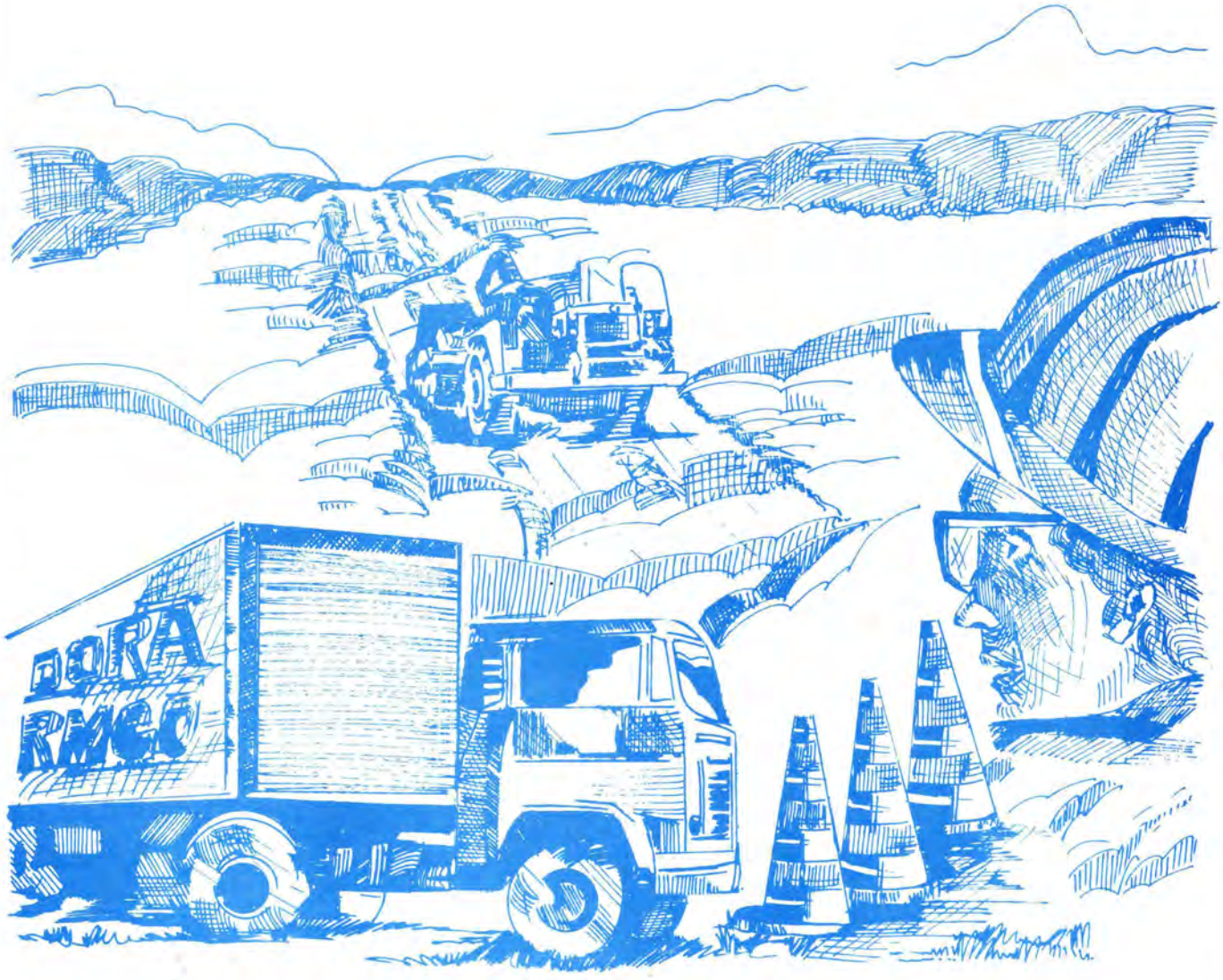
REPÚBLICA FEDERATIVA DO BRASIL

MINISTÉRIO DOS TRANSPORTES

United Nations Development Programme (UNDP)

Research on the Interrelationships Between Costs of Highway Construction, Maintenance and Utilization

Final Report - 1981



VOLUME 1 – SUMMARY OF THE ICR RESEARCH

REPÚBLICA FEDERATIVA DO BRASIL

MINISTÉRIO DOS TRANSPORTES

United Nations Development Programme (UNDP)

Research on the Interrelationships Between Costs of Highway Construction, Maintenance and Utilization

Final Report - 1981

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WITH THE PARTICIPATION OF:

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VOLUME 1 – SUMMARY OF THE ICR RESEARCH

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Conteúdo: v.1 Summary of the ICR Research v.2 Methods and organization v.3 Instrumentation v.4 Statistical guide v.5 Study of road user costs v.6 Study of vehicle behavior and performance v.7 Study of pavement maintenance and deterioration v.8 Highway cost model (MICR) v.9 Model of time and fuel consumption (MTC) v.10 Model for simulating traffic (MST) v.11 Fundamental equations v.12 Index to PICR documents.

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PREFACE

This research project was funded through an agreement signed in January, 1975 by the Brazilian Government and the United Nations Development Programme (UNDP). The Ministry of Transportation, acting through the Brazilian Transportation Planning Agency (GEIPOT), assumed the responsibility for the project on behalf of the Brazilian Government, and the International Bank for Reconstruction and Development (IBRD) acted as the executing agency for UNDP.

The research was carried out by GEIPOT and the National Highway Department (DNER), acting through its Road Research Institute (IPR). Funding from the Brazilian Government was channeled through the Institute for Economic and Social Planning (IPEA) and the Secretariat for International Economic and Technical Cooperation (SUBIN), along with the Ministry of Transportation.

The World Bank contracted the Texas Research and Development Foundation (TRDF) to organize the international technical staff and to select and purchase the imported equipment needed for the research. The participation of the TRDF continued until December of 1979.

This report is comprised of twelve volumes (each edited in both English and Portuguese) which summarize the concepts, methods and results obtained by December, 1981 by the project entitled "Research on the Interrelationships Between Costs of Highway Construction, Maintenance and Utilization (PICR)". It includes a documentary index volume which will aid researchers in locating topics discussed in this report and in numerous other documents of the PICR. This report contains much detailed analysis which is being presented for the first time, and also incorporates relevant parts of earlier reports and documents produced under the 1975 Agreement, updating them through the inclusion of new results and findings.

A special mention is due the Highway Departments of the States of Minas Gerais and Goiás, the Universities of Aston, Birmingham, Juiz de Fora, Minas Gerais and Texas, and the Western Australia Main Roads Department, which placed some of their best and most experienced personnel at the service of this project to fill many key positions on the research staff.

Finally, thanks are due the Transport and Road Research Laboratory for its assistance during the initial stages of the project, along with specialists from various countries who periodically visited Brazil to discuss the work being done in the PICR and to assist the permanent research staff in conducting analyses.

