

for what is supposedly the "best" transportation solution.

7. The model does provide some indication as to what might be the optimal output of a region given the efficient allocation of resources.

CONCLUSIONS

The linear programming technique can be used to provide a quick and reasonably accurate solution to the possible net dollar effect of transportation investment in regions that have poor accessibility. In situations where the number of requests for improved transportation far

exceeds the allowable transportation budget, the techniques can be used, in combination with other "goal-oriented" techniques, to establish a financially feasible list of projects.

Transportation investments in inaccessible regions that would normally be considered infeasible based only on quantifiable benefits attributable to traffic volumes can be assessed by the model for their true effects on a region.

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Relating Vehicle Use to Highway Characteristics: Evidence from Brazil

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Data derived from a large-scale user-cost survey currently being conducted in Brazil are presented and analyzed. Equations for six vehicle classes that are used to predict rates of vehicle use (defined as kilometers traveled per month) as a function of highway characteristics are presented. The highway characteristics studied are surface roughness and three measures of vertical geometry. These data were collected by two specially instrumented vehicles that measured a network of 597 routes totaling 38 000 km. Vehicle-use data representing 1220 vehicles were used as the main analysis set; the set comprised 265 cars, 57 utility vehicles, 655 buses, and 243 trucks. A further 261 heavy vehicles were used to derive predictions for this class after the main analyses had been conducted. Equations derived from the analyses were tested against a further set of 145 vehicles. Reference to previous studies is made, and an example that shows the derivation of differential depreciation costs per kilometer is included. Preliminary results on the effect of vehicle age are given, and details of further work are specified.

Vehicle use is an important component in the economic evaluation of highway construction and maintenance policies. It permits vehicle operating costs to be calculated on a lifetime, annual, or kilometer basis as well as directly influencing time-related benefits such as depreciation, interest, crew costs, and the value of passenger time. Therefore, total user-cost differentials attributable to alternative construction and maintenance policies are significantly influenced by decisions made about the appropriate levels of vehicle use. There has not been extensive primary research into levels of vehicle use, despite their importance, and estimates of use normally involve assumptions that are difficult to substantiate.

The earliest-reported information on the effects of road surface type on vehicle operating cost and use was developed at Iowa State University in 1939 by Moyer and Winfrey (1) based on a survey of vehicles used as rural mail carriers. Moyer and Winfrey showed that the use of a vehicle decreased with age and that annual vehicle mileage increased substantially as a higher percentage of vehicle operation switched to paved or gravel roads from earth roads.

The results of a survey carried out in Africa by Bonney and Stevens (2) provided additional information on differential rates of vehicle use for vehicles operating on different types of surfaces. The results were

based on 65 passenger and freight vehicles operating over 27 routes of different types over a period of two years. Routes were grouped into three major types: bituminous, improved gravel, and unimproved gravel. The results clearly show differential rates of use among the three types of routes, which enabled Bonney and Stevens to derive depreciation costs per kilometer for each surface category.

Predictions of vehicle operating costs were published in 1975 as a result of the Transport and Road Research Laboratory (TRRL) study in Kenya (3) but, although the calculation of depreciation required annual vehicle use as an input, it was derived exogenously and not predicted from user data (3, p. 62). The results of the Kenya user survey were subsequently modeled (4), and vehicle use was derived from the product of vehicle speed and estimates of hours driven. This approach is widely used—for example, in the World Bank's Highway Design and Maintenance (HDM) model (6)—and justifies careful examination.

Highway characteristics are generally considered to affect vehicle use through changes in speed. Variations in surface condition (such as roughness) or geometric design (such as vertical profile) alter the speed at which a vehicle can be driven, and estimates of use can be derived by multiplying average speed by hours driven. Although average speed can be accurately determined from the data available on this subject, the analyst is forced to make assumptions about hours driven. Sometimes the average number of hours driven per vehicle is considered a constant, so clearly use varies proportionately with speed. However, although an increase in vehicle speed should generally lead to a greater number of trips being undertaken, nondriving time will also increase so that the effect on use is probably less than proportional. The analyst must make judgments about what is appropriate based on very few data. The broad choices that are available are described in the user's manual to the World Bank's HDM model (6).

The difficulties inherent in estimating hours driven are highlighted by remembering that the commercial vehicle operators who constitute the majority of users on highways in developing countries should be viewed

as rational, profit-seeking individuals. They will try to minimize their costs with respect to changes in highway characteristics. Some of the factors that influence their cost structure are cargo value, customer requirements, crew costs, and route length. A deterioration in surface condition that results in a reduction in vehicle speed might well, in certain cases, be fully compensated for by users proportionally increasing their hours driven to maintain constant use. The situation is clearly rather complex. Since reliable data on hours driven are sparse and relations between hours driven and highway characteristics are entirely absent from the literature, hours driven should be used with care.

