THE EFFECT OF ROAD DESIGN AND MAINTENANCE ON VEHICLE OPERATING COSTS-FIELD RESEARCH IN BRAZIL

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The design and methodology of the survey of vehicle operating costs on rural and inter-urban roads in a large area of central, western and southern Brazil is described. Data were collected from 117 operators for 1326 vehicles by a team of 20 researchers. Road roughness and geometric characteristics were measured on 423 routes nearly 40000 km in length using two specially instrumented cars. The method of analysis is explained and some preliminary relationships are presented and discussed. Special attention is being given to depreciation and vehicle maintenance costs. An example is used to show that on typical unpaved roads in Brazil increases in fuel consumption are small in relation to the overall increase in costs, when compared to paved roads. Analysis is in its early stages and will continue until November 1979.

Since October 1975 research has been underway in Brazil to determine the relationships between the cost of highway construction, maintenance and utilization, primarily for low volume roads. The project is sponsored by the government of Brazil and the United Nations Development Program, and is managed by the Ministry of Transport through its affiliate GEIPOT (Brazilian Transport Planning Corporation). The project is based at the headquarters of GEIPOT in Brasilia the Federal Capital, and will continue until November 1979.

This paper describes the vehicle operating cost survey and gives the results of some preliminary analyses. It is emphasized that the results are from early analyses of selected data. Field data collection has not yet been completed and final analysis of all data has not begun. The results should be considered with this in mind.

Research Objectives

The objective is to develop and improve relationships between construction, maintenance, and road user costs and combine them in a predictive model which will assist in minimizing the total cost of Brazil's highway network. The model calculates the construction cost of a road and predicts its condition over time for given traffic levels. Having predicted road condition the model estimates costs of road maintenance and vehicle operation.

Survey Design and Scope

In planning the survey it was realized that successful analysis would depend on how effectively the design and data collection could cover the extremes of operating conditions in Brazil, in terms of surface roughness and vertical and horizontal geometry. The need was for a sample from all major vehicle types, stratified by the important decision variables - road geometry and surface type. A very simple pre-stratification was used (Figure 1) to aid selection of operators of buses, trucks and automobiles, for two main reasons. First, it was not possible to pre-stratify road characteristics with any great degree of precision, and secondly, since very few vehicles operated on only one route it was necessary to consider vehicles using several routes of a broadly homogeneous character. The search for suitable vehicle operators was therefore concentrated in regions as widely different as possible with respect to topography, and in areas with the most unpaved roads.

Apart from buses, for which published data were available, little was known about the vehicle operators and their itineraries in the various regions, often remote from Brasilia.

It was generally fairly easy to locate operators with good cost records for vehicles on paved roads. However suitable operators on unpaved roads were much harder to find. There were fewer fleets in areas of largely unpaved roads, and fleet sizes were generally smaller. The need for homogeneous routes limited the areas available. Thus, areas of rolling terrain were avoided as far as possible while flatter or hillier areas were thoroughly searched.

It was necessary to search much wider and farther than had originally been planned, since many operators, although using roads suitable for the research, lacked adequate vehicle cost records. Almost one thousand operators, from large fleets to owner-drivers, were contacted in the initial searches and a mail-shot questionnaire was sent to a further 1500. Data quality was an important consideration. It was sometimes found necessary to be less restriccurve's effect on a steep grade. In order to quantify these kinds of effects algorithms were developed (5) defining a function for each grade and curve, weighted by the effect of the previous geometric condition. The weights are based on speed changes under various conditions derived from experimental data. Separate calculations are made for each grade and curve from the raw data file, summed and divided by the route total km to give the index (V and H) values.

Typical Roughness and Geometry Values

The mean value of the roughness index (QI*) for all the paved roads in the survey is 39 QI* with a standard deviation of 8, and for all unpaved roads 140 QI* with a standard deviation of 33. For geometry, a fairly flat and straight road would have a vertical index (V) of 4.5 and horizontal index (H) of 0.04, while a mountainous road would have V of 8.5 and H of 0.45.