JOSÉ MENEZES SENNA
President

*VOLUMES IN THIS REPORT**

VOLUME 1 - SUMMARY OF THE ICR RESEARCH

VOLUME 2 - METHODS AND ORGANIZATION

VOLUME 3 - INSTRUMENTATION

VOLUME 4 - STATISTICAL GUIDE

VOLUME 5 - STUDY OF ROAD USER COSTS

VOLUME 6 - STUDY OF VEHICLE BEHAVIOR AND PERFORMANCE

VOLUME 7 - STUDY OF PAVEMENT MAINTENANCE AND DETERIORATION

VOLUME 8 - HIGHWAY COSTS MODEL (MICR)

VOLUME 9 - MODEL OF TIME AND FUEL CONSUMPTION (MTC)

VOLUME 10- MODEL FOR SIMULATING TRAFFIC (MST)

VOLUME 11- FUNDAMENTAL EQUATIONS

VOLUME 12- INDEX TO PICR DOCUMENTS

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* Volume 1 contains a brief description of the contents of each volume, while Volume 12 provides a subject index to this report and all other PICR documents, including technical memoranda and working documents.

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SUMMARY

This volume describes the objectives of the Research on the Interrelationships Between Costs of Highway Construction, Maintenance and Utilization (PICR), as well as the data and variables covered by its surveys and experiments.

The original objective of the PICR was the development of methods and models which would minimize the cost of highway transportation in Brazil, particularly on non-urban highways characterized by a low volume of traffic. To reach this objective, wide-ranging field research was performed - one of the largest projects of its type ever carried out in Brazil or abroad - with the objective of determining the costs of the three major components of the *total cost of highway transportation*, namely: the costs of highway construction, maintenance and utilization. In short, an effort was made to determine the influence of highway characteristics on the cost of vehicle operation. As major factors, highway geometry and surface quality were studied, to quantify their influence on operating cost. Traffic-provoked highway deterioration was also studied, as well as the behavior of highway users.

This first volume of the Final Report presents a brief description of the work carried out during the PICR, its organization and the basic data surveyed. It also indicates where this information can be found in the different volumes of this report, and provides an evaluation of the tasks performed.

This Final Report is composed of 12 volumes, 6 appendices (in the form of Manuals for the three models developed) and 53 Working Documents (containing all of the documentation produced during the research project). Chapter 5 of this volume presents a description of the other volumes of this report, with a summary of the subjects treated in each volume, as well as a listing of the working documents produced by the PICR, together with capsulized information on the content of each.

CHAPTER 1
BACKGROUND, OBJECTIVES, ORGANIZATION

1.1 BACKGROUND

Transportation planners and technicians seek to maximize the return on highway transportation investments, particularly in the case of roads characterized by low volumes of traffic, by minimizing the overall costs of construction, maintenance and utilization of these roads.

These costs are correlated, since a highway constructed on the basis of high quality design and materials will result in lower maintenance costs, and the operating costs of the vehicles utilizing the highway will also be reduced. However, the fact that this alternative demands a high level of initial investment reduces the number of highways that can be built, while unnecessarily increasing the overall costs of the road. This is demonstrated by the fact that the additional costs of construction will be greater than the reductions in the costs of highway maintenance and vehicle operation. On the other hand, if construction is based on an overly modest standard of quality, the costs of highway maintenance and vehicle operation will be excessive and the final overall costs will be greater. Therefore, one can perceive that, between these two extremes, there is a project of intermediate quality which minimizes the total cost of highway transportation.

However, to determine which project yields the lowest total costs, one must know: (1) the costs of each of the alternative projects; (2) the costs of maintenance consequent upon the interaction of project quality with traffic volume, in the context of local climate and soil conditions; and (3) the influence of the project parameters - the surface quality and the horizontal and vertical geometry of the future road - on the operating costs of the vehicles which will utilize the highway during its life span.

The construction cost of a given project can be obtained by calculating the costs of the operations of earth moving, paving, drainage and complementary tasks, such as tunnels, viaducts, etc., either through the utilization of economic engineering methods or through the evaluation of proposals submitted in past public bidding.

However, it is more difficult to specify the cost of maintenance, since highway wear depends on the interaction of project quality with the type and volume of traffic. Particularly in the case of Brazil, studies on the quantitative nature of this interaction were few.

Notwithstanding this, the major unknown factor in the composition of the total cost of highway transportation was the cost of vehicle operation on roads with differing parameters of geometry and surface quality.

The Research on the Interrelationship of Highway Construction, Maintenance and Utilization Costs (PICR), was planned and executed with the objective of gaining more precise knowledge of the composition of the total cost of highway transportation, composed of the costs of construction, maintenance and utilization of highways.

The sponsors of the project were the Secretariat of Planning of the Presidency of the Republic (SEPLAN), acting through the Institute of Economic and Social Planning (IPEA) and the Secretariat of International Economic and Technical Cooperation (SUBIN), both of which are subordinated to SEPLAN, and the United Nations Development Programme (UNDP).

The Brazilian Transportation Planning Agency (GEIPOT) was charged with the execution of the project. In order to carry out its task efficiently, GEIPOT associated itself with the National Highway Department (DNER), through its Institute of Highway Research (IPR).

The International Bank for Reconstruction and Development (IBRD) was designated as executor of the UNDP responsibilities. After consulting with GEIPOT and receiving its approval, the Bank contracted the Texas Research and Development Foundation (TRDF), to act in its name in the technical direction of the project.

This research project has been previously planned in a study ordered from the consulting firm *Centre Experimental de Recherches et d'Etudes du Batiment et des Travaux Publiques* (CEBTP).

1.2 OBJECTIVES

In the agreement between the Brazilian government and the UNDP, the short-term objective was that of ascertaining the correlation among the three major components of the total cost of highway transportation: the costs of highway construction, maintenance costs, and the costs of vehicle operation. In the form of equations and/or parameters, these correlations could be used individually by highway transportation planning technicians, in the evaluation of the gains or savings implicit in the diverse investment alternatives, thus making it possible to arrange the outlays of the sector in hierarchical form.

The long-term objective was that of minimizing the total cost of highway transportation. To attain this objective, adaptations or modifications would be introduced into the model produced by the Massachusetts Institute of Technology (MIT), or into that of the Transport and Road Research Laboratory (TRRL), while the correlations, equations and parameters developed by the PICR would be utilized.

The aforementioned models calculate and add - with the aid of computers - the annual costs of construction, maintenance and utilization corresponding to each highway project under consideration.

The results of the simulations produced by the models would then constitute a discrete series of results, which would then make it possible for the planner - with considerable speed and at low cost - to effect comparisons and opt for a specific investment policy.

1.3 ORGANIZATION

To attain these objectives, it was necessary to obtain information on the physical characteristics of different types of roads and on the operation of representative vehicles of the national fleet, in the context of the widely varied combinations of highway geometry and surface roughness. Among other things, this demanded

a complex and detailed survey of the surface quality and vertical and horizontal geometry of thousands of kilometers of roads, as well as tests which would determine travel time, fuel consumption, wear of tires and parts, etc., in different combinations of roughness and geometry.

A research project of the scope of the PICR demanded an adequate organization, as well as technical-scientific support that was not available in Brazil at the time work began. Other necessities included special measuring instruments and a multidisciplinary team with a high degree of knowledge of the problems associated with highway research.

To obtain the additional human and financial resources, the Brazilian government sought out the United Nations Development Programme (UNDP), and obtained from this agency the complementary support necessary for contracting a multidisciplinary team, as well as for selecting, acquiring and testing the necessary equipment and bringing it to Brazil.

The UNDP delegated the task to the World Bank which, after consultations with GEIPOT, contracted the Texas Research and Development Foundation (TRDF), to act as its project agent.

