Calibrating the Relationship Between Operating Costs of Buses and Road Roughness on Low-Volume Roads

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Vehicle operating costs (VOCs) are a key element of user costs on low-volume roads and their prediction from highway design variables dominates economic evaluations of design and maintenance strategies. The results of a number of primary VOC studies are now available in which extensive experimental and survey data bases have been employed to determine a variety of vehicle cost-design relationships. Considerable efforts were made to ensure that these results would transfer well to other countries, although potential users are advised to ensure that they are appropriate for local conditions. Some of the difficulties encountered when trying to calibrate existing relationships to a regional environment are described. The discussion is based on a small-scale VOC study currently being conducted in South Africa to develop a set of cost-roughness relationships. Study resources are scarce and a priority program has been developed to identify those cost components that are most sensitive to roughness and that take more time to calibrate. General calibration issues are presented and the lack of guidelines is noted. Results on the calibration of bus VOCs are then discussed with an emphasis on a rolling resistance experiment to permit the mechanistic determination of fuel consumption and the prediction of tire lives, maintenance parts, and depreciation charges from survey data. Recommendations and general conclusions based on the experience of the study to date are then made to assist users who are considering the calibration of primary VOC relationships.

Relationships between vehicle operating costs (VOCs) and highway design variables were reported from the Caribbean, Brazil, and India at the Third International Conference on Low-Volume Roads in 1983 (*1-3*). Primary research on this scale is both expensive and time-consuming. Therefore, an attempt was made to develop relationships that would be applicable over a period of time and could be transferred efficiently to other environments. Many of the results obtained are now being employed in evaluation models such as the World Bank's HDM3 and the Transport and Road Research Laboratory's (TRRL's) RTIM2 (*4, 5*). The results are also being employed as the basis for smaller models that evaluate specific design and maintenance issues on low-volume roads, for example, the determination of grading frequencies in Bolivia and fuel consumption in Brazil (*6, 7*).

The users of the HDM3 and RTIM2 models and those interested in incorporating reported VOC results in other evaluation and management systems are advised to ensure that the relationships are appropriate to local conditions. The process by which this is achieved can be termed calibration. Potential users who are seeking guidance in this regard usually discover that little is available; guidance ranges from a chapter in the HDM3 manual to virtually nothing in the other studies.

In South Africa, VOC relationships are the main determinant of road user costs in pavement and maintenance management systems (PMS and MMS). In the development of the maintenance and design system (MDS) for unpaved roads, provisional cost-roughness relationships were derived from the Brazilian results after intercept values were adjusted to reflect local prices. These cost-roughness relationships for buses are depicted in Figure 1. The magnitude of the various cost components and their sensitivity to road roughness demonstrate the need to correctly address nonfuel items in VOC relationships.

The evidence from the primary studies indicated that VOCs were sensitive to roughness but that this relationship varied between the different components. Most important, significant variations existed in the cost magnitudes and differentials reported by the various primary studies. These variations highlighted the need to develop a series of cost-roughness relationships specifically for representative vehicles in southern Africa.

It was decided that these relationships would be most effectively determined by conducting a small-scale VOC study to evaluate the available cost-roughness relationships and calibrate them for local conditions. A detailed understanding was first developed in the study of the various primary studies; operating cost data were then collected for a variety of vehicle types. Bus data were the first set to be assembled and most of the discussion is devoted to the early efforts to calibrate existing bus relationships and to develop new ones when necessary. Lessons learned, however, are thought to apply to other vehicle classes.

Calibration issues are considered in the following section, which is followed by three sections that detail specific examples of different forms of calibration work undertaken to determine local bus operating costs. In the first of these sections the results are reported of an experiment to determine rolling resistance coefficients to predict fuel consumption from a mechanistic-kinematic model. Preliminary results are provided in the second section of tire consumption and maintenance costs. Depreciation charges obtained from a survey of bus operations are discussed in the third section. General conclusions and recommendations are then made in the final section.

CALIBRATION ISSUES

Calibration activities can be based on both primary and secondary data sources. Primary data are composed of direct

