RELATING VEHICLE OPERATING COSTS TO LOW VOLUME ROAD PARAMETERS IN BRAZIL

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Overview of a 12 million dollar Brazil Ministry of Transport and United Nations Development Program supported research study aimed at determining relationships between vehicle user costs, roadway design standards and maintenance policies for low volume roads. The relationships are based on an analysis of data generated in a survey of vehicle users operating on over 60,000 km of homogeneous paved and unpaved routes that has produced up to two year of user costs data on over 1200 vehicles, together with 450,000 observations based on radar speed measurements of vehicle behavior in Brazil plus fuel measurements from nine project test vehicles. Finally, data developed from 187 paved and unpaved roadway test sections is being used to develop equation to predict road performance. All of the relationships are being incorporated into a computer based planning model to be used for evaluating alternative highway transportation strategies.

A 12 million dollar research project aimed at improving highway transport planning is concluding in Brazil. This jointly sponsored Brazilian Government - United Nations Development Program (UNDP) project started in July 1975. It is being conducted by Empresa Brasileira de Planejamento de Transportes (GEIPOT) and Departamento Nacional de Estradas de Rodagem (DNER), as arms of the Brazilian Ministry of Transport, and by Texas Research and Development Foundation (TRDF), as the contractor for the World Bank, which is serving as the executing agency for the UNDP.

The study reflects the Brazilian Government's desire to improve planning tools used for allocating scarce highway resources, particularly analytical procedures used to predict the economic consequences of alternative highway design standards and maintenance policies. An important component of these economic analyses is the determination of vehicle operating costs. The relationship between these costs and roadway characteristics, particularly for low-standard roads, has not been well defined in the scientific literature. Further, the relationships that are reported in the literature do not necessarily apply to Brazil. The Brazilian Government expects this study to provide the basis for updating and developing improved relationships between roadway and design maintenance standards and the cost of vehicle operation; the study is also seen as the foundation for establishing objective economic criteria for policy decisions directed toward minimizing total highway transportation cost.

The final product of the Brazil study is to be a computer-based planning model that incorporates the relationships developed from the data collected over the past four-years study period. The models basic function is to determine, for a specified roadway design and maintenance policy, the total transportation costs for a given road project. Total transportation costs is the sum of all construction, maintenance and road user costs over the life of the project, which may be 20 years or more.

The model is based on the adaptation of an existing model entitled "The Highway Design and Maintenance Standards Model (HDM)", which is the result of a series of studies initiated by the World Bank in 1969. These studies had as their objective the development of an analytical model to predict the costs of different highway design and maintenance options for low-volume road projects. The Bank first contracted a Research Group at the Massachusetts Institute of Technology to develop a conceptual framework for interrelating construction, maintenance and vehicle operating costs. A framework schematic for the resulting model is shown in Figure 1.

Many of the relationships used in the first conceptual model could not be supported by sound empirical data, but this deficiency did indicate areas of needed research. Subsequent efforts have involved field studies that focus on developing primary information to be used to improve the empirical relationships between vehicle operating components and roadway characteristics. The first such effort in Kenya between 1971 and 1975, was a cooperative venture between the World Bank and the Transportation and Road Research Laboratories (1).

The Kenya Study (1) succeeded in expanding the understanding of the underlying engineering-economic relationships between vehicle speed, user cost and roadway condition. This new information is incorporated in the current HDM model which reflects the best features of the efforts by both the MIT and TRRL. Subsequent efforts are still in progress and include both the work carried out in Brazil and reported herein, and a substantial effort in India which has been underway for the past one and half years.

Research Approach

Figure 2 schematically illustrates the key components of the planning model being adopted in the study. The components being addressed are delineated by dashed lines and include predictions of maintenance quantities, roadway condition and vehicle consumption. The actual research is organized into three study areas, one on pavement performance and the other two on vehicle operations.

The pavement and maintenance studies have been structured to determine how different pavement designs perform for two extreme levels of maintenance in the Brazil environment. The objective is to predict the condition of a paved or unpaved roadway surface at any point in time for inclusion in the planning models. Knowing the condition of a road surface is important because the quality of the ride, reflected by the interaction between vehicles and the roadway surface, has an important impact on vehicle operating costs.