Preliminary Analyses

Fuel, utilization, and parts data were obtained directly from the vehicles in the fleets of the companies. The mean costs per company/cell were analyzed since the variance from company to company within a cell was significantly greater than the variance from vehicle to vehicle within companies. Labour hours and tire data were collected directly at the company level. For these two items the mean value per company was analyzed as the dependent variable.

The dependent variable for all cost items is expressed in units per 1000 km. In the case of parts and depreciation costs where the units are Brazilian cruzeiros, (Cr$), the data values are transformed to constant cruzeiros of January 1976 when one U.S. dollar was approximately Cr$ 10,00. (6)

Weighted regression analysis was used. For fuel, utilization, and parts the reciprocal of the sample variance of the mean per company/cell was used as the weight. For labor hours data the fleet size was used as the weight, and for tyres, the number of tyres analyzed in each fleet.

For all cost items, the effects of vehicle characteristics were tested. The correlation between the highway characteristics and the vehicle characteristics was eliminated by adjusting the mean value of the latter per company/cell by its mean per cell. Thus the coefficient of each of the highway characteristics reflects the influence of that variable given the vehicle characteristics present in each cell of the factorial. The effect of the vehicle characteristics is calculated within the cells of the factorial and therefore can be interpreted independently of the highway characteristics. An interpretation of the equation for utilization is given after the discussion of depreciation.

Depreciation and Interest

The main objective was to develop a method of calculating vehicle depreciation with respect to differing highway characteristics. Two potential approaches were examined, one emphasing market valuations, and the other, vehicle utilization. The market valuation approach was finally rejected, because while it was possible to collect data for many actual sales, the vehicle histories, in particular routes operated, were unknown. Of vehicles included in the main survey, less than 10% were sold during the data collection period, an insufficient number for analysis.

Vehicle utilization (km per month) was analyzed using the hypothesis that if differential rates of utilization could be predicted, then differential depreciation costs could be calculated from average sale prices for vehicles of a given age. Two components were therefore used.

1. Utilization rates by vehicle class
Prediction equations were developed where monthly or annual km is a function of highway characteristics and vehicle characteristics.
2. Average market values by vehicle class
Curves were drawn representing the average decline in value for each year over the entire vehicle life. The data source was dealers specializing in used vehicles in the São Paulo area. Values were checked for consistency with actual sales of vehicles from the main survey. In addition, data on vehicle survival rates was obtained from the national vehicle registration authority. These data are not central to the methodology outlined above but are useful for the Brazilian model when calculating average lifetime depreciation and interest by vehicle class.

The components above were combined to predict depreciation cost, per km. Between given ages in a vehicle's life, depreciation per km is equal to the change in market value divided by utilization during that period, such that:

$$D_{c,j} = \frac{NP_c \; 1-DC_{c,j}}{\sum_{i=1}^{j} AV_{c,i}} \qquad (1)$$

Where:

j = 1,.....k
k = maximum vehicle age in years
$D_{c,j}$ = Depreciation cost per km at age j
NP_c = New vehicle price less tires for class c
$DC_{c,j}$ = Value of class c vehicle at age j, as a proportion of new price
$AV_{c,i}$ = Annual utilization in year i for class c vehicle

Interest. Interest should be included in vehicle operation cost calculations, normally as equal to the opportunity cost of capital. Having chosen the rate to be applied, the same components used above can be used to calculate interest cost, such that:

$$IC_{c,j} = \frac{NP_c R_c \sum_{i=0}^{j} DC_{c,i}}{\sum_{i=1}^{j} AV_i} \qquad (2)$$

Where:

$IC_{c,j}$ = Interest cost per km at age j for vehicle class c
R_c = Annual interest rate for vehicle class c