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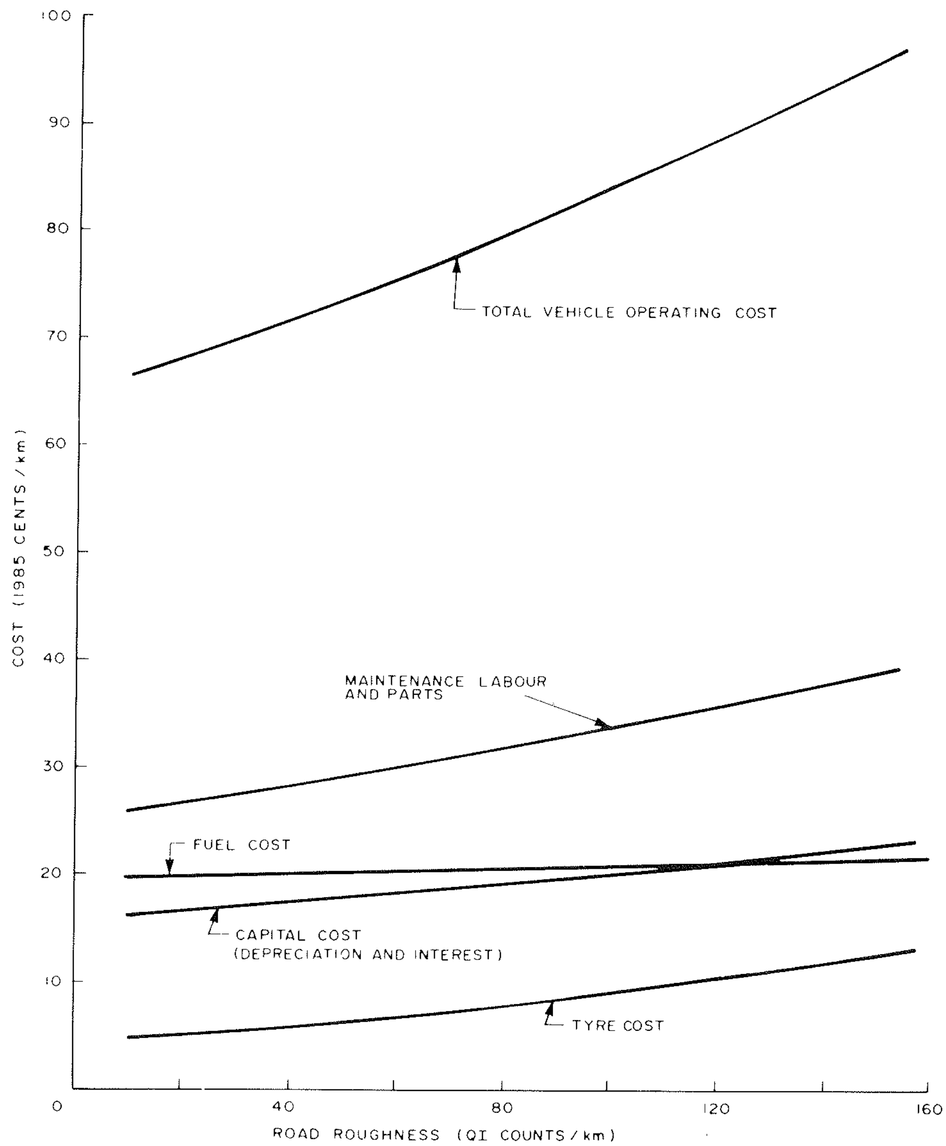

FIGURE 1 1985 vehicle operating costs for a bus on rolling terrain.

comparisons between costs and highway characteristics, whereas secondary data provide information about the economic or operating conditions of a region. The latter information can be used to adjust the results from primary studies that were conducted elsewhere.

The calibration of VOC results ranges from the selection of available relationships on the basis of few data to the estimation of local relationships using specially collected data and model forms reported in the various major, primary studies. The activities that have been identified in the small-scale South African VOC study are classified in Table 1. The impact of increasing calibration resources on data type and quality is shown in this table. Some users have only secondary data on which to base their choice and unless this information is good, it may be purely fortuitous if the relationships the users develop match local conditions. In cases in which good secondary data are available, mechanistic models can be modified with local inputs and empirical relationships can be selected on intercept values and slope differentials. Calibration work can be based on a combination of secondary data and experimental or survey activities if adequate resources are available. Most of the activities detailed in Table 1 represent different combinations of expertise, cost, and complexity, and they need to be performed in a comprehensive calibration exercise.

The basis for any calibration work is a good understanding of the research reports that provide the cost relationships of interest. This covers a wide variety of items that range from the scope of the research (vehicle types, research methods, and study size) to the economic environment at the time of the research. Economic growth and free competition, or regulation, for transport services influence loads carried, utilization, and vehicle speed. Knowledge of these effects in the countries in which the primary studies were conducted is extremely valuable when calibrating primary relationships. Unfortunately, most study reports do not adequately describe such effects. However, the World Bank compendium of results contains much relevant material to assist calibration activities (*8*).

Once the various, available primary studies have been examined and their regional macroeconomic and technical features have been assimilated, a preliminary choice of equations

TABLE 1 CALIBRATION ACTIVITIES DICTATED BY AVAILABILITY OF RESOURCES AND DATA

Type of Data	Sources or Needs	Increasing Resources Required		
Secondary Available	Government publications Industry technical reports VOC research reports Manufacturer's literature Consultants reports Operator organizations Road condition inventories	Choose primary study results which correspond to local conditions	Choose data sets and vehicle types Calibrate mechanistic models for technology changes (e.g. BHP).	Examine intercept and slope values for vehicle types with available cost and road condition data
Survey Calibration	Small-scale research collecting cost data from companies operating over a good range of highway characteristics. Personnel with industry knowledge Rates survey Route classification	Confirm intercept values and assess slope magnitudes Determine vehicle utilization by age and road condition	Estimation of tire and depreciation costs Confirm slope values for total costs	Estimate new local relations, especially for maintenance costs Compare predicted VOCs with rates
Experimental Calibration	Small-scale research of vehicle performance and roadway characteristics Trained personnel Analytical capabilities	Speed calibration	Fuel consumption calibration	Estimate new relations, for example, for rolling resistance and road roughness.

can be made. It was found useful in the small-scale study to plot the selected relationships so that a basis for comparison with local data could be established. This point may appear rather obvious but the major primary studies report a variety of different variable forms such as roughness, parts costs, labor values, and so forth, that could complicate comparisons between studies.

The resulting predictions give intercept and slope values, although the latter are generally sought in modeling roughness effects. The magnitudes of costs reported in the primary studies cannot be taken to represent general cost levels, even in the countries in which the studies were performed. This is because the surveyed companies were chosen for their operations over various combinations of route characteristics instead of because they form a representative sample of vehicle operators. Users who require cost levels in addition to cost differentials are advised to conduct an extensive calibration of equations to suit local conditions. In general, users should not mix equations from the various studies, especially for the maintenance parts, labor, depreciation, and interest results in which each study's results represent a coherent price/wage trade-off. If resources do not permit much calibration, then that study closest to the local environment should be chosen and efforts should center on the critical cost components that were identified by secondary data as being sensitive.

Data should then be collected. In some models this must be accomplished by experimentation, such as rolling resistance, and in other cases by a survey of the costs of vehicle ownership. In the case of survey data, a single company that provides a similar service over a representative range of highway types is the ideal company to survey.