Two different study approaches were taken for developing improved vehicle operating costs-roadway characteristic relationships. One approach involved defining a series of controlled experiments that are designed to generate data to be used in formulating equations to predict vehicle speed and fuel consumption. In the second approach, a survey of road users was implemented, since no practical experimental procedure seemed appropriate for the other vehicle operation parameters, i.e., tire wear, maintenance, oil consumption, and depreciation.

Factorial experiments were defined and the levels set to insure that the inference space over which data would be collected covered the range of environmental and physical factors that prevail in Brazil. As an example, the design factorial for an experiment directed toward predicting speed patterns by vehicle class is illustrated in Figure 3. This shows that the three factors, surface type, roughness, and vertical profile, are to be investigated for their effect on vehicle speed. It shows that there are two levels of roughness, two levels of surface type, i.e., paved and unpaved, and three levels of vertical profile.

By establishing similar factorial experiments for all study areas it was possible to discern the interaction effects between the various factors being considered, which not only enhanced the analysis but reduced the actual amount of data needed.

Finally, each of the factors identified for study were defined in a manner that allows the study results in Brazil to be used elsewhere in the world. The Brazil results, when combined with previous work in Kenya, in the United States, and work currently underway in India, will permit broad application of the concepts to road problems all over the world.

Organization of the Project

The project was organized to support the three principal study efforts. This is illustrated in Figure 4 where the Surveys, Experiments and Pavement studies are highlighted and shown to be receiving the support of both the administrative and service groups. Ten of the 160 people assigned directly to the project are supported by the UNDP. The actual leadership is shared between the Brazilian and International personnel in a counterpart arrangement as also shown in Figure 4.

Geographic Scope

The original plan called for conducting the entire study in the State of Minas Gerais. This was the recommendation of the French Consultant ("Centre Experimental de Recherches et d'Études du Bâtiment et des Travaux Publics") in their preliminary planning report for this project to the Brazilian Ministry of Transport in 1973 (2).

GEIPOT is located in the Federal District so when the study was actually initiated in mid-1975 the original study area included Goiás and Minas Gerais and the D.F. area itself as shown in Figure 5. Later, to satisfy the inference space established in the experimental factorials, the States of Mato Grosso, São Paulo, Rio Grande do Sul and Bahia were added. Consequently, more than half of the paved and unpaved kilometrage in Brazil are included in the project study States.

Instrumentation and Equipment

One of the major project undertakings has been the acquisition, modification and fabrication of various instrumentation and equipment needed to carry out the substantial measurement program required for the majority of the project activities. An even more substantial challenge has involved the maintenance and repair needed to keep this equipment, valued at over $750,000, operational during the conduct of the study. Some of the more substantial equipment purchases included a Dynaflect, a Weigh-in-Motion System (WIM), a Dynamic Modulus Tester (MR), a GMR Profilometer, and an Analog-Digital (A/D Converter System).

The Dynaflect, together with a Benkelman Beam are being used to measure the deflections on 140 paved test sections three times per year. The WIM was rotated between six locations where it was operated continuously at each site for seven days, 24 hours per day to develop truck weight data. This data is being used to establish axle-load information to be used in analyzing pavement performance.

The Dynamic Modulus equipment is used in the project's soil laboratory to establish the strength characteristic of bituminous cores taken from the project paved test sections. The GMR Profilometer is used to standardize road roughness measures while the A/D System is being used to transform data to digital format for computer processing.

Modified or fabricated to meet project requirements were seven Mays-Ride-Meters, nine Volumeter Fuelmeters, three Camera Boxes systems, needed to develop incremental distance measurements, three survey vehicle measurement systems that were developed for rapidly collecting roadway vertical and horizontal geometry together with roughness, and finally a Traffic Flow Data Logger (TFDL). This latter equipment was designed to automatically generate spot speed, space mean speed and headway data for calibration of project traffic-flow models. All of the project equipment has been completely documented as to its design, calibration, operation and maintenance. This documentation is available to anyone on request.