GEIPOT joined with the National Highway Department (DNER) in the constitution of the project's technical team, while also assuring itself of the cooperation of the Highway Departments (DERs) of Goiás, the Federal District, Minas Gerais and São Paulo. GEIPOT assumed the task of overall project coordination, while the TRDF, acting in the name of the World Bank, took on the responsibility for the technical direction.

In terms of data gathering, three groups were created with the following specific tasks:

1. To gather information on the costs of vehicle operation, including such major components as consumption of fuel, lubricants, grease, parts, tires, mechanic labor, operating labor and travel time;
2. To observe the behavior of the highway users, in the context of the geometric characteristics of the road,

environmental factors, surface quality, etc.; and to simulate this behavior in controlled experiments, while measuring fuel consumption;

3. To collect data and carry out tests on selected highway segments, with the purpose of observing the process of gradual deterioration.

To provide adequate technical support to the groups responsible for the gathering of data, three general technical support groups were formed:

1. The group of analysis and statistics was given the task of designing and accompanying the data gathering process of each group, while also analyzing the resulting data;
2. The group responsible for the measuring instruments was charged with the task of maintaining the instruments and equipment in good operating condition, while carrying out the adaptations indispensable to local conditions;
3. The data processing group had the major task of punching, filing and maintaining the data gathered by the different groups in a suitable way, for the later task of statistical analysis.

A consultative group designated the Expert Working Group (EWG) was formed, which was composed of six specialists of international renown. This group was given the specific task of providing guidance in the determination of methods and techniques that would better satisfy the demands of the research project, while also holding periodic meetings with the project team for the purpose of discussing the course and progress of the work.

Detailed information on the work carried out and on the localization of the information produced by the PICR is found in the eleven subsequent volumes of the present report, as well as in the working documents and manuals described in this volume.

CHAPTER 2
METHODS, INSTRUMENTS AND BASIC DATA

2.1 METHODS

To gain knowledge of the total cost of highway transportation, broken down into its major items (costs of highway construction, maintenance and utilization), one must be familiar with the Brazilian highway environment, its organization, practices and standards of highway construction and maintenance, as well as the organization and practices of the users of these roads.

As mentioned in the previous chapter, the most complex tasks are those of identifying and quantifying the costs of highway maintenance and utilization, with the objective of correlating maintenance expenditures with the quality of the road surface, as well as the costs of vehicle operation with the characteristics of the road (geometry and surface quality).

During the period extending from July 1975 to December 1981, the great effort expended in this research project was concentrated on obtaining information, gathering data and performing experiments, with the aim of determining the costs of highway maintenance and vehicle operation on selected segments of the highway network.

Since the PICR was, from various points of view, a pioneering task, it was necessary to develop specific methods of work, test them and adapt them and, only after all this, begin the systematic work of collecting data and information both on the selected road sections and on the costs incurred by selected users.

In the light of the material impossibility of researching the entire highway network, as well as the population of users, the solution arrived at was that of establishing, by consensus among the technicians, those factors of greatest relevance which would include the totality of the highway universe. These factors were combined into factorial matrices, composed of cells resulting from the conjugation of two or more factors.

The data and information obtained are divided into three basic categories:

a) Data and information supplied by highway authorities and by highway users,

b) Tests and physical measurements, and
c) Experiments with all the factors under control.

Fundamentally, the first group contains the information gathered from the highway authorities with respect to the highway network under their jurisdiction (geometric, geological and geotechnical characteristics of the pavement structures, traffic and its composition, maintenance practices). Also included in this group is the information obtained from highway users on the costs of the various items which make up the operating cost (fuel, lubricants, parts and mechanic labor, tires, operating labor, type of operation and load, travel time, etc.).

The physical measurements consisted of identifying and determining the speeds of the highway users, weighing the vehicles and determining the physical characteristics of the materials which compose the road structures, such as texture, roughness, granulometry, *in-situ* resistance, etc.

In the category of experiments, one should mention the measurements of fuel consumption as a function of roadway characteristics (geometry and roughness), and the laboratory tests, the latter carried out with to obtain better knowledge of the physical characteristics of the highways under study.

The specific methods utilized by the different groups responsible for the gathering of data and information are described in detail in Chapters 3, 4 and 5 of Volume 2 of this report, while the conclusions are presented in Volumes 5, 6 and 7.

2.2 *INSTRUMENTS*

The scientific and measuring instruments available to the PICR were of good quality and considered to be the best on the market at the time work began.

Conventional equipment widely used in highway engineering was utilized, together with technically sophisticated instruments used for the first time in Brazil. This equipment is described

in volume 3 of this report, together with information on its operation, the special care to be taken in utilization, major operating defects, and the minimum team required for maintenance.

Special mention should be made of the following equipment and instruments utilized for the first time in Brazil:

1) *Mays-Ride-Meter* (or Maysmeter) - a rather simple instrument which detects the vertical movement of the differential of a vehicle (rigid axle) in relation to the body, as the vehicle moves over the highway. After covering a specific unit of distance, these movements are added together and transformed into statistics corresponding to the surface quality of the road segment in question. Though this is a relatively simple measurement, it is influenced by a number of factors, such as tire pressure, state of the vehicle suspension system, speed of movement, etc. However, this low-cost, relatively simple equipment made it possible to obtain data on roughness at the same speed of circulation as that of highway users.

2) *GMR Profilometer* - also known as the Surface Dynamics Profilometer is a technically sophisticated instrument used basically for calibrating the simpler measuring instruments (Maysmeters). This consists of a utility van in which complex electronic equipment has been installed, and which receives, analyzes and computes the movements of a pair of sensor wheels in contact with the highway, producing a recording of an analogical profile on magnetic tape. This profile can be adequately analyzed and simulated within the vehicle, generating statistics that are interpreted as the roughness of the road surface, with which the measurements generated by the Maysmeters are correlated.

The Profilometer was not widely used, since it could not circulate at speeds above 32 km/h (20 miles/h) and thus interfered with the normal flow of traffic, besides presenting complex maintenance problems.

3) *Resilient Modulus* - this is a test which consists of measuring the deformities introduced into a test body through the application of a small weight at regular time intervals. In short, it is the practical application of Prof. Lobo Carneiro test, also known as the *Brazilian method*. During the PICR, this test was for the

first time systematically and intensively carried out in Brazil.

4) *Scale for Weighing in Motion* - this consists basically of transducers installed in the road surface. When they come under the pressure of vehicle wheels, the devices emit a signal which, after being interpreted by adequate electronic equipment, gives the weight of each wheel of the vehicle. As supplementary equipment, two *loops* are also installed in the roadway to detect the circulating speed and the length of the vehicle. This equipment proved to be of little use, due to the virtually constant defects which appeared in its electronic components. The description of this equipment and recommendations as to its operation and maintenance are described in Volume 3 of this report.

2.3 BASIC DATA

The data, information and measurements obtained during the PICR constitutes a highly valuable file, which can be used in the future to improve highway planning techniques.

The three groups responsible for the gathering of data labored intensively from July 1975 to December 1981. The work of collecting data on vehicle performance in relation to acceleration and deceleration is being concluded in 1982. Observations and measurements of the deterioration of selected test sections should continue for the next several years, so as to improve and enrich the files and the performance models of the roads.