However, if data on vehicle use are collected directly from road users and then related to highway characteristics, problems over hours driven are avoided. The product of speed times hours driven appears on the vehicle odometer, which provides the data record, and rational decisions made by operators with respect to changes in highway characteristics are subsumed. Vehicle use can be simply determined without making any assumptions about hours driven. It was decided to test this approach in Brazil. Since no literature exists that directly links vehicle use with highway characteristics, this constituted a first attempt at estimating vehicle use in this manner.

BACKGROUND OF THE PROJECT

The government of Brazil and the United Nations Development Program are currently sponsoring a major research project to determine the interrelationships in Brazil between the costs of highway construction, maintenance, and use. The Brazilian Ministry of Transport provides management to the project through a related organization, the Empresa Brasileira de Planejamento de Transportes (GEIPOT). Technical assistance is provided by the staff of the Texas Research and Development Foundation. The World Bank acts as the executing agency for the United Nations Development Program, and the research is based at the headquarters of GEIPOT in Brasilia. The research began in September 1975, the first phase terminated in November 1979, and work is continuing in 1980.

The central objective of this project is to assist the government of Brazil in minimizing the total cost of its highway network by making possible thorough and rapid evaluations of alternative highway strategies. This requires that individual relations for the three components of construction, maintenance, and user cost first be developed and then be combined in a computer model. The relations between user costs and highway characteristics are important because benefits attributable to improvements are largely composed of reductions in user costs.

User costs were related to highway characteristics through a series of experiments and surveys. In the surveys, vehicle operators' cost records were examined. These surveys were particularly important because the majority of user-cost components could not be experimentally determined from the available resources. Vehicle use, defined as kilometers traveled per month, was included in the surveys to provide an input to the calculation of vehicle depreciation and interest. This paper briefly describes the data-collection techniques used, presents predictions of use for five vehicle classes (specifying vehicle use as a function of pavement roughness and various highway geometry measures), and discusses the implications of these results.

COLLECTION OF DATA ON VEHICLE USE AND ROUTE CHARACTERISTICS

The wide range of procedures and skills necessary for the efficient collection and analysis of data on vehicle operating cost from company records required the formation of a specific team, the User Costs Surveys Group, within the structure of the Brazil study. The broad objectives given to this team required data on operating cost to be associated with quantifiable road characteristics so that cost differentials, attributable to changes in highway characteristics, could be determined. Data on vehicle operating cost collected by the group were first assigned to routes. Then, before analysis could be undertaken, the characteristics of these routes had to be determined. Route data were collected by using two specially designed survey vehicles instrumented and serviced by project staff.

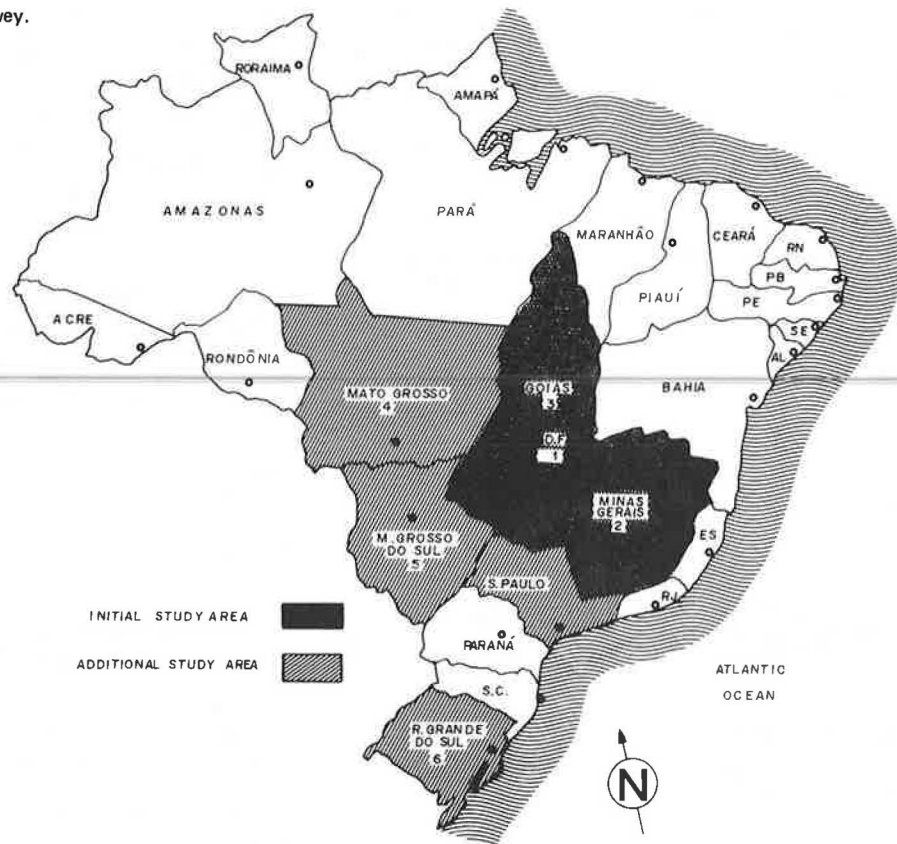
Collection of data on vehicle operating cost was initially concentrated in the states of Minas Gerais and Goiás and in the Distrito Federal (see Figure 1). The major proportion of the vehicles recruited for the survey derived from these regions, but it became necessary to supplement these vehicles with others operating in states with different geographic features to ensure that the greatest possible range of highway characteristics was covered for analysis. Accordingly, vehicle data were collected in Mato Grosso, Rio Grande do Sul, and São Paulo. The survey vehicles collected 85 000 km of geometry and roughness data to produce highway characteristics for the network of routes used by the vehicles in the survey.