Elements Requiring Major Attention

Using economic analyses for the highway project planning process has steadily increased over the years although mostly for high-volume highway arterials and for streets in urban areas. The underlying foundation of information needed to permit a effective analysis related to low-volume roads is very deficient, particularly in being able to explain the influence of varying roadway surface conditions on user costs. On unpaved access roads, both the vertical and horizontal alignment can be very severe. The influence of extremes in this geometry on vehicle operating costs need to be better defined.

A broad spectrum of cause and effect relationships between roadway characteristics and vehicle operating costs were addressed in the study. Special efforts were made to insure that reliable information would be developed between roadway surface conditions and user cost so that the following questions could be answered.

1. How do varying highway maintenance policies influence the performance of a given road pavement design?
2. What is the influence of roadway performance on road surface conditions and how does this surface condition affect vehicle
    a) speed,
    b) fuel consumption,
    c) tire wear,
    d) maintenance and repair,
    e) oil consumption?
3. How do roadway characteristics and surface conditions influence vehicle utilization and service life?

Road surface condition for practical reasons means road roughness because it is the roads riding quality that affects the vehicle and, therefore, vehicle operating costs. This is a critical variable to decision processes because poor roadway performance manifests itself in a rough ride to the roadway user. Poor riding quality is translated into increased vehicle operating costs, so decisions relating to surface design standards and levels of roadway maintenance eventually impact directly on vehicle operating cost. Figure 6 shows the 40 major variables being addressed in the study. Roughness is shown to be effected by 17 and to directly affect seven others or over 60% of the interactions being studied. There is also a recognized need in the world to have a standardized roughness measure that can be used in comparing roadway performance and the resulting roadway condition on vehicle operating costs in different countries. Consequently, diligent efforts were made during the study to standardize the roughness measures obtained.

The principal roughness measurement instrument has been the Mays-Ride-Meter. This equipment, modified to permit direct digital output, was installed in seven vehicles. These seven roughness measurements systems have been operating continually throughout the study period and between them have been driven over 70,000 km in the process of developing 50,000 km of roughness measurements on paved and unpaved roadways in Brazil.

The reliability of the measurements obtained with the Maysmeter has been rigorously controlled. Each system is checked at the beginning and end of a day's work to insure the measurements it is generating are under control. Anytime a change in the response of a Mays-Ride-Meter system is observed it is completely recalibrated. This involves running the system over 20 control sections covering a spectrum of roughness conditions. The runs are made over all 20 sections on five different days, and the average roughness numbers are used to define a calibration curve which is used to transform the Mays-Ride-Meter system measurements to a standard roughness measurement.

A GMR Profilometer served to define the unchanging roughness standard that was used throughout the study period. This was accomplished by making periodic measurements of each control section with the GMR Profilometer. These measurements were used to define the roughness of each control section to which each Mays-Ride-Meter system was calibrated. Use also was made of the GMR Profilometer in transforming the roughness measurements obtained in Kenya (1) and those currently being obtained in India to the scale being used in Brazil. This allowed a direct comparison to be made between the relationships involving roughness for the three different studies. Recommendations for a worldwide roughness standard are currently being reviewed and studied. Regardless of the form the final standard takes, it will be possible to transform the Brazil measures to this final standard using the permanent tape records obtained with the Profilometer.

Pavement and Maintenance Studies

The Pavement and Maintenance Studies had as their ultimate objective establishing equations to predict the performance of any roadway in terms of its roughness. Such equations in the hands of decision makers is an invaluable tool, one that permits them to examine alternative design standards, construction strategies, and maintenance policies and for each combination predict the resulting roadway riding quality at any point in time.

The equations developed to predict the performance of both paved and unpaved road are based on information generated from a series of test sections. The paved sections were selected to satisfy a 64-cell design factorial where two levels were designated for each of six factors as shown in Figure 7.