The group responsible for the collection of data on user costs systematically obtained data on the different components of total operating cost, in the form of monthly information supplied by the users themselves. When this information did not exist, systems adapted to the characteristics of the companies were installed, and data were gathered on the following items:

- fuel consumption;
- consumption of lubricants;
- tire consumption;
- spare parts;
- maintenance labor;

- operating time;
- operating crew; and
- depreciation.

In addition to these data from the major survey, information was also collected on the following items:

- age of the vehicles;
- load, freight, passengers transported;
- travel time;
- number of stops, loading and unloading;
- speed of the vehicles; and
- vehicle specifications.

With respect to the routes used by the vehicles for which cost data were collected, a survey of the following characteristics was made:

- type of surface;
- roughness of the surface;
- vertical geometry;
- horizontal geometry;
- width of the riding surface;
- use of the soil in the region; and
- traffic.

For logistical reasons, the area covered by the study was initially restricted to the Federal District and the states of Goiás and Minas Gerais. However, in order to widen the scope of the factorial matrix of the study, it was necessary to extend data gathering to the states of Mato Grosso, Mato Grosso do Sul, São Paulo, Espírito Santo and Rio Grande do Sul.

The description of the methods and techniques utilized in the gathering of data are found in Chapter 3 of Volume 2. Volume 5 of this report contains the conclusions, parameters and equations obtained.

The group responsible for the collection of data on vehicle performance on the highways was organized with the objective of identifying the operation patterns of the highway users, measuring the speed of circulation of the different classes of vehicles, and

relating it to road characteristics (horizontal and vertical geometry and surface quality).

After these observations, the operation was simulated in vehicles equipped with adequate instruments, and fuel consumption was measured with all factors under control.

The carrying out of these tests made it possible to create performance models for the different types of vehicle in the national fleet, including automobiles, utilities, light, medium and heavy trucks, as well as intercity buses. The equations resulting from the analysis of the data generated a family of equations capable of predicting the operating speed and the fuel consumption of the vehicles as a function of the geometric characteristics of the highway and the quality of the riding surface.

The methods and techniques utilized by the group are described in Chapter 4 of Volume 2 of this report, while the result of the statistical analysis of the data collected is found in Volume 6 of this report.

After an intensive search, the group responsible for the study of road performance and maintenance identified those highway sections with characteristics that fitted the cells of the general matrix of the experiment. Pavement deterioration was observed on these sections, and the effect of maintenance operations was measured.

To evaluate the effect of maintenance on the highway, the selected test sections were divided into two subsections: one received no maintenance, while the other received the routine maintenance, normally practiced by the highway authorities.

In selected sections of badly deteriorated highways, experimental sections were constructed on which different maintenance techniques were applied, ranging from slurry sealing to varying thicknesses of asphaltic concrete (4 to 12 cm). The performance of these sections is still under observation.

Probe holes were drilled in the selected test sections for the purpose of extracting materials from the different pavement

layers, and determining the CBR *in situ*. The material withdrawn from these holes was later tested at the soil laboratory to determine such physical characteristics as granulometry, limits, CBR. Test samples of the surface material were also withdrawn, while undeformed samples were extracted from the subgrade with the use of Shelby tubes.

In addition to the characterization of the pavement structures of these sections, information was also gathered on the climate and traffic (its composition and weight). A systematic survey of the pavement condition was also carried out. This was done through measuring the areas of cracks, potholes and patches; measuring deflection with the Benkelman beam; and measuring riding surface roughness.

The methods and techniques utilized by the group are described in Chapter 5 of Volume 2 of this report, while the results of the statistical analysis of the data (represented by equations and models of pavement performance and deterioration) are presented in Volume 7.

CHAPTER 3
EQUATIONS AND MODELS

3.1 INTRODUCTION

The objective of this research project - as defined in the initial documents and reaffirmed in the Agreement between the Brazilian government and the UNDP - was to obtain the interrelationships of the costs of highway construction, maintenance and utilization. These interrelationships would then be expressed in the form of equations and/or parameters, for direct utilization in the planning of highway transportation in Brazil.

To attain the objective of minimizing the total cost of highway transportation - consisting of the sum of the costs of highway construction, maintenance and utilization - the equations obtained would be used in one of the already existent models of highway costs. Among these, the best available models were those developed by the Massachusetts Institute of Technology (MIT) and by the Transport and Road Research Laboratory (TRRL).

The objectives expressed in the PICR terms of reference were achieved, and are presented in this report in the form of equations which express the operating costs of vehicles, as related to the characteristics of the route utilized. Aside from this, modifications were introduced into the World Bank's version of the MIT model, denominated *Highway Design and Maintenance Model (HDM)*, the Brazilian version of which has been termed the *Model of Interrelationships of Highway Costs (MICR)*.

Equations for general use in highway planning are presented in Volumes 5, 6 and 7 of this report, while Volume 11 demonstrates how such equations may be programmed in electronic calculators and micro-computers.

The models produced as a result of the combination of the equations are described in Volumes 8, 9 and 10 of this report.

3.2 EQUATIONS

The equations obtained by the PICR were derived from the

data obtained by the different data gathering groups. These equations are divided into three groups, for the purpose of calculating:

1 - Operating cost of the different classes of vehicles, broken down into their major items, as a function of the road characteristics (geometry and surface quality);

2 - Equations and models capable of determining free-flow speeds and fuel consumption for the different classes of vehicles, as a function of the road characteristics (geometry and roughness);

3 - Equations and models which, once the characteristics of climate, traffic, etc. are known, simulate the deterioration of a highway and make it possible to evaluate the costs and benefits of alternative maintenance standards.

3.2.1 *User's Costs*

The analysis of the data gathered made it possible to develop a series of equations capable of calculating the operating costs of the different classes of vehicles, and of correlating them to the roughness and the horizontal and vertical geometry of the section under study.

Whenever possible, the result was expressed in physical quantities, so as to eliminate the effect of inflation. For example, fuel is expressed in liters per 1,000 km, and tires are expressed in units per 100,000 km, etc. The prices, therefore, will be those in force on the market when the user applies the equations. Only in the case of parts and mechanic labor was this procedure not applied. In this case, the manufacturers supplied data on the growth of the prices of parts from January 1976 to December 1981, and these were compared to the prices of new vehicles. During this period, the percentage relation between the prices of parts and of new vehicles remained constant. The prices considered in the equations were those in force in December 1981.

By the fact that the comparison between the costs predicted by the equations and the rates charged by the transportation companies showed a high degree of correspondence, it was concluded that the predictions were compatible with the national highway transportation market.

The results, as well as the methods and techniques of analysis utilized, are fully documented and described in Volume 5 of this report.

3.2.2 *Traffic Performance and Fuel Consumption*

On the basis of the data gathered on vehicle performance, equations were generated to calculate the speed of circulation of the different vehicle classes, at differing load levels, as a function of surface roughness and horizontal and vertical geometry.

By means of controlled experiments, vehicle operation was simulated on sections which included different combinations of geometry and roughness, on which fuel consumption measurements were carried out. These simulations and measurements were carried out in the following speed modes: constant speed, acceleration and deceleration.