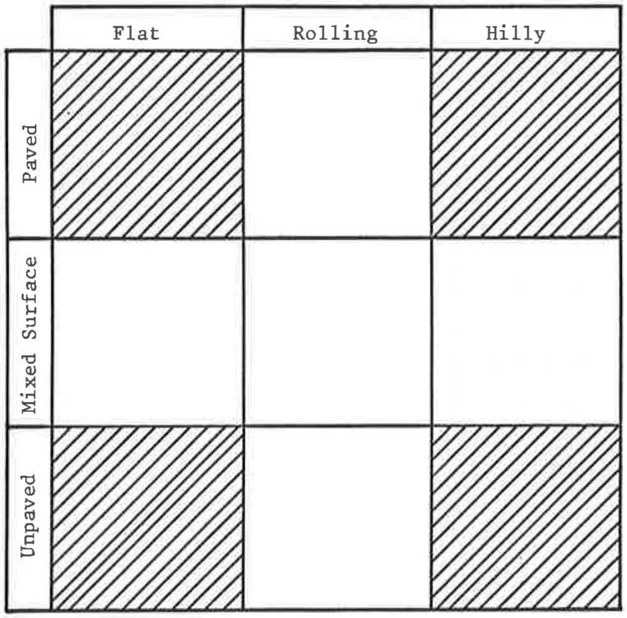
Preliminary Results

Utilization

The equation for utilization will be discussed to show how the influences of the vehicle characteristics can be interpreted for the other equations presented below.

The following generalized regression model spec-

Figure 1. Pre-stratification of vehicle operators.



Note. Searching was concentrated in the shaded cells.

tive on route characteristics in order to include a fleet operator with reliable and comprehensive cost records.

The geographic area of the survey now covers one million km^2, containing 30% and 40% of the total Brazilian paved and unpaved networks respectively. Data is collected regularly in 28 cities in the States of Minas Gerais, Goiás, Mato Grosso, Mato Grosso do Sul and Rio Grande do Sul, several locations being well over 1500 km from Brasilia.

The survey encompasses 653 buses, 442 trucks and 231 automobiles, from 62 fleets and 55 owner drivers, during an average data period of 16 months. The factorial dispersion of vehicles and routes is shown in Figure 2. All aspects of vehicle operating costs are being investigated, but special attention is given to depreciation, and spare parts and maintenance costs. Separate controlled experiments have been carried out in Brazil to investigate fuel consumption and vehicle speeds (1).

Methodology

Two separate but complementary tasks were involved-collection of vehicle cost data, and identification and measurement of the vehicle's routes. Coordination of these activities was the main rôle of survey management. The importance of the computer must be noted. More than 50 programs were specially written, and extensive use was made of a package for data retrieval and analysis.

Vehicle Cost Data

Information is collected on fuel, engine oil, workshop labor hours, spare parts and materials used, tyres, routes operated, and number of trips and kilometers on each route.

The basic approach is that frequent and regular visits are made to the vehicle operator's offices and workshop, so that the field researcher is as familiar as possible with the vehicle operations and company cost reporting procedures. Besides the benefits that such routine visits produce in terms of convenience to company managers, who give their time voluntarily, it is necessary to know something about the quality of data from such diverse sources. It is essential to know exactly how the data are assembled by the operator, and the use to which he puts the information.

The primary method of data collection is to make the maximum possible use of the vehicle operator's own records. When experience has been gained in interpretation of the material the method is considered efficient. At the outset, a detailed examination of all relevant company records is made by senior members of the research team in order to establish the reliability of the data. As noted above, it is then important that the field researcher makes regular visits to the company to become completely familiar with the costing system. Whenever possible, original records are photocopied for permanent reference. In the research office, data are compiled on a monthly basis and transferred to a keypunch form by the field researcher himself. In this way guidance on interpretation can be given, and closer supervision exercised by senior staff. Having been processed and edited the data are output to reports designed to facilitate screening and consistency tests. Errors are refered back to the field researcher for correction on numbered enquiry forms, while other less obvious inconsistencies are investigated by senior staff in direct field enquiries. If alterations to file data are necessary a separate computer report is generated so that new values can be checked.