Eventually, 128 different paved test sections were established. Each section was split into two 320-meter segments where two extreme levels of maintenance were sought. For the low or nil level of maintenance only pothole patching was permitted and this for safety reasons. For the high level of maintenance sections, the predominant maintenance response was to slurry seal the surface at the first sign of cracking. In the case of severe distress, complete replacement in kind of base and surface were implemented.

There were 48 unpaved test sections and these were also split into two segments. The principal maintenance response was roadway grading and this was varied from two weeks to five months so that data on roadway performance for various grading frequencies could be established.

A substantial measurement program was established to develop data on the performance of each of the test sections. For the paved sections this involves a detailed surface condition survey every four months on each section. Further, periodic road roughness and deflection measurements are obtained on each section. The roughness measuring system was described earlier. The deflection measurements are being made with both a Dynaflect and with a Benkelman Beam. The initial material characterization test on each section were subcontracted to a soils consultant and consisted of measurements for field density, field CBR, field moisture, and layer thickness. From samples of each layer, laboratory testing has established material grading, Atterberg limits, and laboratory CBR and density.

Road User Costs Survey

Over 200 vehicle users having fleets of either passenger cars, buses or trucks varying from 1 to 1000 vehicles are participating in the survey of vehicle operating costs. The cost components being addressed in the survey include fuel, oil, tires, maintenance parts, labor and depreciation. The routes over which each vehicle operates are essentially homogeneous in character. Quantitative measures of the roadway characteristics have been obtained for each route using the survey vehicles described earlier; included are horizontal and vertical geometry measurements on each route together with continuous roughness measurements at .2-mile intervals.

This is the largest survey ever undertaken to develop relationships between roadway characteristics and vehicle operating costs. New and meaningful relationships have been established for all of vehicle operating cost elements. Depreciation is one of the most important because almost no empirical data exist which can be used to substantiate a real-world-based procedure for defining differential depreciation rates on roads having different characteristics.

The rate at which the capital investment in vehicles is depreciated is normally tied closely to the life time mileage of a vehicle which in turn is a function of the vehicle's years of service and annual mileage. In general, road improvements are expected to reduce the physical wear on vehicles and increase speed. Both of these effects are assumed to increase the vehicle's life time mileage by first extending the service life and second by increasing the annual mileage, although not proportionately, because increased speed also accelerates the wear on a vehicle. The problem is to establish if and how a vehicle's service life and annual mileage is actually related to operation on roads of widely ranging character, i.e., different geometry and surface conditions.

Road User and Traffic Experiments

Time and fuel savings are two of the established benefits that accrue to highway users through road improvements. Considerable published information exists on both the prediction of vehicle fuel consumption and speed as a function of roadway characteristics. However, the available information is not necessarily applicable to Brazilian vehicles and conditions. Further, this information does not adequately address the effect of roadway condition on speed and fuel. Nevertheless, the ability to design experiments to develop detailed relationships between roadway characteristics and vehicle speeds and fuel consumption is well documented.

Brazil, like many other countries throughout the world, is concerned about the increasing levels of oil consumption, particularly for highway travel. Therefore, understanding how decisions related to highway design standards and maintenance policies influence vehicle consumptions takes an added importance. Given the desire to identify the parameters influencing fuel consumption, particularly road surface condition, and the demonstrated ability to design experiments that can produce the required detailed relationships, the decision was made to develop a computer-based model (TAFA) that would simulate the speed and compute the fuel consumption for a vehicle as it traversed a section of road with given vertical and horizontal alignment and road surface conditions.

Thirty different individual experiments were identified, designed and implemented to develop the data required to establish the relationships needed to create and calibrate TAFA. The speed experiments involved monitoring the behavior of traffic at 176 control locations established along the roadway. The sections were selected to cover as wide an inference space as possible so that the data being analyzed included a wide spectrum of grades and roughness on both paved and unpaved roadway sections. At each location, the road characteristic and the environment during the period of observations were identified through measurements of:

1. Road characteristics including:
   a) grade
   b) horizontal alignment
   c) pavement width
   d) surface type
   e) surface roughness
   f) surface rutting
   g) gravel looseness (unpaved)
   h) surface material moisture (unpaved)
2. Environmental characteristics including:
   a) rainfall
   b) dust level
   c) altitude
   d) wind velocity and direction
   e) cloud cover
   f) traffic volume and composition

Nine vehicles were purchased and instrumented for the fuel studies. They included a VW1300, two VWKombis, one gasoline-powered truck, four diesel-powered trucks, and a diesel bus. This emphasis on diesel vehicles was supported by the current trend showing increased use of these more economical fuel consumption vehicles on the road. The same parameters identified for speed measures applied to the 28 sections selected for the fuel experiments.