The observations, measurements and simulations carried out by the team have made it possible to gain knowledge on the performance of Brazilian highway vehicles at differing levels of traffic, ranging from low volume roads, on which the vehicle travelled at free-flow speed, to very high volumes roads, on which lines of vehicles formed and even traffic congestion were found to exist.

The results, as well as the methods and techniques of analysis, are fully documented and described in Volume 6 of this report.

3.2.3 *Pavement Deterioration*

The analysis of the data obtained by the group responsible for the study of pavement deterioration produced a series of equations capable of supplying indications on road performance, quantifying their deterioration and measuring the benefit of maintenance activities.

In some respects the results are promising, since the data gathered has led to improved understanding of the phenomenon of highway deterioration under the effect of traffic and Brazilian climatic conditions.

In the case of sections with no maintenance or those with only routine maintenance, the equations obtained made it possible to predict the beginning of deterioration and its evolution, as a function of climate, traffic and the structural characteristics of the pavements.

The deterioration of a highway can be characterized by the roughness of the riding surface and by the fatigue of the materials that make up its structure. Even though there is a certain correlation between these phenomena, the factor which has the greatest influence on the operating costs of vehicles is, certainly, the condition of the riding surface, for it constitutes the interface between the road and the vehicle.

The equations and models produced on the basis of the analysis of the data collected seek to predict road deterioration and express this in terms of structural fatigue and increased surface roughness.

The results, as well as the methods and techniques of analysis utilized, are fully documented and described in Volume 7 of this report.

3.3 *MODELS*

The Model of Interrelationship of Highway Costs (MICR) is an adaptation of the 1979 version of the model produced by the World Bank, which was derived from the *Road Investment Analysis Model (RIAM)*, as conceived by the Massachusetts Institute of Technology (MIT) for the World Bank. Equations, correlations and parameters obtained by the PICR were incorporated into this model.

This model - cited in the PICR Terms of Reference as its long-term objective - should make it possible to minimize the overall costs of highway transportation. Though it is an important instrument of highway planning, it still needs to be improved.

It should also be made clear that the expression *minimize*

the overall costs of highway transportation should not be interpreted as the minimization of a continuous and derivable function, since the MIT/TRRL/MICR models provide a discrete series of project options of construction, maintenance policies and highway utilization. It would be more correct to state that it deals with a heuristic procedure of choice of the lowest cost option within a limited series of alternative projects. Furthermore, this process refers to the standards of construction and maintenance of a link, which is the result of subdividing a highway section into various segments, for the purpose of obtaining the necessary homogeneity.

During the period of analysis under consideration, the Model makes an annual calculation of the costs of construction and maintenance of a road, together with the operating costs of all the vehicles which utilize the road. It then adds them together for the period under consideration and applies the discount rate chosen by the analyst.

The Model of Interrelationships of Highway Costs (MICR) is presented in Volume 8 of this report.

The data obtained in the Traffic Studies described the performance of the different classes of vehicles in the national fleet, as a function of the vertical and horizontal geometry and surface quality (roughness) of the road. This information made it possible to develop the Model for Simulating Traffic (MST) and the Model of Time and Fuel Consumption (MTC).

The Model for Simulating Traffic makes it possible to evaluate the service levels of the highway, determining where and when lines form and congestion occurs as a result of traffic growth and vehicle-vehicle interaction. Since it makes it possible to evaluate the capacity of our highway network on a link by link basis, it is an important instrument which is expected to be widely used in Brazilian highway planning.

The Model of Time and Fuel Consumption, which was originally conceived only for the purpose of generating aggregate equations of speed and fuel consumption for use in the MICR, proved to be potentially even more important for use in highway planning and, as a consequence, came to be treated separately. The MTC makes it possible

to calculate, at each moment, along a given highway section, the time necessary to cover this section and the fuel consumed during this time.

The conjugation of these two models will make it possible to obtain the speed profile of a given highway section and, on the basis of this information it will be possible to calculate travel time and fuel consumption.

The Traffic Simulation (MST) and Time and Fuel Model (MTC) are presented in Volumes 10 and 9 of this report.

CHAPTER 4
GENERAL EVALUATION

4.1 INTRODUCTION

The singular magnitude of this research project required that many Brazilian and foreign technicians, from various national and international teaching and research institutions, be brought together into a multidisciplinary team. At one point, the technical team had 36 professionals with undergraduate or graduate degrees, 11 of whom were foreigners. During the entire course of the work, the team was involved in a highly valuable professional exchange of experiences.

In the light of the substantial progress made in terms of knowledge of highway costs, the result obtained can, in general, be considered as satisfactory. However, just as in any other research project, many doubts and questions were raised, and their clarification will demand a good deal of additional work. Although they may be modified or updated as a consequence of the studies and research going on both here and abroad, the equations that represent the interrelationships of highway costs may henceforward be utilized by Brazilian technicians in the task of highway planning.

There is a need to improve the three models - a task GEIPOT is now undertaking - so that new versions of the Model of Highway Costs (MICR), the Model of Time and Fuel Consumption (MTC) and the Model for Simulating Traffic (MST) will be forthcoming and overcome some of their current limitations.

4.2 SURVEY OF USER COSTS

This was the aspect of the PICR that involved the greatest number of problems and uncertainties since, at the very beginning of the work it was found that the majority of the highway users did not possess trustworthy records of the different items that compose the total operating cost of vehicles, with the sole exception of fuel consumption.

The group responsible for gathering data on user costs had to develop special techniques, adapted to the size and structure

of the companies and individuals involved. In some cases, when the desired information did not exist, specific methods were created or adapted to the records of the transportation companies. Special attention had to be given to the data gathered from owner drivers. Normally, these users did not possess detailed records on operating costs, thus demanding additional work in order to obtain trustworthy information on the different cost elements, some of which are essential to the composition of the total cost.

Another important aspect was the reference file on the routes chosen for collecting information on operating costs. It was necessary to design, construct and adapt the instruments which, installed in the PICR vehicles, would quantify routes in terms of their horizontal and vertical geometry and surface quality.

The methods and techniques utilized by the group responsible for collecting this data are described in Chapter 3 of Volume 2.

Equations for calculating the costs of the different items which compose the operating cost of vehicles resulted from the analysis of the data collected. As a consequence of both a reanalysis of the data collected in the PICR file and of new research efforts, the results obtained should be perfected in the future. The results are fully documented in Volume 5 of this report and, contrary to certain previously utilized procedures, are consistent with the rates and freights charged by transportation companies.

The cost variables in the equations are expressed in physical terms, with the exception of parts and expenditures on mechanic's labor. Since it is impossible to quantify the latter in physical terms, the values are expressed in cruzeiros. This preference for physical units was designed to prevent the invalidation of the PICR results due to disproportionate increases in the prices of the different cost items. In the case of parts, a specific deflator was created to correct the nominal monetary values, since it was observed that increases in the prices of spare parts closely accompany the percentage increases in the prices of new vehicles.

The results of the PICR represent a distinct improvement on other studies whose hypotheses are less reliable and whose empir-

ical basis is several decades old. In the future, additional research will be necessary to adapt the conclusions of this study to a changing of the national vehicle fleet, to the use of new fuels and to the technological development of vehicles. However, since these modifications will occur in a gradual and progressive manner, the conclusions presented herein will be of great utility in the years to come, while the PICR models can be updated as such changes come about.