Data on operating cost were collected by the field research staff, who made regular, usually monthly, visits to each participating company. The data were subject to various edits and checks before being stored on computer file. Vehicle use was defined and recorded as the average number of kilometers traveled by a vehicle per month and was based on an average data period of 16 months for vehicles in the main survey. This period was considered perfectly adequate, particularly as it covers all the seasonal changes that might be expected to influence vehicle use. Fuel consumption per kilometer was used as a check on the recorded data on vehicle use.

Data were collected on more than 1500 vehicles that represented more than 100 companies and a wide range of vehicle makes and models. The individual vehicles were grouped into five classes: commercial automobiles, utility vehicles, buses, medium trucks, and heavy trucks. Details of these classes are shown in Figure 2. It will be noted that utility vehicles is a very broadly defined class that incorporates different vehicle types. This class was studied because dual-purpose vehicles (such as pickups) and light trucks form a significant traffic group on low-volume roads. Despite the problems that such amalgamation causes, it was considered worthwhile to attempt to estimate the patterns of use for such vehicles. Very few private automobiles were registered in the survey, and few reliable data were available for analysis. Although commercial automobiles achieved levels of use that were considered inappropriately high for private automobiles, it was decided to analyze this class to see if any useful data could be obtained that could subsequently be used for modeling private-automobile use. The main survey data were supplemented by a special study on the use of heavy trucks to ensure that this class was not under-represented.

Two specially instrumented cars were fabricated by the project staff to rapidly measure the characteristics of operators' routes identified in the main survey. The

Figure 1. Study area for user-costs survey.



survey-vehicle instruments are shown in Figure 3. The road-roughness-measuring system consisted of a Mays road meter and an accurate odometer, the distance-measuring instrument (DMI) (7). These instruments combined to form the "Maysmeter" system, which, when in operation, produced a count every 320 m. The system was maintained in strict calibration with an established roughness base, here provided by the GM Profilometer and its Quarter Car Simulator (8). Each vehicle was regularly checked by correlating the output of the Maysmeter system with roughness numbers produced by the Quarter Car Simulator on profiles recorded by the Profilometer as the vehicle traveled over a special calibration course. This correlation produced roughness values in units referred to here as QI^* counts per kilometer. QI^* is the unit of roughness analyzed in this paper.

To rapidly measure the vertical profile of a route, it was necessary to develop a device that could identify grade changes from a moving vehicle. Several instruments were evaluated, and an electronic accelerometer connected to a panel meter and designed to display grade measurements up to ± 12 percent was finally selected. Horizontal measurements were obtained by using a standard aircraft-type directional gyro compass (7) and the DMI. The start and finish of the curve were identified by the driver, and the operator noted its direction and length.

All vehicle-use and route data were screened before analysis; 1220 vehicles comprising 265 cars, 57 utility vehicles, 655 buses, and 243 medium trucks were used as the main analysis set. A further set of 145 vehicles was reserved as a verification set to test the equations derived from the main analyses. Heavy vehicles (40-t gross vehicle weight) were poorly represented in the main file, and no data were available

for analysis. A supplementary study was undertaken to collect more data for this important vehicle class.

DEPENDENT AND INDEPENDENT VARIABLES

The factorial shown in Figure 4, which was used to direct and manage the data-collection effort, shows the dispersion of vehicles used in this analysis. The generic classifications defining each of the cells were quantified at the start of the analysis in terms of the geometry and roughness measures selected as the independent variables. All subsequent references to "cell" refer to the factorial partitions shown in Figure 4 (figures in parentheses show the number of company means per vehicle class).

The data-collection procedures located companies that operated in the various cells of the factorial, in an effort to ensure a good spread of data. Each company was evaluated and, where appropriate, vehicles were selected for inclusion in the survey for a period sufficient to establish estimates of the various user costs. Dependent data can therefore be considered at either the company or the vehicle level. The companies can be seen as constituting the sampling units, that is, the units from which inferences can be drawn, whereas the vehicles are the observation units used to obtain the actual vehicle operating information. These definitions are significant because probability statements, in the form of confidence intervals for predictions, must be based on the unit on which the inferences are drawn—the company. As noted before, the dependent variable, vehicle use, was defined as the average kilometers traveled per month during the survey period.