Analysis of the Brazilian and Indian VOC survey data demonstrated the importance of variances between companies and within a company in the estimation of survey data. The use of a single company that operates over a wide range of a relevant independent variable, in this case roughness, avoids the error component of data between companies. The resulting data also have many other advantages, as detailed by Chesher and Harrison (*9*).

It is prudent to check the performance of the equations over the full range of highway characteristics, as defined by local conditions. Most of the equations, whether they are mechanistic-kinematic or empirically estimated, are extrapolated for extreme highway design values. Although it is claimed that mechanistic models perform better on extrapolation than empirical relationships, potential users would be well advised to check predictions with local operating data and to calibrate when necessary, because operators will try to reduce costs in precisely those areas in which they are predicted to be great.

Finally, a survey of transport rates can provide valuable information on the predicted costs of aggregate because the average rates charged by operators should reflect their total operating costs in a competitive economy. At the very least this would serve as a consistency check on total predicted values, whereas rate differentials could be employed to select primary relationships when calibration resources are scarce. When regulation or monopoly conditions affect the supply of transport services, rates data must be carefully interpreted before they can be used.

FUEL CONSUMPTION AND ROLLING RESISTANCE

In all primary studies, except the Brazilian study, the so-called aggregate-empiric approach was used to relate fuel consumption to road characteristics. Fuel consumption was measured directly in a number of types of instrumented vehicles on a great number of roads that varied in geometric properties and roughness. The required relations were then obtained by regression analysis.

The relations obtained through the use of this approach are inflexible because they cannot readily be adapted to suit vehicles with different engines or operating speed cycles. A new, large experiment would be required to obtain such impacts. An alternative approach was used in Brazil to model fuel consumption mechanistically by accounting for engine and drive-train maps, wind resistance, and rolling resistance. Rolling resistance is a function of road roughness and the suspension characteristics of vehicles. This relationship was observed in a small experiment with Brazilian vehicles. Similar, limited work in other studies has produced divergent results. An extensive experiment to obtain the relationship appropriate for local buses with a degree of confidence was accordingly conducted.

Test Procedure

The coast-down technique was used to determine rolling resistance. This involved coasting a vehicle down in neutral from a relatively high speed, usually about 80 km/h, over a road section the grade and roughness characteristics of which were known. Information on time and distance was recorded with a data logger at 1-sec intervals during testing, and the deceleration was computed. A constant cold tire pressure was maintained, and tire pressures were also measured during testing. Air temperature and wind speed were monitored, and tests were only performed when wind speeds were less than 4 m/s.

Two 92-passenger buses were used in the tests, which were performed on paved and unpaved roads that covered a range of roughness from 27 QI to 214 QI (1500 to 11 800 BI mm/km). The buses were fitted with 1100 × 20 cross-ply tires that were typically used by local operators. In a separate exercise, two 14-ton trucks that used essentially the same chassis, suspension, and tires as the buses were tested on a range of paved road sections the roughness of which varied between 16 QI and 73 QI (900 to 4000 BI mm/km).

Results of Rolling Resistance

It was found that the three levels of load conditions that were used and the texture of the road surface were not significant in defining the rolling resistance of the trucks. However, it was found that tire pressure affected the coefficient; consequently, tire pressures were carefully controlled and monitored. The analyses of the trucks and buses were performed separately. It was found that the roughness coefficients in the regression models were not significantly different for the different vehicles; consequently, the data were pooled. The following regression model was developed (*t*-values are in brackets):

$$A = \underset{(17.6)}{0.199} + \underset{(16.6)}{0.000322}\, QI - \underset{(-9.9)}{0.000177}\, TYREP \quad (1)$$

where

A = rolling resistance coefficient (N/kg),
QI = road roughness in quarter-car index (QI counts/km), and
$TYREP$ = tire pressure (kPa).

This model had an R^2 value of 0.56 and a standard error of estimate of 0.0164. Four hundred and four observations were made. Each observation represents a single run. All coefficients are significant at 0.01 percent. The data points, which were standardized to a typical operating tire pressure of 640 kPa, and the prediction model are shown in Figure 2. The unpaved road sections were generally not as uniform in their geometric and roughness characteristics as the paved sections and this is reflected by a larger variance.

The physical interpretation of Equation 1 is as follows:

- An increase in tire pressure results in a reduction of the rolling resistance coefficient, in accordance with the evidence of tire mechanics.
- A decrease in road roughness results in a decrease in the rolling resistance coefficient. The improvement of a rough, unpaved road (200 QI, 11 000 BI mm/km) to a newly constructed, paved road (30 QI, 1650 BI mm/km) results in a reduction of 40 percent in the rolling resistance coefficient.

The implications of a constant 80 km/h fuel consumption are shown in Table 2. At a 640-kPa tire pressure, the fuel consumption on very poor, unpaved roads is 23 percent higher than on good, paved roads. An increase in tire pressure of 100 kPa