Over 450,000 observations were obtained through the speed and fuel experiments. These data were subjected to rigid checking before being incorporated into computer files. Further screening and review of computer-generated reports of the field data files normally resulted in the identification of some data discrepancies. Where the discrepancies could not be satisfactorily resolved, the experiments were repeated and the original data discarded. The final step in data processing was to combine various files identifying test section parameters with the speed or fuel observations and structure appropriate analysis files.

The final data analysis files were considered to be both accurate and reliable and were subjected to very rigorous analysis. The final relationships developed include every variable and variable interaction that could be identified as significant in explaining any of the variation in either of the observed dependent variables, speed and fuel consumption. Also, wherever possible, the equations were generalized, i.e., if vehicle classes could be combined into a single equation, they were combined.

Information Dissemination

Because of the wealth of new information and the nucleus of new knowledge generated in Brazil, the project team has tried to completely document every significant facet of the project. Three levels of reporting were initiated. These include Formal Reports, Project Working Documents and Project Technical Memos.

The 12 formal project reports expected from the project include the following:

1. Inception Report (3)
2. Midterm Report (4)

3. Instrumentation Report
4. User Survey Design and Methodology
5. User Survey Analysis and Results
6. User Experiments Design and Procedure
7. Project Data File Documentation
8. User Experiments Analysis and Results
9. Pavement and Maintenance Studies Design and Procedures
10. Pavement and Maintenance Studies Analysis and Results
11. Executive Summary
12. Documentation and Users Guide for Planning Model (MOBAIR)

The Project Working Documents form a series containing information related to the research that is too detailed to be included in the Formal Reports. They include detailed tabulations of data, descriptions of each of the Experiments, documentation and user guides for project-generated programs and operational and maintenance manuals for various instrumentation systems.

The Technical Memos were devised to capture significant facets of the project as they were completed. These include the formation of procedures to collect data, defining approaches to the analysis of information, interim results of isolated and completed segments of the study, and detailed descriptions of some of the instrumentation developed for the study. The Technical Memos have been consolidated annually into a Working Document so they can be more easily referenced and disseminated.

The majority of the data being generated in the study is being handled by computer-based data processing systems. Over 100 files have been created to store project data, and each of these files is being completely described in a project formal report entitled Project Data File Documentation.

The ICR Model

The final product of this research project is an operational Highway Investment Model that incorporates the relationships developed during the study. The program structure for this model already existed in the Highway Design and Maintenance Standards Model (HDM) developed from the combined MIT/TRRL/WORLD BANK effort. A version of the HDM was adopted for the project in mid-1978 and a series of modifications implemented to transform the HDM for use in Brazil. The modified HDM was designated ICR and a number of different ICR versions have been produced to handle, in a stepwise manner, each of the modifications. These include the conversion of all output to Portuguese, and the establishment of routines to handle new variables which are needed for changes in the subroutines for predicting pavement performance and vehicle operation.

The detailed speed and fuel consumption information that can be generated through using the Time and Fuel Algorithm (TAFA) is being handled at both a micro and macro levels, and therefore two different ICR versions are being produced. An entirely new subroutine for computing depreciation has been developed and major changes were made in the subroutine used to determine vehicle oil consumption, tire wear, and maintenance and repair costs. The final model will be called Modelo Brasileiro para Avaliação de Investimentos Rodoviários (MOBAIR-1) and represents the final version produced by this project. Further improvements will unquestionably continue to be made in the future as additional data is collected and data files are further expanded. In subsequent analyses the individual equations will be improved further and the new relationships will be incorporated into MOBAIR-2 and later versions of the model.