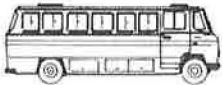



The extensive inventory of user routes permitted a series of geometric indices to be examined for their

explanatory power with respect to vehicle use. Indices were constructed for both vertical and horizontal geometry, and an attempt was made to correlate both with the dependent variable. However, because of multicollinearity, it was not possible to perform an analysis that used both types of measures. This is not really

surprising when one considers that terrain requirements often force a degree of correlation between vertical profile and horizontal alignment on the highway planner; Flat roads are often straight, whereas mountainous roads tend to have many curves. The preliminary analysis, therefore, concentrated on measures of vertical geometry, since this was known to exert a greater influence on speed and hence on use.

Figure 2. Vehicle classes used in main survey.

Three measures of vertical geometry are reported in this paper:

TYPE	CLASS	REPRESENTATIVE VEHICLE CHARACTERISTICS
CAR 	1	GROSS WEIGHT - 1 T 46 BHP (DIN) GASOLINE 4 CYLINDER
UTILITIES 	2	GROSS WEIGHT - 2.7- 3.3 T LOAD 1.2 - 2.2 T 133 BHP (DIN) GASOLINE 4 CYLINDER
UTILITIES 	2	GROSS WEIGHT - 6 T LOAD - 4 T 98 BHP (DIN) DIESEL 4 CYLINDER
UTILITIES 	2	GROSS WEIGHT - 6 T LOAD - 2 T 98 BHP (DIN) DIESEL 4 CYLINDER
BUS 	3	GROSS WEIGHT - 11 T LOAD - 4 T 130 BHP (DIN) DIESEL 6 CYLINDER
MEDIUM TRUCK 	4	GROSS WEIGHT - 15 T LOAD 8 - 10 T WITH THIRD AXLE, GROSS WEIGHT - 22 T LOAD 13 - 15 T 130 BHP (DIN) - DIESEL 6 CYLINDER
HEAVY TRUCK 	5	GROSS WEIGHT - 40 T LOAD 24 - 28 T 275 BHP (DIN) DIESEL TURBOCHARGED 6 CYLINDER

1. Rise plus fall (RPF), in meters per kilometer, has been used in a previous study (3) as an independent variable to explain variations in fuel consumption, vehicle speed, and so on. The following approximate formula can be used to calculate this index:

$$RPF = \sum_{i=1}^n |g_i| l_i / 100 * \sum_{i=1}^n l_i \quad (1)$$

where

- g_i = i th grade value ($i = 1, \dots, n$) (%)
- l_i = length of i th grade (km), and
- $|\cdot|$ = absolute value.

Intuitively, this index can be understood to substitute for the real vertical profile of an equivalent roadway that has a mean percentage grade of (RPF/10).

2. One can use a percentage measure of mean grade (MG) derived from a grade distribution, as follows:

$$MG = (C_1 + 3.6C_2 + 5.6C_3 + 7.6C_4) / 100 \quad (2)$$

where

- C_1 = percentage of route length whose grade is from -3 to +3 percent,
- C_2 = percentage of route length whose grade is between -3 to -5 percent and +3 to +5 percent,
- C_3 = percentage of route length whose grade is between -5 to -7 percent and +5 to +7 percent, and
- C_4 = percentage of route length whose grade is from ≥ -7 to $\geq +7$ percent.

Figure 3. Specially instrumented survey vehicle.

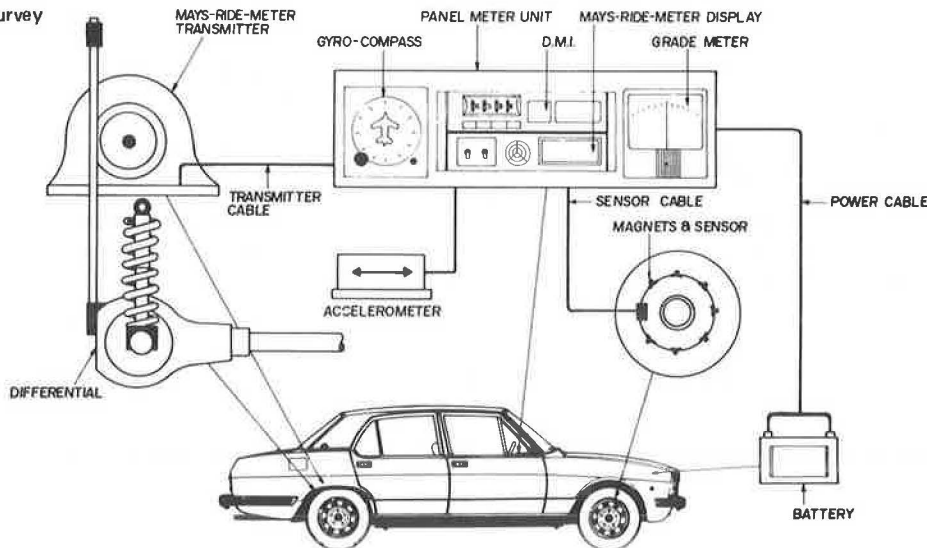


Figure 4. Factorial of distribution of vehicle classes by road-geometry and roughness measures.