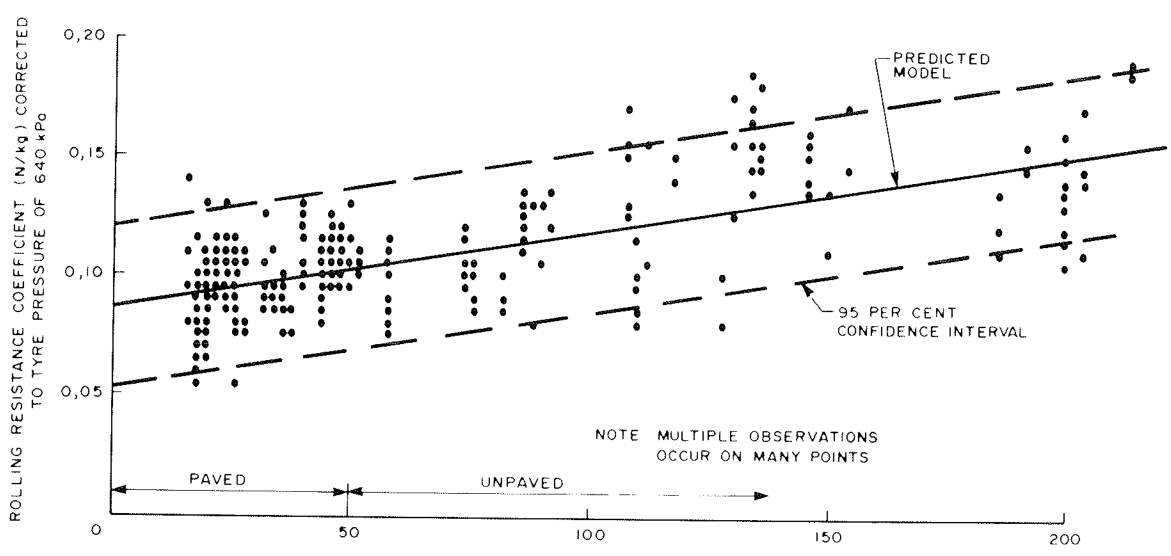

FIGURE 2 Comparison of measured rolling resistance, corrected to tire pressure of 640 kPa, with predicted model.

TABLE 2 ROLLING RESISTANCE AND ESTIMATED FUEL CONSUMPTION FOR 12 000 kg BUS AT 80 km/hr ON A LEVEL ROAD

	Road Roughness (QI counts/km)			
Tire pressure (kPa)		Good paved (20)	Poor paved (80)	Very poor unpaved (200)
540	RR[a]	0.110	0.133	0.178
	FC[b]	30.7	33.0	37.4
640	RR[a]	0.093	0.116	0.161
	FC[b]	29.1	31.4	35.8

Note: 1 unit QI = 55 units BI.
[a]RR = predicted rolling resistance (N/kg).
[b]FC = fuel consumption (liters/100 km).

from 540 kPa to 640 kPa on a good, paved road results in a 5.2 percent reduction in fuel consumption. Although higher tire pressures reduce fuel consumption, a tire cost penalty is incurred when tire pressures are higher than the manufacturer's recommendations, and this could lead to premature failure.

Comparison With Other Studies

Relatively little work has been performed to relate rolling resistance to road roughness. The results of Watanatada and Bester are compared with examples of Equation 1 that demonstrate the effect of tire pressure in Figure 3 (*10, 11*). The results of the study by Bester show the same intercept value as this study but, even though a constant cold tire pressure was maintained in that study, the effect of road roughness was much greater. However, in view of the experimental scatter evident in Figure 2, the relatively small roughness range covered may have produced a spurious result. Watanatada also maintained a constant, but unknown, tire pressure. The coefficients of rolling resistance are generally higher than in this study but the roughness slope is a little less. Discrepancies could be the result of differences in vehicle characteristics or experimental error. In any event, the variability obtained in this study and the role of tire pressure indicate the care needed to define the scope of this type of experiment.

It should be noted that the fuel implications attributed to differences in rolling resistance apply to a constant speed of 80 km/h. In practice a driver would adjust the speed according to road conditions and the operating schedule. The driver could repeatedly change speeds on very rough roads in an attempt to avoid major deformations. Therefore, driver behavior should be studied to derive fuel consumption relations and compare them with aggregate-empiric studies.

The work described was performed on cross-ply tires; further work will be performed on radial-ply tires, which are gaining in popularity, even for use on unpaved roads. The effect of loose material on unpaved roads was not considered in this study, but it will be examined in future studies.

RESULTS OF THE USER SURVEY

A literature survey of available VOC relationships was conducted to group the selected equations by cost component and to plot their predictions. The economic and vehicle operating

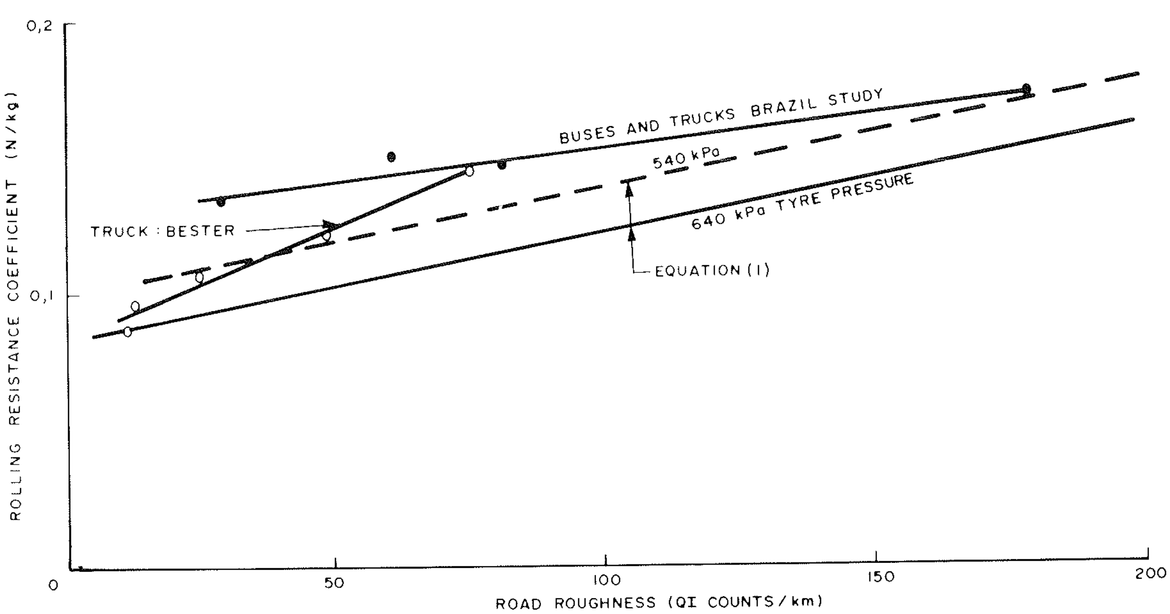

FIGURE 3 The effect of road roughness on rolling resistance coefficient for heavy vehicles.

conditions that prevailed in the relevant countries or regions were then noted. This provided valuable secondary information for the interpretation of predicted values.