4.3 TRAFFIC STUDIES

The work developed in this area consisted of observing and surveying road users' behavior in terms of vehicle speed under different combinations of road geometry and surface quality. This behavior was then simulated in vehicles that were representative of the different classes and which were equipped with instruments designed to measure fuel consumption.

The results of these observations and experiments made it possible to characterize the performance of the different classes of vehicles of the national fleet and to develop two simulation models that will be quite useful in highway planning. They are the Model of Time and Fuel Consumption (MTC) and the Model for Simulating Traffic (MST).

The results obtained are of good quality, since they are derived from experiments carried out with the major factors under control. In the future, some complementary experiments, together with improved analysis techniques, will generate more solid equations and data.

The methods and techniques applied to obtain the data are described in Chapter 4 of Volume 2 of this report. Volume 6 deals with the analysis of the data and describes and documents the conclusions.

4.4 STUDY OF HIGHWAY DETERIORATION

During the research period, data was collected and measure-

ments were made on highway sections that fitted the factorial matrix cells, which were designed in such a way as to represent the varied universe of Brazilian paved and unpaved roads, with different levels of traffic.

The characterization of the structures obeyed the test techniques practiced in Brazil under DNER norms. For the first time in this country, the test for determining the resilient modulus (MR) of the materials utilized in road construction was applied in a systematic manner.

Also for the first time in Brazil, systematic measurements of road roughness were made. The *Mays-Ride-Meter*, known simply as the *Maysmeter*, was utilized in these measurements. To ensure the trustworthiness of these measurements, the *GMR-Profilometer*, also called *Surface Dynamics Profilometer*, an instrument of high technical sophistication, was employed in the calibration of the Maysmeters.

The methods and techniques utilized in collecting data, and undertaking measurements and experiments are described in Chapter 5 of Volume 2, while the results obtained from data analysis are documented and presented in Volume 7 of this report.

In general, the equations and models developed to calculate the beginning and progression of paved-road deterioration are of good quality and, in some aspects, represent a substantial increase in our understanding of the performance of the structures of Brazilian paved roads.

Insofar as unpaved roads are concerned, the results obtained still seem to be inadequate for general use, and should thus be employed with caution and reservations. Additional studies have already been recommended so as to obtain more realistic and trustworthy models for use in highway planning.

4.5 MODELS

Among the initial objectives of the PICR, the adaptation and development of a model of highway costs for Brazilian needs was

explicitly included. In the terms of reference of the project, the *Highway Design Model* (*HDM*) and the *Road Transport Investment Model* (*RITM*) are explicitly cited as those most studied for this adaptation.

The 1979 version of the HDM was selected and the equations and correlations obtained by the PICR were introduced into this model. This adaptation was termed *Model of Interrelationship of Highway Costs* (*MICR*) and is described in Volume 8 of this report.

At the present time, the MICR is being tested by the DNER and by GEIPOT in studies of the feasibility of investments in highway maintenance and rehabilitation. The knowledge acquired through the use of the HDM will make it possible, over the short term, to produce a new, more flexible and improved version of this Model, for wider use in the future.

Initially, the traffic studies and experiments made it possible to develop the Model of Time and Fuel Consumption (MTC), which had the sole function of determining the parameters for use as inputs for the Highway Cost Model. However, since the MTC proved to have greater potential for application, a new and improved version of this Model will be developed for use in highway planning. The description of the current version of the Model and the outlook for future improvements are found in Volume 9 of this report.

The Model for Simulating Traffic (MST) was developed as a subproduct of the traffic studies, and is described in Volume 10 of this report. In the new version of the MST, the MTC will be included as a subroutine. In this way, the MST will acquire the capacity to calculate travel time and fuel consumption in non-free traffic flow.

The combined use of these models (MST and MTC) will make it possible for the highway planner to evaluate the performance of the fleet on a given highway section, in terms of both travel time and fuel consumption. It will also make it possible to determine when and where a given highway ceases to possess free-flow traffic conditions, a situation that causes a decline in service level and performance of the fleet by reducing circulation speed and increasing fuel consumption. These data will indicate where and when highway authorities should intervene to ensure a better flow of traffic on

the highway, through the rectification of design, construction of a third (climbing) lane, duplication, etc.

In their present versions, the models contain certain deficiencies and must be perfected insofar as conception and computer language are concerned. These shortcomings will be corrected in the new versions, a task GEIPOT is now carrying out, with the aim of providing increasingly useful models for Brazilian highway planning.

CHAPTER 5
OVERVIEW OF THIS REPORT

This Final Report on the ICR Research is composed of 12 main volumes, each published in both Portuguese and English, which provide a full description of the activities of this research project - its creation and organization, its data collection, methods and techniques, and its results and conclusions.

In addition to these main volumes, both the user's manuals and the documentation of the computer programs for the models developed by the PICR are available as appendices (bound separately and printed in limited editions).

As complementary information for technicians and planners, all the documentation produced during the research, under the form of progress reports and technical memoranda, has been grouped into 53 volumes termed "Working Documents", which are also listed in this chapter.

The following pages present a summary of each of the 12 volumes of the Final Report, as well as a list of the Working Documents with a synopsis of their content.

5.1 VOLUME 1 - SUMMARY OF THE ICR RESEARCH

5.1.1 Structure of Volume 1

CHAPTER 1 - Background, Objectives, Organization

CHAPTER 2 - Methods, Instruments and Basic Data

CHAPTER 3 - Equations and Models

CHAPTER 4 - General Evaluation

CHAPTER 5 - Overview of this Report

5.1.2 *Summary of Volume 1*

This volume describes the objectives of the Research on the Interrelationships Between Costs of Highway Construction, Maintenance and Utilization (PICR), as well as the data and variables covered by its surveys and experiments. It contains a brief description of the work carried out during the PICR, its organization and the basic data surveyed, and also indicates where this information can be found in the different volumes of this report, evaluating the tasks performed.

The principal objective of the PICR was the development of methods and models which would minimize the cost of highway transportation in Brazil, particularly on non-urban highways characterized by a low volume of traffic. To reach this objective, wide-ranging field research was performed - one of the largest projects of its type ever carried out in Brazil or abroad - with the objective of determining the costs of the three major components of the *total cost of highway transportation*, namely: the costs of highway construction, maintenance and utilization. In short, an effort was made to determine the influence of highway characteristics on the cost of vehicle operation. As major factors, highway geometry and surface quality were studied, to quantify their influence on operating cost. Traffic-provoked highway deterioration was also studied, as well as the behavior of highway users.

This Final Report is composed of 12 volumes, 6 appendices (in the form of Manuals for the three models developed) and 53 Working Documents (containing all of the documentation produced during the research project).

5.2 VOLUME 2 - METHODS AND ORGANIZATION

5.2.1 Structure of Volume 2

CHAPTER 1 - Introduction

CHAPTER 2 - General Method

CHAPTER 3 - User Costs Survey

CHAPTER 4 - Methods of Gathering Data on Traffic Behavior

CHAPTER 5 - Pavement Deterioration Studies

CHAPTER 6 - Analytical Procedures

CHAPTER 7 - An Evaluation of Methodology and Organization

5.2.2 *Summary of Volume 2*

This volume describes the objectives of the Research on the Interrelationships Between Costs of Highway Construction, Maintenance and Utilization (PICR), the data and variables included in PICR surveys and experiments, and the procedures followed in data collection and analysis.