VERTICAL SURFACE TYPE		HORIZONTAL		FLAT		ROLLING		HILLY	
		1	2						
PAVED	1	Cars 1 (1) Utilities 10 (1) Buses 58 (4) Trucks 2 (1)		Cars 82 (3) Utilities 13 (4) Buses 160 (13) Trucks 92 (9)		Cars 6 (2) Utilities 3 (2) Buses 28 (2) Truck 1 (1)			
	2	Cars 3 (3) Buses 13 (2)		Cars 68 (4) Utilities 1 (1) Buses 22 (6) Trucks 3 (1)		Cars 35 (2) Trucks 20 (4)			
MIXED	1	Buses 4 (1) Trucks 2 (1)		Cars 10 (2) Utilities 2 (1) Buses 47 (10) Trucks 47 (3)		Car 1 (1) Utilities 1 (1) Buses 2 (1)			
	2	Car 4 (1)		Cars 21 (2) Buses 4 (2) Trucks 10 (6)		Cars 19 (2) Buses 3 (2) Trucks 3 (2)			
UNPAVED	1	Utilities 1 (1) Buses 96 (7)		Cars 6 (2) Utilities 6 (1) Buses 150 (9) Trucks 4 (2)		Utilities 1 (1) Buses 4 (2) Trucks 38 (24)			
	2	Buses 8 (1)		Cars 7 (2) Utilities 6 (6) Buses 38 (9)		Cars 2 (2) Utilities 13 (11) Buses 18 (7) Trucks 21 (3)			

HORIZONTAL 1 = STRAIGHT, 2 = CURVY

The constants in Equation 2 represent midpoints of the distribution of grades.

3. A measure of extreme geometry (EG), derived from a grade distribution, can be used. This index, in percent, is defined as

$$EG = G_1 + G_2 \tag{3}$$

where G_1 = percentage of route length whose grade is ≥ -5 percent and G_2 = percentage of route length whose grade is $\geq +5$ percent.

The roughness measure QI^* , used to characterize the quality of the riding surface, was derived from data collected in 320-m intervals by the survey vehicles. To describe the roughness of a route as determined by these measurements, a summary statistic was necessary. The following procedure was used:

1. The roughness measurements were sequentially examined and grouped into homogeneous bands in accordance with acceptable variance levels established through tests on both paved and unpaved sections.
2. An average roughness for the route was calculated as the weighted average of the means of the homogeneous bands, by using the band lengths as weight.

To better characterize the various geometry measures, the table below gives the ranges of each measurement found for the general classifications of flat,

rolling, and hilly terrain on the routes surveyed by project vehicles:

Measure	Flat Terrain	Rolling Terrain	Hilly Terrain
RPF (m/km)	5-24	14-37	29-52
MG (%)	1-2	1.5-3	2.3-4.5
EG (%)	0-10	3-30	10-54

For the same routes, the roughness measure QI^* produced the following values for various surface types:

Surface Type	QI^* (counts/km)		
	Mean	Minimum	Maximum
Paved	43	21	159
Mixed	84	25	157
Unpaved	145	41	265

Several statistics for the geometry and roughness data used in the analysis that assist in defining the inference space are given below:

Variable	Mean	Standard Deviation	Minimum	Maximum
R	90.92	56.92	22.00	203.00
RPF	30.39	7.08	8.00	48.00
MG	2.47	0.57	1.00	3.87
EG	18.81	10.94	0.00	43.52

Table 1. Regression equations for vehicle use as a function of highway characteristics.

Geometry-Measure Variable	Intercept	C ₂	C ₃₄	C ₅	Geometry Measure	Q	QXC ₁₅	A	S ²	R ²
RPF	9.729 (0.12)	-0.314 (0.11)	-0.251 (0.09)	-0.213 (0.13)	-0.001 93 (0.003)	-0.007 52 (0.003)	0.004 85 (0.001 4)	-0.0594 (0.0094)	0.480	0.52
MG	9.757 (0.12)	-0.316 (0.11)	-0.252 (0.09)	-0.164 (0.13)	-0.056 7 (0.037)	-0.007 55 (0.001 3)	0.004 84 (0.001 3)	-0.0594 (0.0094)	0.478	0.52
EG	9.721 (0.09)	-0.325 (0.11)	-0.261 (0.09)	-0.120 (0.13)	-0.004 39 (0.002 0)	-0.007 51 (0.001 3)	0.004 84 (0.001 4)	-0.0591 (0.0093)	0.470	0.53

Note: All regressions are based on 194 means. Figures in parentheses are the standard errors of the coefficients. Base vehicle class is that of commercial automobiles (i.e., C₂ = C₃₄ = C₅ = C₃₄₅ = 0). The weight used is the number of vehicles observed in the highway-characteristic/company cell combination.