For reasons that were detailed in a study by Chesher and Harrison, a single company that operated over a wide range of road roughness was sought to provide survey data (*9*). The following results are based on the data of such a company that operated 740 buses from nine depots with a combined annual fleet use of 50 million km. In order to provide the best range of road roughness values, operating cost data were taken from five of the nine depots over a complete calendar year, as recommended by Hide et al. (*12*). Traffic and workshop managers from the bus company were interviewed to ensure that vehicle operation and maintenance policies were fully understood and the cost data were correctly interpreted. Distinct highway characteristics were associated with the data of each of the five depots that were selected. It was believed that this would permit discriminations to be made between the major primary study results and would make the determination of equations for local conditions possible.

Roughness measurements were made with a response-type device, the Linear Displacement Integrator (LDI), and converted to QI units in counts/km. The network classification and use figures provided by the depots enabled sample measurements to be taken of the roughness of each of the five selected networks. Because individual route roughness values would affect the aggregate cost data in proportion to route length and use, it was decided to calculate a roughness average, weighted by fleet use, for each depot. The resulting weighted averages ranged from 42 to 120 QI (2300 to 6600 BI mm/km) and were used in the analyses of both tire and maintenance parts.

Tire Consumption

Each depot maintained a tire record system in the form of cards that detailed the history of each casing. Information was provided on the service lives of new and retreaded tires in kilometers traveled, and reasons were given for withdrawal from service. Monthly average tire costs were provided for both new and recapped tires. These costs and the service lives of the tires made it possible to calculate equivalent new tire life values. This calculation was first used in Kenya, and was subsequently adopted by all major studies. This is discussed in a study by Visser and Curtayne that can be found elsewhere in this publication. Equivalent new tire lives were derived from the following equation:

$$ENT = TK/(1 + NR/R) \quad (2)$$

where

ENT = equivalent new tire life (km/tire),
TK = total kilometrage per casing (km),
NR = number of retreads per casing, and
R = ratio of new tire price to retread price.

The new tire price was divided by the ENT values and the result was multiplied by the number of tires per vehicle to allow a comparison to be made with other studies.

Data were plotted and a simple log-linear relationship was determined from the various models that were fitted to the data. The relationship is as follows (*t*-values in brackets):

$$ENT = \underset{(6.6)}{152.1} - \underset{(4.7)}{25.5} \ln QI \quad (3)$$

$R^2 = 0.88$; standard error = 4.48.

where ENT = new tire life (10^3 km/tire).

This relationship is plotted in Figure 4, in which the relationships from Kenya, the Caribbean, India, and Brazil are also shown. Predictions of the number of tires per bus per 10 000 km are given in Table 3.

An examination of the data in Figure 4 and Table 3 shows a degree of similarity between the local bus tire predictions and those of the TRRL studies in Kenya and the Caribbean, whereas divergence is shown in the results of the Brazilian and Indian studies. Other independent variables, such as road geometry, vehicle age, and pavement width were significant in predicting tire usage in the Brazilian and Indian studies. However, this does not explain the significant differences in the service life versus roughness slopes. Because tire technologies are similar worldwide, other reasons must exist to explain the differences. Driver behavior, which is extremely difficult to quantify, could be one reason. Another reason could be the characteristics of the gravel materials.

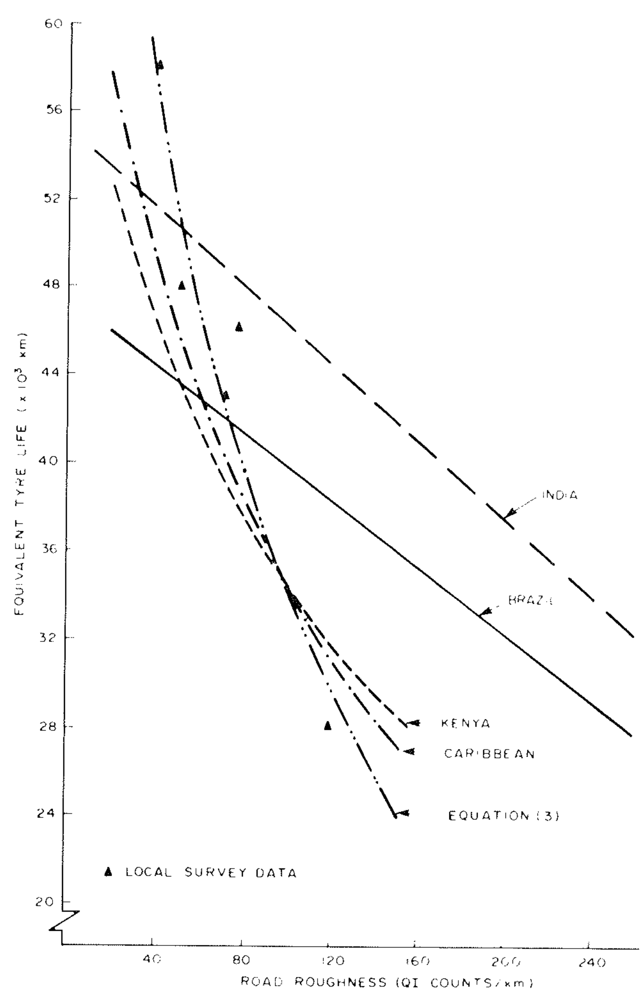

FIGURE 4 Predictions of equivalent new tire life for a medium-sized, 12-ton, two-axle bus.