The principal objective of PICR was to develop methods and models to minimize the cost of transportation on both paved and unpaved low-volume roads in Brazil. To obtain this objective, one of the largest highway research projects ever undertaken, here or abroad, was initiated to determine the interrelationships of the three main components of highway transportation, namely, road construction costs, road maintenance costs, and the operating costs incurred by the users of these roads. It was assumed that the variables which characterize a road, such as riding surface quality, and vertical and horizontal geometry, affected significantly the operating costs of vehicles which used the road. If mathematical functions could be obtained to describe the impact of each variable on vehicle operating costs, it would be possible to evaluate the effect of different construction and maintenance standards on the total cost. The ICR Research developed a model to depict the interrelationships of the highway costs, termed the Highway Costs Model (MICR). This Model includes these equations and was designed to allow planners to choose, among a given number of design and maintenance alternatives, the one that minimizes the total cost of highway transportation.

During the research it was noted that other results and applications would be very useful as a means of improving the MICR equations or for independent applications. The information obtained is useful as an aid in developing energy conservation policies, and furnishes new concepts for establishing the dimensions of flexible pavements, as well as correlations on the capacity of roads, permits the calculation of the benefits resulting from improving the design of a road and the determination of the speed where minimum fuel consumption occurs for different types of vehicles. The PICR has also developed one of the most complete studies on user costs presently available.

On the basis of the models and studies previously developed by the Massachusetts Institute of Technology and by the Transport and Road Research Laboratory, the PICR staff sought to perfect the specifi-

cation of the interrelationships of costs in Brazilian conditions. The basic information consists of (1) data furnished by road users and by highway authorities; (2) physical measurements; and (3) experiments with the major variables under control.

To analyse the effects of different highway characteristics on maintenance and utilization costs, a factorial matrix was designed whose cells represent different combinations of roughness and levels of horizontal and vertical geometry on Brazilian roads. Pavement structures were characterized through *in-situ* measurements and laboratory tests. At selected sections, the PICR applied several different maintenance levels and observed the subsequent deterioration of these sections.

The researchers and supporting personnel were divided into three groups:

The User Costs Group was responsible for surveying the different components of transportation costs by enterviewing company representatives and ower-drivers operating on the routes studied. This Group sought to obtain the costs for routes of different characteristics, by systematically collecting data on fuel, oil, grease, spare parts, maintenance labor, tires, operating labor, travel time, kilometers run, etc. It also made an inventory of the routes used and measured their riding quality.

The Traffic and User Cost Experiments Group sought to determine experimentally, using its own vehicle fleet, the influence of road characteristics on fuel consumption and travel time, in order to develop the Model of Time and Fuel Consumption (MTC). Subsequently, it studied the possibility of extending the potential usefulness of the PICR to the analysis of roads with a higher level of vehicles, where traffic congestion occurs. The Model for Simulating Traffic (MST) was thus developed to analyse the effects of traffic congestion on fuel consumption and travel times.

The Pavement Performance and Maintenance Studies Group analyzed the effect, over time, of alternative standards of construction, maintenance and traffic volume on road surface roughness.

To accomplish these tasks, the PICR called on the expertise of statisticians and specialists in data processing and analysis, along with technicians in instrumentation maintenance. The personnel respon-

sible for the maintenance of the measuring instruments came to modify the instruments acquired at the outset of the research, since almost all of them had to be adapted to PICR requirements, and also developed new instruments to meet unanticipated needs. The knowledge thus gained is documented in detail in technical memos, and constitutes an important advance in technical and scientific knowledge not envisioned at the beginning of the research.

Doubts and questions also arose as to the nature of the postulated interrelationships, the precision and adequacy of the concepts, and the quality of the measuring instruments. For some of these a satisfactory solution has already been obtained, while additional studies and experiments were required for others and are presently being carried out in Brazil.

5.3 VOLUME 3 - INSTRUMENTATION

5.3.1 Structure of Volume 3

CHAPTER 1 - Introduction

CHAPTER 2 - Road Surface Roughness Measurement System

CHAPTER 3 - The Survey Vehicle

CHAPTER 4 - Traffic Behavior Measuring Equipment

CHAPTER 5 - Pavement Deflection Equipment

CHAPTER 6 - Fuel Consumption Measurement Equipment

CHAPTER 7 - Traffic Counters

CHAPTER 8 - Vehicle Weight Measurements

CHAPTER 9 - Data Conversion Equipment

CHAPTER 10- Measurement of Road Surface Conditions

CHAPTER 11- Meteorological Measurements

CHAPTER 12- Conclusions and Recommendations

5.3.2 *Summary of Volume 3*

The Research on the Interrelationships Between Costs of Highway Construction, Maintenance and Utilization (PICR) was carried out in Brazil included the objective of providing a fundamentally new data base for the economic cost/benefit evaluation of alternative standards of highway construction and maintenance. To form this data base, measuring instruments with a total cost of more than US$750,000 were utilized. The most important of these instruments were manufactured in the U.S.A. specifically for this Research and, therefore, cannot be considered as either completely developed or tested. A major share of the work of the Instrumentation Group of the PICR consisted of developing these instruments and adapting them to the operational conditions found in Brazil. Due to the dimensions and innovative aspects of the Research, it was necessary to design and build highly original apparatuses *in loco*.

Volume 3 presents a brief description of the instruments used in the PICR, explains what they measure, the reason why they were chosen or built, their precision, how they were employed and their degree of trustworthiness. The text also contains bibliographic references, providing the reader with access to the technical and operational details of the equipment described. Manufacturers are also indicated.

Taking into account both the technical problems which arose, as well as the significance and usefulness of the data produced, an evaluation of the performance of each instrument is also presented.

The conclusion in the final chapter is that, in projects of limited duration, such as the PICR, one should avoid the use of instruments which have not been fully tested. Should this prove impossible, it is recommended that sufficient time be dedicated to the development and refinement of the instruments in the environment in which they will be utilized, before initiating actual data gathering.

5.4 VOLUME 4 - STATISTICAL GUIDE

5.4.1 Structure of Volume 4

CHAPTER 1 - Introduction

CHAPTER 2 - PICR Statistics and Sources

CHAPTER 3 - How to Locate the Statistics

CHAPTER 4 - Statistical Index

5.4.2 *Summary of Volume 4*

The *Statistical Guide* provides information on the availability and sources of the statistics contained in the PICR files. It contains an index to allow the reader to locate those parts of the Guide dealing with each alphabetized statistic and its respective file.

The statistics were classified into subgroups by cross referencing the method used to obtain them (collection, survey, and experiment) with their objective (pavement, traffic, and road users). The Guide indicates the purpose of the statistics of each subgroup, along with their sources and the procedures used in gathering them.

In the chapter *How to Locate the Statistics*, a brief comment is made on each of the statistics and the file where they are kept. The location code is also given.

The *Statistical Index* presents all the statistics alphabetized according to their designations, indicates the item in the chapter *PICR Statistics and Their Origin* where each one can be found, gives the code that leads to a specific comment about the statistic, and indicates the card(s) or file(s) showing where they can be located.