These statistics are very important in determining the robustness and wide applicability of the relations presented.

ANALYSIS AND RESULTS

An analysis of variance performed on the analysis set showed that the variance of vehicle use between companies in a cell was significantly larger (approximately seven times) than that between vehicles in a company. This is probably attributable to unmeasured effects of company policy, such as the choice of vehicle, and thus to the company's performance characteristics, customer needs, and managerial efficiency. In view of the previous comments on sampling and observation units, one would expect greater homogeneity between vehicles in the same company (sampling unit) than between different companies within a cell. The broad choices for analysis narrowed down to individual vehicles or companies; both were evaluated, and the latter are reported in this paper. It was decided to aggregate company vehicles in each cell to produce a company-cell mean for each company in each cell. Company-cell means were preferred because they enabled the analyst to comprehend more of the statistical influences, especially those related to policy effects. Furthermore, at the company-cell level, the ranges of independent variables were broader because the survey methodology placed great importance on selecting vehicles that operated on homogeneous route types (hence, relatively narrow ranges).

All of the vehicle data for each company in each cell were aggregated, and means were derived for both dependent and independent variables. If a company had vehicles operating in more than one cell, means for each cell were calculated by using the company vehicles operating in the cell. The 1220 individual vehicles in the analysis set resulted in 194 company-cell means.

By using the data for commercial automobiles, utility vehicles, buses, and medium trucks, the effect of surface condition (roughness) and vertical geometry on vehicle use was estimated by means of weighted least squares, the weight being the number of vehicles within each company-cell mean. The regression analyses resulted in the formulas given in Table 1, where

- C₂ = 1 if utilities, 0 otherwise;
- C₃₄ = 1 if buses or medium trucks, 0 otherwise;
- C₅ = 1 if heavy trucks, 0 otherwise;
- C₃₄₅ = 1 if buses or medium or heavy trucks, 0 otherwise;
- Q = road roughness (QI* counts/km);
- A = vehicle age (years);
- R² = coefficient of multiple determination; and
- S_e² = standard error of the equation.

The log-linear form of the model is reported because

the hypothesis of homogeneity of variance across factorial cells is rejected at the $\alpha = 0.001$ level and so some form of transformation—such as log linear—is desirable.

The heavy-vehicle supplementary study yielded data on 261 vehicles, which constitute 15 company-cell means. Heavy vehicles rarely operate regularly on unpaved routes, and the narrow range of roughness associated with the observations caused difficulties in the main analysis. These vehicles were therefore excluded from the analysis set and reintroduced in the final stages of the analysis to provide a usage estimate. This was done by calculating the mean use for paved, rolling highways and adjusting the intercept of the equation by assuming that the effect of highway characteristics on heavy-truck use is the same as that predicted for medium trucks.

The adjusted equation for heavy trucks gives good predictions for paved roads (<50 QI*), but extrapolation to levels of roughness for mixed and unpaved highways should be done with caution. It is likely that, if heavy trucks were used regularly on unpaved routes, they would show levels of use similar to those of medium trucks and not as high as those predicted. It is recommended, therefore, that the heavy-truck equation not be used where highway roughness exceeds 50 QI* and that, where predictions of use on unpaved routes are required, the medium-truck equation be used.

The equations in Table 1 show roughness as a significant main effect. This paper is the first in the literature to demonstrate such a link between vehicle use and road-surface condition (roughness). Use of a vehicle such as a medium truck decreases by 30 percent if it operates in Brazil on an average unpaved route in comparison with an average paved route, if the geometry characteristics remain constant. Further comments are made later in this paper about roughness effects and their influence on depreciation and interest.

It can also be seen from the results that all of the derived equations are weak for the geometry measures. Not only are the coefficients small but also they are not significant at the 90 percent level. This is contrary to expectations and apparently in conflict with the mass of experimental data on vehicle speed, which clearly demonstrates that vehicle speed is strongly influenced by vertical geometry. Vehicle speed is related to use through hours driven, and thus vertical geometry would be expected to be a main effect in any prediction of use from highway characteristics.

The answer may come from further analyses. A larger data set is being assembled, and further analyses will be conducted when it is complete. It should be stated, however, that many different forms of analysis have already been tried and that none have produced large, well-determined coefficients for the geometry measures.