Where the operator's own records are inadequate, as is frequently the case with owner drivers and some smaller fleets, the operator is given blank forms each month, and guidance on how to fill them out. The response rate was generally low, but dependent to a large extent on the effort given by the field researcher in setting up and maintaining such a system. In a number of cases contact with the research team has stimulated the operator to develop a more efficient cost control of his own.

Route Network

The routes extend throughout Goiás, Minas Gerais, Mato Grosso, Mato Grosso do Sul, and Rio Grande do Sul, with some sections into Espírito Santo, Rio de Janeiro, São Paulo and Santa Catarina.

So far, 423 routes have been measured totalling 66000 km, however since many routes have common links the actual road length is 39000 km, of which 18000 km is unpaved. Paved routes average about 220 km in length and unpaved 105 km. Traffic volumes average 2500 vehicles per day for paved routes and an estimated 200 v.p.d. for unpaved routes.

For each route the detailed itinerary was checked with the vehicle operator and transferred to a specially drawn map. Turning points on a route , or "nodes" were numbered and the location described in a computer file. For each route, the file then lists the complete sequence of nodes.

Roughness and Geometry Measurement. Two 2500 c.c. station wagons were used, crewed by a driver and an observer. Two passes of each link were normally made, measuring roughness in one direction and road geometry in the other.

For roughness, a Mays-Ride-Meter (2) was used, connected to a digital display giving counts every 322 meters (5 counts per mile) the count being noted by the observer on a keypunch form. Regular cali-

Figure 2. Vehicle and route final stratification.

Roughness	Horizontal \ Vertical	Flat	Rolling	Hilly
Paved	1	80 vehicles 10 routes	349 vehicles 82 routes	53 vehicles 2 routes
Paved	2	16 vehicles 13 routes	89 vehicles 67 routes	163 vehicles 37 routes
Mixed Surface	1	6 vehicles 7 routes	49 vehicles 21 routes	4 vehicles 5 routes
Mixed Surface	2	4 vehicles 5 routes	31 vehicles 28 routes	9 vehicles 12 routes
Unpaved	1	138 vehicles 28 routes	147 vehicles 38 routes	58 vehicles 10 routes
Unpaved	2	17 vehicles 5 routes	60 vehicles 27 routes	53 vehicles 26 routes

Note. Horizontal level 1 = low or average curvature, level 2 = high curvature

bration was of paramount importance, because readings are sensitive to the condition of the vehicle's springs, shock absorbers, wheel alignment and tyres. The vehicles were calibrated before and after each field trip on 20 control sections against GMR Profilometer measurements. (3)

Horizontal curvature was measured with a standard aircraft type gyro compass. The start and end of each curve is called by the driver to the observer who notes the bearings from the gyro compass, and length of the curve in meters from the distance measuring instrument (DMI) (2).

Vertical profile was measured using an electronic linear accelerometer connected to a panel meter, scaled to plus or minus 12% grade. The instrument senses the gravitational acceleration resulting from tilting the axis of sensitivity off the level plane parallel to the ground. Drivers were trained to hold the vehicle speed constant while the reading is noted at approximately the mid-point of the grade. As with horizontal curvature, the driver calls the start and end of the grade and the observer notes the DMI readings. Transition grades are noted when the grade change is 1/2% or more and when the length of the grade is sufficient to record a stable reading from the panel meter. The system has been tested with known road profiles up to 15 km in length and although by no means exact, produces a satisfactory approximation to the known profile.

