquad (-4.48)$$

Truck:

$$UPD = 68.12MU^{**} + 221.35HU^{**} - 85.11LU^{**}$$
$$+ 5.1637V_T^{**} \quad R^2 = 0.492 \qquad (33)$$
$$(6.87)$$

The above equations indicate clearly how the use of vehicles increases as speed increases, and speeds are influenced largely by road geometry, pavement width, and roughness.

In order to arrive at the use rates per year, the data from all the 939 vehicles were analyzed and the percentage use rates were derived. These are given below:

Sector	Truck (%)	Bus (%)	Car and Jeep (%)
Government	52.76	84.4	69.0
Private	78.80	86.0	86.2
Overall	62.36	85.6	75.7

Thus the use in kilometers per year can be obtained from the use rates in kilometers per day times 365 times percentage use rates.

The use in kilometers per annum provides the basis for the calculation of depreciation cost allocatable per kilometer when the yearly depreciation cost is known.

Fixed Costs

The fixed costs include crew costs and other fixed costs such as interest on capital, insurance, taxes, registration fees, license charges, office expenses, and overhead.

The crew costs (in rupees) have been found as follows (15) ($1 U.S. = 9.00 Rs):

Crew Category	Cost/Bus/Day (Rs)	Cost/Truck/Day (Rs)
Driver	64	40
Conductor	48	--
Cleaner	24	16
	136	65

The other fixed costs per year have been worked out as given below (16) ($1 U.S. = 9.00 Rs):

Type of Operator	Vehicle Type	Fixed Costs/Year/Vehicle (Rs) Including Taxes	Excluding Taxes
Government	Bus	78 142	47 065
Private	Bus	36 088	13 545
Private	Truck	68 041	59 057

The crew costs and fixed costs per kilometer can be worked out by dividing the above values by the corresponding use rates.

The use in kilometers per annum provides the basis for the calculation of depreciation cost allocatable per kilometer if the yearly depreciation cost is known.

CONCLUSIONS

The results of the research amply prove the following:

1. Curvature and rise and fall of terrain influence almost all VOC components significantly. It would thus be a wise policy to design the horizontal and vertical profiles of roads after a careful consideration of the VOC with alternative design variables.
2. Pavement width significantly affects most of the VOC components. Although paucity of funds in India dictates the selection of pavement widths, the economic loss caused by narrow roads can be enormous at certain levels of traffic volume. The ad hoc norms for widening of roads by stages need to be reviewed in light of VOC relationships.
3. Roughness has a dominant influence on almost all of the VOC components. The benefits that can be derived for providing smooth surfaces can be large. The need for paving the unsurfaced roads becomes imminent. Similarly, a careful policy of maintenance of the road surfaces at a satisfactory roughness level becomes self-evident.
4. Fuel shortages are a serious problem in India. This research has shown clearly the ways and means of achieving fuel economy by improving roads and controlling speeds.
5. The VOC relationships established can be used for economic appraisal of schemes in India and in other developing countries with similar road and traffic conditions.

6. When the cost of construction of the initial facilities and the cost of maintenance are considered with the road-user cost, a better understanding of the total transportation cost is possible. This will be the final and satisfactory answer to all highway investment questions. The Indian Government's future research on highway design and maintenance aspects will go a long way in this direction.

The results presented here are likely to be of great value to highway planners in India and in other developing countries that have similar conditions.