A potential reason for this phenomenon lies in economic theory. The companies that furnished data can be regarded as rational profit seekers. They must

cover all costs and achieve some rate of return to remain in business. The fact that speed is influenced by vertical geometry is a physical relation, not an economic one. Vehicle use, however, is an economic response (rates exceeding all costs), not a physical one. So there, perhaps, we have it. We know that surface condition affects practically all user-cost items (9), whereas vertical geometry affects essentially only fuel and time-related costs. Therefore, a very rough route results in very high user costs, very high rates charged, and a reduced demand for transportation. A very hilly route does not result in such higher costs, the rates charged are not so high, and more demand (use) results. A further point is that a user route, as opposed to a particular road section, has compensating features. Even in very hilly terrain, vehicles go down as well as up, thus reducing the effect of vertical geometry on average vehicle trip speed.

It may be, therefore, that vertical geometry has a very small effect on vehicle use (and thus time-related costs such as depreciation and interest), and this itself could be even more important than the relation between vehicle use and roughness.

So it is possible to defend a small vertical-geometry effect, but why is it not well determined? This may be due to an overestimation of the model's pure residual error in hypothesis testing. The data set is not an experimental one and therefore not truly randomly derived, so it is possible that the residual error has two components: (a) a constant (or constants) attributable to fixed but unmeasured effects and (b) the true pure-error term. The constants may, for example, be present because of company policies. Such constants are present in many large surveys. [Income studies are good examples of this: Constants for rich and poor members of the community make hypothesis testing questionable, low R^2 values abound (often less than 0.20), yet predictions remain surprisingly good.] They will recur in any new population and will not affect the accuracy of the prediction. Therefore, if they can be removed from the residual error of the model, hypothesis testing can be done by using the valid pure-error term. Since this component must by definition be smaller than the residual error currently used, geometry might become more significant. In these circumstances, it seems preferable to report the geometry effect in the equations so that a user can make up his or her mind as to their inclusion in any prediction. It is thought that geometry should have some effect on levels of vehicle use, although perhaps a much smaller effect than previously believed, and there are not yet sufficient grounds for fully rejecting the coefficients reported in the equations. Future work will include an attempt to estimate this fixed component, which is believed to be part of the current model's residual error. Mention was made earlier that it might be preferable to use individual vehicles, rather than company-cell means, in regression analyses. Aggregation is to be regarded with suspicion because one risks losing statistical efficiency and masking (perhaps deliberately) certain effects. A series of regressions were therefore run in which only individual-vehicle values were used. The results were interesting because they confirmed the earlier analysis of variance results of the between-company and within-company effects. The equation coefficients are very similar to those reported in this paper. There is clearly nothing to be gained from pursuing this approach in preference to company-cell means. The latter approach does not mask any important effects that are revealed by analyzing individual vehicles and

indicates more about the statistical influences at work in the data set.

Since it was known from the work of Moyer and Winfrey (1) that vehicle age could have a significant effect, the analyses performed included the influence of age. Some of the results are given below (from the RFP formula in Table 1):

Age of Vehicle (years)	Use (percentage of use of vehicle when new)
1	94
2	89
3	84
4	79
5	74
6	70
7	66
8	62
9	58
10	55

The table indicates that a 10-year-old Brazilian truck exhibits a 55 percent reduction in use from the level of use when it was new. Vehicle use with respect to age tends to be "stepped" in actual vehicle operation, as shown by Edwards and Bayliss (10), and this is confirmed in Brazil. The preliminary analyses on the age effect have smoothed out this feature to give an annual change of use of approximately 6 percent. The purpose of this paper, however, was to determine the relation between vehicle use and highway characteristics, so age is not a central theme. Nevertheless, it is gratifying to see that the age effect confirms prior reasoning and that its coefficient was significant. Clearly, more work is warranted in this important area of vehicle characteristics and use.

VERIFICATION OF RESULTS

An effective way of verifying the robustness and strength of a model is to test it by using data that are not used to derive the regression coefficients. The equation can be tested by comparing the original coefficients with coefficients estimated from the supplementary data set.

This has been done for the RPF formula in Table 1 by using 145 of the 200 vehicles excluded from the original data set because of lack of route characteristics, which were subsequently obtained. These 145 vehicles resulted in 39 means derived from highway-characteristic and company cells (Figure 4), distributed as follows:

1. Commercial automobile—7 means;
2. Utility vehicle—3 means;
3. Bus—23 means; and
4. Medium truck—6 means.

No heavy trucks were available.