MOBAIR-1 is expected to find a number of specific applications in Brazil. It can be applied to any proposal for the improvement of an existing highway facility or the construction of a new facility. The application can be to a specific project, a number of projects making up a long route, a system of highways or a complete geographic area varying from a local municipality to the entire country. Another prevalent use will be in selecting between alternative route locations both at the feasibility and pre-feasibility level of study or to make comparisons between reconstruction and/or construction on existing alignment or right-of-way and that of a new location.

Considerable interest has been expressed for using the model to set design guidelines for both vertical and horizontal geometry. This is an area where the micro subroutine version of TAFA can have application. In addition, some other uses that can be made of the model include establishing warrants for truck lanes on steep grades; making decisions related to stage construction options, establishing policies on permissible vehicle weights and dimension or vehicle speed limits, and of course in the important area of establishing highway maintenance levels.

A Brazil Highway Maintenance Study has been underway concurrently with this reported study and the individual maintenance activities included in the model are based on the productivity and labor, equipment and material requirements established in the maintenance study. Consequently, the MOBAIR Model can be used to examine alternative maintenance strategies. The resulting predictions of maintenance work can be used as a direct input into the budget procedures established for managing highway maintenance in Brazil.

Summary

The Brazil study has expanded the empirical foundation on which many vehicle-operating cost relationships are based. These new relationships between vehicle-operating costs and roadway characteristics, traffic and environmental conditions are being incorporated into a highway planning model that will be known as MOBAIR. This model is expected to be implemented widely in Brazil. Further the model and the underlying relationships together with the data used in their development are available for use throughout the world.

References

1. R. Robinson et al. A Road Transport Investment Model for Developing Countries. TRRL, Laboratory Report No. 674. Transport and Road Research Laboratory. Department of Environment, Crowthorne, 1975.
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3. Inception Report, Research Concepts and Procedures. Research on the Interrelationships between Costs of Highway Construction, Maintenance and Utilization, (UNDP Project BRA/74/012)-GEIPOT, UNDP, IBRD, Brasilia, Brazil, Apr. 1976.
4. Report II, Midterm Report, Preliminary Results and Analysis. Research on the Interrelationships between Costs of Highway Construction, Maintenance and Utilization, (UNDP Project BRA/74/012)-GEIPOT, IBRD, Brasilia, Brazil, Aug. 1977.

Figure 1. Flow chart for highway cost model developed in the MIT study (Ref 1)