REFERENCES

1. Basic Road Statistics, 1975-1979. Transport Research Division, Ministry of Shipping and Transport, New Delhi, India, 1980.
2. Motor Transport Statistics, 1977-1978. Transport Research Division, Ministry of Shipping and Transport, New Delhi, India, 1980.
3. C.G. Swaminathan and L.R. Kadiyali. Road User Cost Study: A Major Research Project in Transportation in India. Presented at the Workshop on Transportation Research, School of Planning and Architecture, New Delhi, India, 1982.
4. Road User Cost Study: Draft Inception Report. Central Road Research Institute, New Delhi, India, 1977.
5. Road User Cost Study: Final Report, Vols. 1-8. Central Road Research Institute, New Delhi, India, 1982.
6. H. Hide and others. The Kenya Road Transport Cost Study: Research on Vehicle Operating Costs. U.K. Transport and Road Research Laboratory, Crowthorne, Berkshire, England, TRRL Rept. 672, 1975.
7. Empresa Brasileira de Planejamento de Transportes (GEIPOT). Research on the Interrelationships Between Costs of Highway Construction, Maintenance, and Utilisation. Brasilia, Rept. 1, Mid-Term Report, 1977.
8. L.R. Kadiyali and others. Measurement of Road Geometry and Roughness for the Road User Cost Study. Journal of the Indian Roads Congress, Vol. 42, No. 2, 1981.
9. T.D. Gillespie and others. Calibration of Response-Type Road Roughness Measuring Systems. NCHRP, Rept. 228, 1980.
10. J.C. Wambold. State of the Art of Measurement and Analysis of Road Roughness. TRB, Transportation Research Record 836, 1981, pp. 21-29.
11. W.R. Hudson. Rough Roughness: Its Elements and Measurement. TRB, Transportation Research Record 836, 1981, pp. 1-7.
12. H. Hide. Vehicle Operating Costs in the Caribbean: Results of a Survey of Vehicle Operators. U.K. Transport and Road Research Laboratory, Crowthorne, Berkshire, England, TRRL Rept. 1031, 1982.
13. L.R. Kadiyali and E. Viswanathan. Roughness Measurements for the Road User Cost Study. Central Road Research Institute, New Delhi, India, RUCS Tech. Paper 80, Fifteenth Quarterly Report, 1981.
14. L.R. Kadiyali and others. Depreciation of Vehicles. Central Road Research Institute, New Delhi, India, RUCS Tech. Paper 89, Seventeenth Quarterly Report, 1982.
15. T.V. Gopalaswami and others. Crew Cost of Vehicles. Central Road Research Institute, New Delhi, India, RUCS Tech. Paper 107, Eighteenth Quarterly Report, 1982.
16. T.V. Gopalaswami and others. Fixed Cost of Vehicles. Central Road Research Institute, New Delhi, India, RUCS Tech. Paper 108, Eighteenth Quarterly Report, 1982.

Socioeconomic Evaluation and Upgrading of Rural Roads in Agricultural Areas of Ecuador

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A national socioeconomic methodology to evaluate rural roads was developed. This methodology presents the relationship among road accessibility, rainfall, drainage conditions, engineering properties of the subgrade and pavement materials, cost analysis, and agricultural benefits. A production-loss function was developed to determine the relationship between road surface conditions and losses in quality and value to agricultural products. Approximately 6000 km of rural roads along the Pacific Coast of Ecuador, 70 percent of which are dirt roads that are not usable during the wet season, were evaluated by using this methodology. A road inventory was conducted to evaluate surface conditions, soils and materials properties, drainage and structural facilities, geometric properties, and accessibility. The percentage of the cultivated area was determined together with the type of crop and the influence area of each road. Population density and the illiteracy rate within the area of influence were also determined. It was concluded that the socioeconomic evaluation of road improvement is best executed in two stages; the first, as a threshold analysis, is to determine the most economical alternative for each given traffic volume. The second stage is a complete socioeconomic analysis with determination of the internal rate of return, first-year benefit ratio, net present value, population density, and illiteracy rate. Under a total budget of U.S. $34 million, 1300 km were upgraded as a result of this study.

The provinces of El Oro, Guayas, and Los Rios, located along the Pacific Coast of Ecuador, are the biggest agricultural producers in the country. These three provinces cover 32 000 km^2 (about 11.3 percent of the total area of Ecuador). The annual agricultural exports of this region in 1978 were valued at $240 million. The population in 1979 was 3 million, approximately 35 percent of which, or 1.3 million, is the rural population.

There are approximately 6000 km, or about 1000 links, of rural roads in these three provinces. About 70 percent of these are dirt roads (Figures 1 and 2) that are not accessible during the wet season. The other 30 percent are constructed mainly of local granular-cohesive materials that have low to medium plasticity. About 55 percent of these rural roads carry less than 20 vehicles/day in both directions; 75 and 90 percent carry less than 50 and 100 vehicles/day, respectively. Only 1.5-2.0 percent of