An F-test was performed to test the hypothesis that

$$H_0 : b_{\text{new}} = b_{\text{old}} \quad (4)$$

where b_{new} and b_{old} are the vectors of coefficients of the regressions on the new data set and the original one, respectively. The appropriate F-value is

$$F_{P, J-P} = [(b_{\text{new}} - b_{\text{old}})^T X^T W X (b_{\text{new}} - b_{\text{old}}) / P] \div [SSE_{\text{new}} / (J - P)] \quad (5)$$

where

P = number of coefficient estimates = 7,
 J = number of means in the new data set = 39,
 X = matrix of independent variables in the new data set,
 X^T = transpose of X ,
 W = matrix of weights from the new data set, and
 SSE_{new} = error sum of squares for the regression on the new data set.

The calculated $F_{7,32}$ value was 0.58, which is less than the tabled value at $\alpha = 0.25$, so we accept the hypothesis that the coefficient estimates from the supplementary data set are not significantly different from the original values and thus verify the applicability of the latter to the new data.

SUMMARY OF RESULTS

The preliminary results of work currently being carried out in Brazil on vehicle use are extremely interesting to the transportation economist and the highway planner. Previously, estimates of vehicle use were most popularly derived from the product of speed predictions and hours driven, the latter both being sensitive and lacking any empirical base for estimation. The approach reported in this paper attempts to predict vehicle use directly from highway characteristics and is both simpler and potentially more accurate than previous approaches. Difficult issues, such as hours driven, are subsumed within usage data taken directly from operators' records. These individuals, who are rational decision makers in the sense of wishing to remain in business, can be regarded as being in long-term cost equilibrium with their highway characteristics. Vehicle use is an economic response, and direct observation—through collection of cost records on operators' economic behavior (vehicle use) with respect to highway characteristics—clearly has merit.

Preliminary equations reported in this paper show promise. A clear relation between vehicle use and roughness (surface condition) is demonstrated and, more controversially, a small vertical-geometry effect is reported. These equations have considerable importance in the widely used procedure for calculating depreciation and interest, a method that regards vehicle value and its change over time as a constant with respect to highway characteristics. Differential rates for depreciation, and hence interest, per kilometer are then determined by the different levels of use with respect to highway characteristics:

Measure	Paved Road	Unpaved Road
Roughness (QI*/km)	43	145
Vertical geometry (RPF)	30	30
Life (years)	10	10
Depreciable value (\$)	20 000	20 000
Lifetime use (km)	976 850	676 630
Depreciation cost (\$/1000 km)	20.47	29.56

In the table above, it can be seen that the depreciable value of the vehicle is constant at \$20 000, irrespective of the road type. The information is based on a truck with a gross vehicle weight of 15 t that operates all its life on routes characterized by the mean roughness values of the paved and unpaved roads in the Brazil study. A differential rate of 1.44 between unpaved and paved is predicted; this makes it possible to calculate a differential rate of depreciation per kilometer. In-

terest is not included, but it would be similarly influenced by use.

In addition, it is useful to make some comparisons with previous studies. Unfortunately, this has to be tentative since no other work has attempted to quantify vehicle use from highway characteristics. Nevertheless, it seems worthwhile to try and make some comparisons. The following table compares the percentage decreases in use of a medium truck on various road surfaces:

Source	Differential Rate of Decrease in Use	
	Paved Versus Improved Gravel	Paved Versus Unimproved Gravel
Brazil	0.91	0.77
Bonney and Stevens (2)	0.86	0.68
Hide and others (3)	0.87	0.71
HDM (6)	0.95	0.87

The following assumptions are made:

- For the Brazil survey data, RPF = 30 m/km, roughness for paved road = 40 QI*, roughness for improved gravel = 80 QI*, roughness for unimproved gravel = 150 QI*, and average medium-truck age = 4.3 years.
- For the Hide and others (TRRL) data on Kenya (3), differentials are based on speed changes (assuming constant hours driven). Rise and fall = 15 m/km each, horizontal curvature = 60°/km, altitude = 1300 m, and roughness for paved road = 2500 mm/km. For improved and unimproved gravel, roughness = 6000 and 10 000 mm/km, rut depth = 19 and 40 mm, and moisture content = 2.6 and 10 percent, respectively.
- For the HDM adjusted utilization method (6), truck speeds (determined from experimental speed data from Brazil) were 60 km/h for paved road, 47 km/h for improved gravel, and 34 km/h for unimproved gravel.

These calculations are made for a medium truck, although the definition for this vehicle varies between studies. The HDM is not a data source but rather a synthesis of previous research and is included in the comparison because it is being widely adopted as a planning guide. The procedure reported is only one of its options for the calculation of vehicle use. Its higher predicted values, particularly with respect to unimproved gravel, indicate that hours driven is a critical assumption in the option and is possibly overestimated.

It is gratifying to note that the Brazilian predictions are not broadly inconsistent with previous research studies. This suggests that this simpler method has much to recommend it, and work is continuing on further analyses. The approach should enable economists and highway engineers to estimate vehicle use in Brazil, and possibly other countries, without having to rely partly on assumptions that are difficult to substantiate.

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