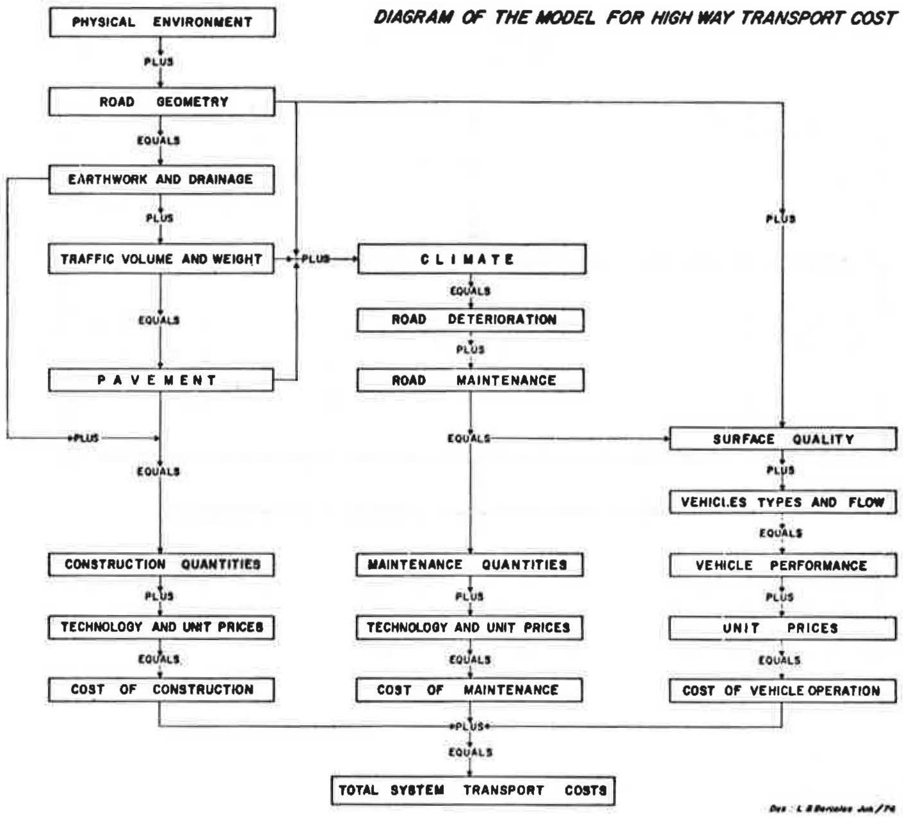

Figure 2. Conceptual framework of highway planning model showing module interfacing