Roughness and Geometry Indices

Roughness. After each field trip the calibration coefficient obtained between the Maysmeter's measurements on the 20 control sections and those of the Profilometer is used to convert the raw data to a roughness index (QI*) scaled by the Profilometer's Quarter Car Simulator (3). A mean QI* value is then computed for each route. (4)

For unpaved roads in particular, roughness at any point on the road may vary considerably during the period of the survey. A replication measurement program is underway for selected unpaved and paved roads to determine the magnitude of this variation across the whole route. Preliminary analysis indicates that although individual points on the road vary due to bladings and the season, the overall effect on the mean roughness of the route is small and unlikely to affect the estimation of the roughness coefficients.

Geometry. It was hypothesized that the relationship between speed and geometry could be used to quantify, at any point out on the road, the effect of grades and curves on operating costs. For example, the effect of a steep positive grade on a vehicle could be greatly reduced by the momentum gained from an immediately preceeding negative grade. Also, that the effect of horizontal alignment was conditioned to a large extent by the vertical profile. For example, the slowing effect of a small radius curve on a level road is much greater than the same ifies the utilization prediction equations derived from preliminary analyses. The exponential model predicts for five vehicle classes - cars, light, medium and heavy trucks, and buses. 158 company/cell means are from a sample of 939 vehicles.

Model:

$$KMES=e^{9.0873-0.5801H+C1\ 0.3532+C4\ 0.2333-IRR.V\ 0.0004-AG\ 0.0558+V.DPM\ 0.0098} \quad (3)$$

Where:

KMES = Average monthly utilization in kilometers
H = Horizontal geometry index
IRR = Roughness, QI*
V = Vertical geometry index
C1 = 1 if cars, 0 if other vehicles
C4 = 1 if medium trucks, 0 if other vehicles
AG = Mean age per company/cell minus mean age per cell
DPM = Mean days operational per month per company/cell minus mean days operational per cell

In the equation the effect of roughness can be examined for medium trucks by setting V equal to 8 and H equal to 0.15. For these combinations of V and H the mean days operational per month on paved routes with roughness 39 QI* was 13.3 and on unpaved routes with roughness 140 QI* the value was 18.2. The mean ages were 7.0 and 6.6 for the paved and unpaved routes respectively. Therefore, if these sample means for age and days operational are entered into the utilization equation the AG and DPM terms equal zero and the model becomes a function of the roughness, horizontal and vertical indices. On the paved route the predicted annual utilization is 108,000 km for 7 year old vehicles operating 13.3 days per month. For the unpaved route annual utilization is 77580 km for 6.6 year old vehicles operating 18.2 days per month. On paved routes, utilization is about 39% higher, even though vehicles are operated 5 days per month less.

It is possible however to estimate the roughness influence if 6.6 year old vehicles on paved routes are allowed to operate 18.2 days per month, i.e. as for unpaved routes. In this case, the predicted annual utilization is 162000 km or 109% higher. It is therefore suggested that the sample mean vehicle characteristics be used when applying all equations, since entering other values may lead to extrapolation beyond acceptable limits.

Other Results

Table 1 gives the regression equations for fuel consumption of cars, buses and medium and heavy trucks, parts costs and labor hours for buses, and tyres for buses.

Discussion of Preliminary Results

In the equations produced so far, road roughness is the most important influence. In the case of fuel for medium and heavy trucks, the influence of a steep vertical profile is substantial, increasing consumption by about 40% on paved roads and 33% on unpaved roads. For car fuel, high horizontal curvature increases consumption by about 9% on paved roads but the effect is reduced to 3% on the average unpaved road. No vertical influence was detected, probably because the range of V is narrower than for other vehicle classes. However even if such powerful effects of road geometry on fuel consumption are confirmed in further analyses, roughness will continue to be the dominant influence when considering total vehicle operating costs, especially economic costs. (i.e. less taxes and transfer payments). This is because fuel is a relatively minor item in terms of total operating costs. Table 2 shows economic cost differences for the typical 4 year old bus in rolling terrain (V=6.0, H=0.15) for a paved (38 QI*) road and an unpaved (137 QI*) road. March 1979 prices are used, when 1 dollar = Cr$ 23,00. The interest rate used is 10%. Table 3 gives supporting information. Fuel costs increase by 6% for the unpaved road, but other costs increase by 60%. For the paved road, vehicle maintenance plus depreciation cost almost twice as much as fuel, and for the unpaved road, three times as much.