TABLE 3 PREDICTION OF NUMBER OF TIRES PER BUS PER 10 000 km FROM VARIOUS STUDIES

Roughness (QI counts/km)	Kenya	Caribbean[a]	Brazil[b]	India[c]	Equation 3[d]
20	1.14	1.03	1.25	1.09	0.79
40	1.29	1.20	1.29	1.13	1.03
60	1.44	1.38	1.33	1.16	1.26
80	1.59	1.56	1.38	1.21	1.49
100	1.74	1.74	1.43	1.25	1.73
120	1.88	1.92	1.48	1.30	2.00
140	2.03	2.09	1.54	1.35	2.30

[a]Paved road operations only.
[b]Tire size 900 20; six tires per bus; rise plus fall 15 m/km; curvature 50 degrees/km.
[c]Vehicle age 250 000 km; six tires per bus; rise plus fall 15 m/km; curvature 50 degrees per km; pavement width 7.4 m.
[d]Six tires per bus.

It was reported at the depot with an average network roughness of 120 QI (6600 BI mm/km) that 45 percent of tire scrapes were caused by sharp, angular stones in the gravel wearing courses that penetrated the tire casings. It is evident from the available data that local gravel materials cause many premature failures and tread wear; further inquiries into this matter are scheduled. In addition, operators on routes of less than 35 QI (1925 BI mm/km) are reporting tire lives significantly higher than values predicted from the results of the primary VOC studies but similar to the extrapolated values of the local equation. Under these circumstances, the preliminary findings suggest that a local equation should be developed instead of a calibration of existing relationships.

Maintenance Costs

Maintenance expenditures are among the operating costs that are most likely to exhibit transferability problems. This is because maintenance expenditures are sensitive to price and wage levels and the trade-offs of depreciation and interest charges, all of which are linked to the size, strength, and structure of the local economy with the type of transport service offered by the operator. The bus company that provided the cost data is chiefly engaged in commuter work in which the reliability of service levels at peak periods is crucial to its success in business.

The company's policy was to set high levels of inspection and conduct preventive maintenance; these costs were balanced by keeping reserve vehicles to a minimum. Over 95 percent of the fleet was typically available for peak periods. During these times, the rest of the fleet received routine maintenance or was held in reserve. Engines, gearboxes, and differentials were changed at target lives of 300 000, 350 000, and 450 000 km, respectively, with a 10 percent variance to allow for local depot conditions. These expenditures were termed units and were treated as a separate cost item in the workshop accounts, which is a commonly adopted procedure in different parts of the world. Because the consumption of units was only partially related to road condition, it was not included in the preliminary analyses of maintenance costs.

The spares data, excluding units, were first examined by plotting costs against road roughness. Although a satisfactory linear relationship was developed, the results of all major VOC primary studies emphasized the importance of vehicle kilometer age in the estimation of maintenance parts costs. The local bus data were therefore assigned kilometer ages and the parts costs were normalized by dividing maintenance costs by new vehicle prices for the various makes and models supplied by company records. The provision of data across highway types from a single company ensured that all purchasing policies in regard to vehicles and spares were identical, and thus prevented the variations in policy from being ascribed to road roughness.

Various models reported in the major primary VOC studies were estimated and the following equation, which is similar to the Brazilian bus maintenance parts equation, showed the best fit:

$$\ln (SP/VP) = \underset{(-6.25)}{-0.7894} + \underset{(13.61)}{0.4153} \ln (QI) + \underset{(40.75)}{0.6313} \ln (AGE) \qquad (4)$$

$$R^2 = 0.82$$

where

SP = spare parts costs in South African (SA) rands/10^3 km (2.5 SA rands = 1 U.S. dollar),
VP = new vehicle price (in 10^5 SA rands),
AGE = bus age (in 10^3 km), and
QI = road roughness (counts/km).

A model form similar to that reported by the Kenyan study yielded an R^2 value of 0.71 when estimated with local data, compared to the value of 0.92 reported in the Kenyan study. Equation 4, for a vehicle age of 250 000 km, is shown in Figure 5, in which the normalized predictions from the Kenyan, Brazilian, and Indian studies are also plotted. The results are regarded as encouraging and further work is to be undertaken on the other maintenance costs and the estimation of labor costs. The evidence of the roughness effect in the local data appears to be in accordance with the slope of the Brazilian relationship, more severe than the Indian data, and significantly less severe than the Kenyan data. The trade-off between maintenance flows and depreciation costs is crucial to vehicle operations because these costs determine purchasing, maintenance, selling, and scrapping decisions, and form a significant portion of total vehicle operating costs.