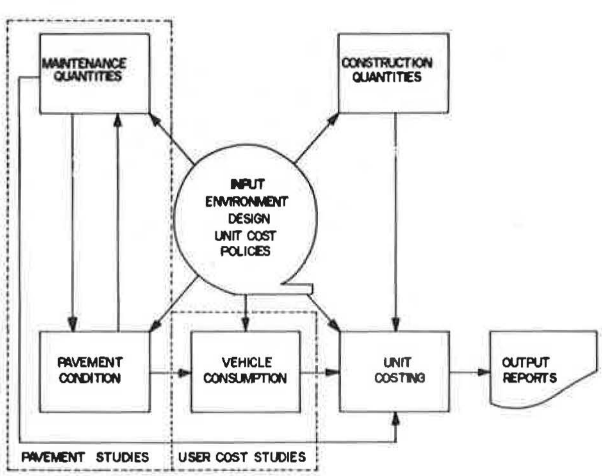

Figure 3. Sampling frame for traffic on positive grades, experiment TB-1

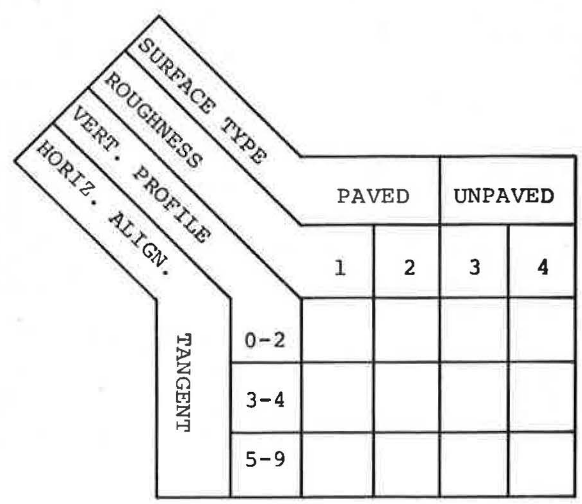

Figure 4. Functional organization chart of project

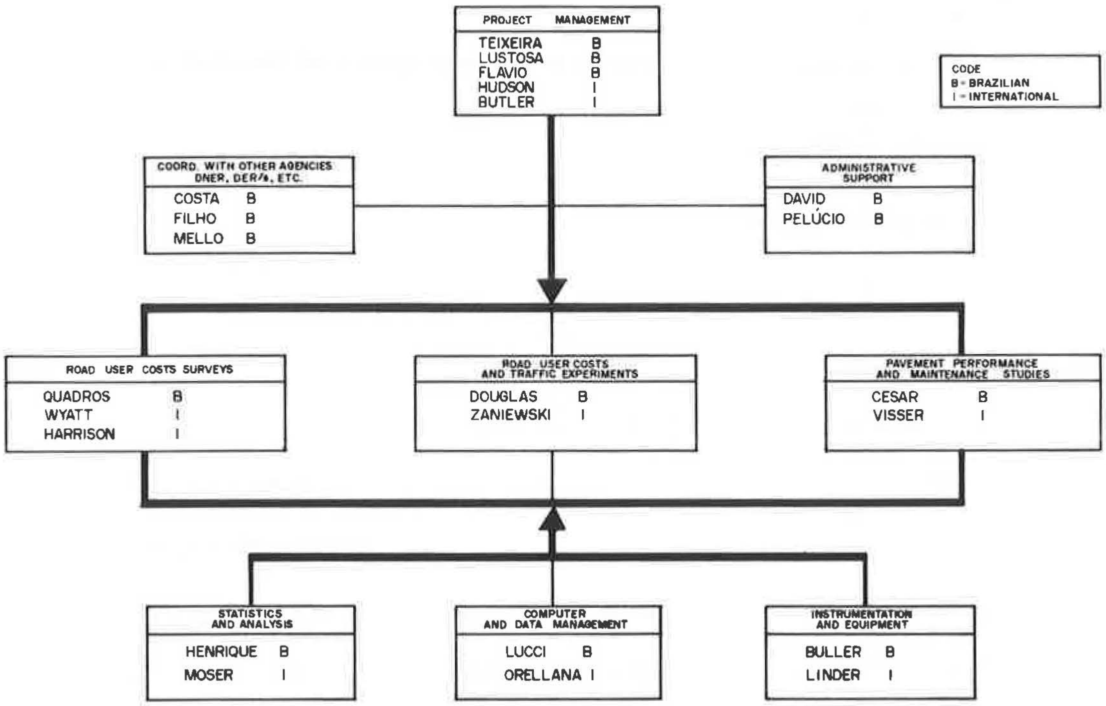

Figure 5. Summary of the variables that have been identified for study in the project

FACTORS \ PREDICTION	Annual Vehicle Use	Vehicle Speed	Depreciation	Maintenance Repair	Tire Wear	Oil Consumption	Grease Consumption	Fuel Consumption	Rut Depth	Pavement Cracking	Surface Looseness	Gravel Loss	Road Roughness
Vehicle Speed	●		●					●					
Traffic Volume	●	●						●	●	●	●	●	●
Traffic Composition	●	●						●					
Accummulated Axle Loads									●	●	●	●	●
Vehicle Class	●	●		●	●	●	●	●					
Annual Vehicle Use			●	●	●								
Vehicle Age	●		●	●	●	●	●						
Vehicle Load	●	●		●	●	●	●	●					
Vehicle Gear		●						●					
Vehicle Activity	●		●	●	●	●	●	●					
Rain Fall	●							●	●	●	●	●	●
Vertical Geometry	●	●		●	●	●	●	●	●	●	●	●	●
Horizontal Geometry	●	●		●	●	●	●	●	●	●	●	●	●
Road Surface Type	●	●		●	●	●	●	●	●	●	●	●	●
Roadway Age									●	●	●	●	●
Rehabilitation Age									●	●		●	●
Material Characteristics									●	●	●	●	●
Pavement Structure No.									●	●		●	●
Pavement Deflection									●	●		●	●
Pavement Cracking												●	●
Road Rut Depth												●	●
Road Roughness	●	●		●	●	●	●	●					
Surface Looseness		●									●	●	●
Regraveling Rate											●	●	●
Blading Frequency										●	●	●	●
Maintenance Level										●	●		●
Roadway Dust		●											

Figure 6. Map of Brazil showing the study's final geographic coverage by state

Figure 7. Sampling matrix for the paved road experiment

SURFACE TYPE			ASPH CONC				D SURF TREATM			
BASE TYPE			GRAVEL		C STONE		GRAVEL		C STONE	
TRAFFIC (ADT)			50-500	>1000	50-500	>1000	50-500	>1000	50-500	>1000
STATE REH.	AGE	V. GEOM. (%)								
OVERLAYED	≥ 8	> 6								
		0-1.5%								
	0-2	> 6								
		0-1.5%								
AS CONSTRUCTED	≥ 12	> 6								
		0-1.5%								
	0-4	> 6								
		0-1.5%								