Summary and Conclusions

Useful results have been derived from preliminary analyses, however final analysis of the complete data sets will continue for some time. The effects of geometric parameters on operating costs will be examined in more detail, and attention will also be given to vehicle characteristics, for example engine size, since it is apparent that to some extent vehicle operators choose or adapt vehicle specifications according to road surface type or geometric characteristics. For this reason, comparisons of different roads using the same vehicle are unwise. Analysis of diesel buses so far shows that road roughness has the strongest influence on total operating costs, but only a small influence on fuel consumption.

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Table 1. Preliminary regression equations

Car Fuel (gasoline) 98 vehicles

COMB=85.34+.078IRR+46.53H-.201IRR*H+.0316ENGP.................................(4)

Medium and Heavy Truck Fuel (diesel) 120 vehicles, 31 means

COMB=78.35+.909IRR+33.805V-.0879IRR*V+9.206PB1+.0001527IRR*ENG1................(5)

Bus Fuel (diesel) 582 vehicles, 66 means

COMB=289.9+.165IRR-.0062ENG1+3.63AGE1..(6)

Bus Parts (Cr$) 513 vehicles, 61 means

PSM=30.23+2.568IRR-.0039KM1...(7)

Bus Workshop Labor Hours 603 vehicles, 17 companies

HORAS=7.38 .087IRR..(8)

Bus Tires 3253 tires, 12 companies

ENT=51.117-.197IRR+11.712RC1..(9)

Where:

COMB = Fuel in liters per 1000 km
PSM = Parts costs in Cr$ of January 1976, when 1 dollar = Cr$ 10,00
HORAS = Workshop man-hours per 1000 km
ENT = New cross ply tire life in 000's km
IRR = Roughness QI*
H = Horizontal Index
V = Vertical Index
ENGP = Adjusted engine size (cc) covariate, (cars)
ENG1 = Engine size (cc) covariate, (trucks and buses)
PB1 = Gross vehicle weight (tonnes) covariate, (trucks)
AGE1 = Age (years) covariate, (buses)
KM1 = Utilization (000's km/month) covariate, (buses)
RC1 = Recapping (No. recaps per new tire) covariate, (bus tires)

Table 2. Economic costs per 1000 km-4 year old bus

Item	Paved Road Cr$	Paved Road %	Unpaved Road Cr$	Unpaved Road %
Fuel	888	22.3	939	15.9
Tires	528	13.3	956	16.2
Parts	307	7.7	917	15.6
Workshop Labor	384	9.6	695	11.8
Driver	923	23.1	1171	19.9
Depreciation and Interest	953	23.9	1209	20.5
Total	3983	100	5889	100

Table 3. Bus costs - supporting data

Item	Paved	Unpaved	Financial Cost	Taxes
Fuel	296 lt/1000 km	313 lt/1000 km	Cr$ 4,80/liter	60%
Tires	43614 km	24111 km	Cr$ 4800(x 6 tires)	25%
Parts	Cr$ 384/1000 km	Cr$ 1146/1000 km	March 1979 prices	25%
Workshop Labor	10.67 hs/1000 km	19.30 hs/1000 km	Cr$ 40,00/hour	10%
Deprecia-tion	Cr$ 5917/month	Cr$ 5917/month	Cr$ 89000 in 4th year	25%
Interest	Cr$ 3000	Cr$ 3000	Cr$ 45000 in 4th year	25%
Driver	Cr$ 8640	Cr$ 8640	Cr$ 9500/month	10%
Km/month	9356	7377	-	-