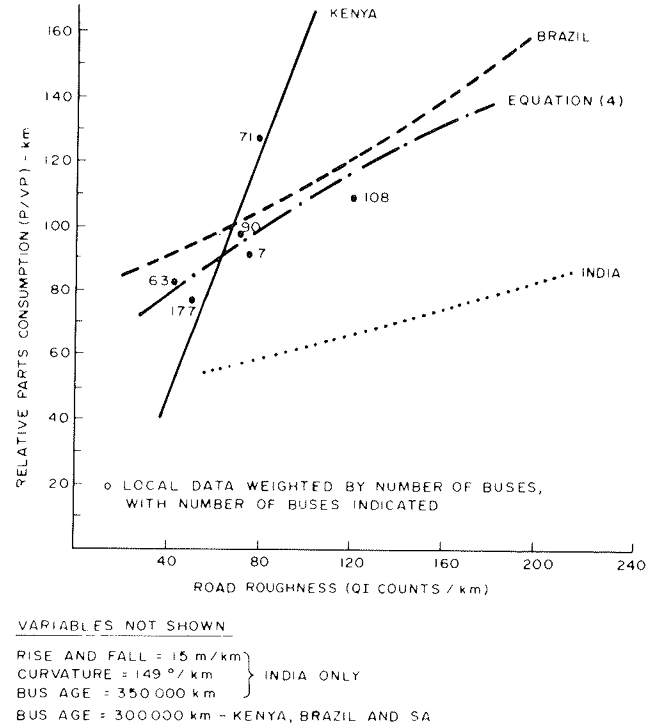

FIGURE 5 Relative parts consumption versus roughness values for buses.

VEHICLE DEPRECIATION

Depreciation costs, which reflect the change in capital value over time and use, can be substantial for vehicle owners, and can influence the costs of providing transport services. None of the primary studies reported relationships of vehicle value as a function of age (in km or calendar years) or of the route characteristics over which the vehicles traveled. All studies instead reported average vehicle age (in years) relationships that were generally obtained from national surveys of used vehicle prices. The effect of highway design characteristics appears to relate only indirectly to depreciation through the number of kilometers traveled. It is assumed that poorer roads lead to lower speeds and thus lower utilization although not necessarily proportionally. Therefore, fixed depreciation costs per time period can be placed on a per-unit time basis by changes in vehicle kilometers traveled.

The average vehicle life of 11 years that was reported by local survey companies was extended to 15 years if the vehicles were rebuilt. At a 15-yr service life, bus design and the availability of spare parts could make the safe and reliable provision of regular passenger service expensive. There is a point at which a case could be made to sell the bus when running costs exceed revenue for a particular service or scrapping the bus when depreciation and interest costs are zero. Chesher and Harrison have developed an optimal scrapping model that requires that vehicle life, s, satisfies the following:

$$\int_0^s \{m(s) - m(t)\}e^{-rt}\,dt = VP \qquad (5)$$

where

$m(t)$ = the per year rate of running costs for a t-year-old vehicle,

r = per time period continuous discount rate, and

VP = new vehicle price (*8*).

It should be noted that Equation 5 is optimal only as long as vehicle use does not vary with vehicle age, a condition which can be satisfied by the provision of data by the local operator. All fleet vehicles are maintained to travel similar distances and must be able to operate over all road types in the depot network. If bus depreciation is calculated by use of vehicle-age relationships, the depreciation does not vary with highway design changes, because the use remains the same. If the main business of the bus companies is to provide commuting services with a relatively inelastic trip demand, then the vehicle-age method cannot produce depreciation differentials for inclusion in models that were designed to select highway maintenance strategies and options.

However, as detailed in a study by Chesher and Harrison, this is inconsistent with economic theory, which states that vehicles that require relatively high maintenance flows will command relatively low sale values (*8*). Improvements in highway conditions that lower running costs should lead to longer service lives or higher age values for the vehicles on the network. Imperfections in markets could make it difficult for prospective purchasers to know the use and maintenance patterns of the vehicles. Therefore, emphasis has traditionally been placed on the year of manufacture, which identifies the vehicle with a particular technological specification and a likely kilometer age. This practice may now be changing, however, because dealers in second-hand commercial vehicles in North America and Europe are offering 3-, 6-, and 12-month guarantees on parts and labor costs, which are influencing buyers in the manner predicted by economic theory. Given the discount rate, the new vehicle price, and the predictions of running costs over time, the optimal vehicle life can be determined using Equation 5. Terminal running costs can then be predicted to provide another means of determining total vehicle operating costs.

CONCLUSIONS AND RECOMMENDATIONS

The small-scale VOC study was designed to select a set of cost-roughness relationships that were reported in major primary VOC studies and to calibrate them to local conditions. Consequently, it was planned that very few equations would be estimated with local primary performance and cost data that were collected from experimental vehicles or operator records. A variety of calibration activities that were influenced by study resources and data availability was identified and detailed in Table 1. This made it possible to determine a program of priorities that reflected the sensitivity of the cost component in the VOC model and the modest resources at the team's disposal. It is likely that other potential VOC users will have insufficient resources to address all potential calibration activities and will need to focus on key components in a similar manner.

Vehicle operating costs are being developed for cars, buses, and trucks on low-volume roads. It was decided to first determine fuel consumption and tire and maintenance parts costs. The remaining costs, like depreciation, would then be addressed. Fuel consumption was to be predicted from a mechanistic model in which rolling resistance was the critical factor affected by road roughness. The other cost components would use calibrated aggregate-empiric relationships estimated from user survey data. The study is still in progress and most results are preliminary and tentative. In terms of the bus results presented in previous sections, the rolling resistance is considered to be well-defined for the front-engined chassis buses that are used in the study region. The results complement earlier research, for example, the research that was incorporated into the HDM3 model, and can be used with confidence for conventional buses and medium-sized trucks.

The tire analysis is proceeding well and seems to be in accordance with the Kenyan study slope for roughness of 40 to 100 QI (2200 to 5500 BI mm/km). Local predictions are more extreme than those of the major primary studies when a calibration curve is fitted to the data and extrapolated. As was previously noted, material properties on the rough, unpaved roads appear to be causing high failure rates, and this will be investigated. Local operators are reporting longer tire lives on good-quality roads that agree with the predictions of the calibrated curve.

The preliminary analysis of maintenance parts data is progressing slowly, as was expected given the problems of measuring this cost component. A cost-roughness relationship similar to that reported in the Brazilian study has been estimated and the model form reported in the Kenyan study also fits the data in a credible manner. No statistical basis currently exists for preferring a linear or log-linear form. The log-linear form was presented in this paper because it performed well when it was extrapolated. New discussions with bus company staff are proposed to check the data and the way data are being grouped. In addition, data from the remaining depots will be collected to determine if the discrimination can be improved.

Work in the area of depreciation has shown that cost differentials cannot be determined from the usual value-age method, because changes in speed do not affect use levels, at least in the short to medium term. In situations in which a road is improved, lower maintenance costs should alter the market value of the vehicle or its service life, and therefore its depreciation. The value-age method is typically insensitive to these effects and its use for local bus operations would not affect cost differentials. In an effort to maintain depreciation as a cost differential, an alternative economic model of optimal scrapping will be tested.

A general assessment of the study is beneficial to those who are contemplating the use of the VOC relationships in the primary studies. The majority of the aggregate-empiric results do not transfer easily and convincingly to the local conditions encountered. The role of calibration in which either few or many data exist is relatively straightforward. Few data permit only the selection of a set of relationships, such as in the Kenyan study, whereas many data permit local relationships to be estimated using model forms that were reported in the primary studies. Because good data are expensive to collect, the challenge to the research community is to develop effective calibration procedures based on secondary data or limited amounts of good primary data.

Encouraging results have been obtained in this study from a survey of a single, large company that operated over a wide range of road roughness. An understanding of operating policy and data quality can be easily gained by visiting a few depots, and inter-company variances can be avoided. Furthermore, this type of survey does not require great resources and provides a data source that is more informative than secondary data. It is hoped that this source of data will provide a basis for accurate calibration to local conditions. Cost differentials from such a source are likely to be extremely helpful in adjusting primary results. In addition, rates surveys are extremely valuable in situations in which competition and little regulation exist. Rates differentials should broadly give the same slope as that derived from total vehicle operating costs.

Finally, the development of mechanistic-kinematic evaluations models, most recently by the World Bank, is in part an attempt to avoid the transferability problems inherent in regression equations that are estimated from aggregate data. The small-scale study adopted the mechanistic argument for fuel consumption but is predicting the other cost components from survey data. Relationships for tire life can be modeled mechanistically with experimental data that were collected specifically to determine such a model. This approach has much to recommend it, but it was beyond the scope of this study. Maintenance parts and labor costs, and their trade-off with depreciation and interest charges, are likely to prove highly resistant to a mechanistic approach. Economics, not technology, is the key factor in the prediction of these components. The local VOCs that are being developed are likely to be a mix of aggregate-empiric and mechanistic models. When they are ready, they will be compared with other evaluation models instead of primary study results. Calibration is proving to be a challenging task and is proving to be more difficult than was anticipated at the initiation of the research. One of the objectives of this research was preparation of calibration guidelines, but the results are tentative at this stage, and the objective will not be fulfilled until the program is completed.

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The Operation of Logging Trucks on Steep, Low-Volume Roads

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The selection of a maximum grade for a road standard is a complex decision that involves design, construction, maintenance, vehicle, amount of use, and cost considerations. In the western United States, steep terrain, high construction costs, and the need to maintain slope stability make ridgetop instead of sidehill road locations attractive. Therefore, the gradability of steep (greater than 16 percent), low-volume roads primarily used by logging trucks and assisting vehicles is of major concern. Gradability is strongly influenced by the coefficient of traction, the most important variable, and by apparent truck grade and turning resistance around curves. The effect of grade on truck speed is also economically important. Truck safety depends on the road surfacing material and truck design, especially the truck braking system. As grades steepen, the amount of energy that the engine and service brakes must dissipate increases, and the rise in brake temperature can become critical. The road surfacing material has a major effect on truck performance. Gradation, particle shape, and in-place density of aggregate surfacing materials strongly influence the gradability of steep roads. Crushed-rock aggregate is preferred because it develops the greatest coefficient of traction under wet-season conditions, although some native soils develop higher coefficients of traction under dry-season conditions. Aggregate strength apparently increases as the fine-grained particle content increases under optimal moisture conditions. Careful planning can identify the conditions under which steep roads are most economical. Management alternatives include the use of assisting vehicles with logging trucks, surface stabilization to avoid erosion and added maintenance costs, and control of the season of use.

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The selection of the maximum grade for a road standard is a complex decision that involves design, construction, maintenance, vehicle, amount of use, and cost considerations. Concerns over vehicle capability and operating costs have historically resulted in limited maximum road grades. More recently, however, the rise in road construction costs resulting from the need to maintain slope stability in steep terrain has prompted a review of recommended maximum grades and encouraged construction of roads at grades steeper than past maximums.

In the western United States, a combination of steep topography and erosive or unstable soils influences the range of physical options available. For example, approximately one-fifth of the roads constructed between 1972 and 1982 in the Mapleton District, Siuslaw National Forest, in the Oregon Coast Range were steeper than a 15 percent grade (*1*). Adverse (uphill) grades as steep as 26 percent for loaded logging trucks without an assisting vehicle and 30 to 35 percent for assisted logging trucks have been reported (*2*).

Road designers in the Oregon Coast Range currently prefer ridgetop instead of sidehill road locations to reduce overall road length and to avoid the cost of hauling and disposing of large volumes of excavated material. As the subgrade width and percent side-slope increase, the volume of excavated material increases dramatically (Figure 1). The USDA Forest Service estimates that ridgetop roads in the Coast Range cost an average of $100,000/mi, whereas sidehill roads cost from $250,000 to $600,000/mi. The disadvantages of ridgetop roads