5.5 VOLUME 5 - STUDY OF ROAD USER COSTS

5.5.1 Structure of Volume 5

CHAPTER 1 - Objectives, Scope and Organization

CHAPTER 2 - Analysis Procedures

CHAPTER 3 - Analysis Results

CHAPTER 4 - Total Vehicle Operating Costs

CHAPTER 5 - Conclusions and Recommendations

5.5.2 *Summary of Volume 5*

Volume 5 records the activities of the PICR User Cost Surveys Group which conducted a large vehicle operating cost survey in Central, Western and Southern Brazil during the period 1975 to 1981. The Group was responsible for the collection and analysis of vehicle maintenance parts and labor costs, tire costs, depreciation and interest charges, and drivers' salaries. In addition, fuel consumption and speed data were collected (the latter when easily available) to serve as consistency checks on the equations derived from experimental data. The Group was also responsible for collecting data on surface roughness, as well as vertical and horizontal geometry characteristics of the routes of those operators registered in the survey.

The primary data collection phase ran from 1975 to 1979 and 26 staff members were employed, comprising 14 field workers, 8 clerical assistants and 4 supervisors. More than two years was spent in developing and testing appropriate methodologies, documentation and data processing systems for the collection, checking, storage and analysis of both operating cost and highway characteristics data. Contact was made with over 300 companies and more than 2500 vehicles were registered for survey membership. Operating cost data were then collected on a regular basis from company records. Many difficulties had to be overcome during this period. A number of companies only had records of a few cost components and, where possible, assistance was given to provide the necessary documentation and training to collect missing items. Some companies dropped out of the survey and data collection in others was discontinued because the route characteristics of their vehicles were found to be redundant for the needs of the PICR. Finally, data on over 1600 vehicles derived from 132 companies were available in 1979 for preliminary analysis.

Highway characteristics were collected using two specially instrumented vehicles. Roughness was measured with a Maysmeter and calibration maintained through a GM Profilometer and Quarter-Car-Simulator which generated a series of profiles for a calibration course of highway sections established near Brasilia. Vertical geometry was measured using a linear accelerometer connected to a panel scale capable of recording grade changes of $\pm$ 1% to $\pm$ 12%. Horizontal measurements were taken from a standard aircraft directional gyro compass, mounted in the survey vehicles. Over 85,000 km of roughness and geometry data

were collected after measuring more than 36,000 km of operators' routes. After editing, these data had then to be combined with the vehicle operating cost data so that a single file comprising both dependent and independent variables could be made available for analysis.

The second PICR Phase covered the period 1980 to 1981. The staff was reduced to 5, who were principally engaged in conducting more detailed analyses. The statistical methods employed were divided into distinct groups of techniques and advanced econometric procedures were used. An important technique which provided a number of the equations reported herein was the generalized least squares estimation of the error component model. The latter considers the company specific error term and the vehicle specific error term which jointly form the components of the unknown random error term considered by ordinary least squares techniques. This is perhaps the first reported application of error components analysis in the field of transportation studies. All the different techniques are detailed in the analysis procedures section of this volume. The analyst was able to run a selection of these techniques simultaneously on any data set. This made comparison of the results and the choices of recommended equations an easier task.

Vehicle operating cost information presented for analysis cover the full range of vehicles operating on Brazilian highways. These are grouped into cars, utility vehicles, buses, medium trucks and heavy articulated vehicles for analysis purposes. The results of the analyses of fuel consumption, oil and grease consumption, maintenance parts and labor, tire consumption, depreciation and interest charges and vehicle speed are presented. All five vehicles classes are used in the analyses, except for speed, which is restricted to cars and buses, and tire costs, which are analysed by tire size. The equations recommended in this volume concentrate on estimating roughness, vehicle age, and other characteristics (where appropriate), and geometry effects only when these appear unambiguous. A substantial amount of time was spent estimating the effect of geometry on the various operating cost items and details on the progress made are given in the main text and selected appendices. It is clear that more time is needed to resolve this issue. Further small analyses, together with the findings of the operating cost study in India, presently being analysed, may result in the emergence of a more coherent pattern of the geometry effect on user costs.

The PICR User Survey data are the most comprehensive collected to date and are important both to Brazil, where out-of-date cost tables are widely used, and to the international research community, where they complement the Kenya, Carribean and India studies. The PICR survey data covers a spectrum of vehicle types and appears to be the only study with a full range of truck classes. The data have now passed through several phases of analysis and the results presented in this volume, together with the relevant technical memoranda, can be regarded as an interim final form. They are now ready for extensive evaluation in a variety of economic exercises. When they have passed these tests they can be viewed as being in final form for the period ending December 31, 1981.

Comparisons are made between total operating costs predicted from the various equations recommended in this volume and prevailing transport service rates and tariffs. The results are encouraging and give confidence to the view that the recommended equations will provide better predictions of vehicle operating costs than anything currently used in Brazil. It is recommended that a user cost manual be prepared to allow the results of the PICR survey to be widely disseminated.

5.6 VOLUME 6 - STUDY OF VEHICLE BEHAVIOR AND PERFORMANCE

5.6.1 Structure of Volume 6

CHAPTER 1 - Introduction

CHAPTER 2 - Influence of Speed Limit on Data Collected

CHAPTER 3 - Influence of Road Riding Quality

CHAPTER 4 - Results of Free-Flow Speed Surveys

CHAPTER 5 - Results of Speed-Mode Survey as Vehicles Approach Obstacles or Small-Radius Curves

CHAPTER 6 - Results of the Experiment on Vehicle Acceleration Measurements on Positive and Negative Grades

CHAPTER 7 - Influence of Adding Alcohol to Gasoline

CHAPTER 8 - Results of the Experiments on Fuel Consumption Measurement at Steady-State Speed

CHAPTER 9 - Influence of Momentum Acquired by Vehicles on Negative Grades

CHAPTER 10 - Results of the Experiment on Fuel Consumption Measurement in Deceleration Mode

CHAPTER 11 - Results of the Experiment on Fuel Consumption Measurement in Acceleration Mode

5.6.2 *Summary of Volume 6*

The type of vehicle, its operating speed, and highway characteristics, such as grades, curves and surface roughness, are key variables in determining fuel consumption and travel times. The Research on the Interrelationships Between Costs of Highway Construction, Maintenance and Utilization (PICR) thus sought to specify the relationships among these variables by conducting controlled experiments and by observing vehicle behavior on highways with given characteristics. This knowledge enabled the PICR team to utilize the Model of Time and Fuel Consumption (MTC) to calculate travel time and fuel consumption for any normal highway design or existing roadway whose characteristics are known. If congestion is present, the MTC can be used in the Model for Simulating Traffic (MST) to achieve similar goals. Volume 6 describes those experiments and observations and their results (the MTC and MST are described in Volumes 9 and 10 of this report, respectively).

The road test sections were selected in such a way as to ensure the inclusion of principal characteristics of different types of roads comprising the Brazilian highway network. These characteristics included type of road surface (paved or unpaved), grades (from 0 to $\pm$ 8%) and curves (radii from 20 m to 3,000 m).

5.7 VOLUME 7 - STUDY OF PAVEMENT MAINTENANCE AND DETERIORATION

5.7.1 Structure of Volume 7

CHAPTER 1 - Introduction

CHAPTER 2 - Paved Road Roughness Analysis

CHAPTER 3 - Paved Road Cracking and Rut Depth Analysis

CHAPTER 4 - Unpaved Road Roughness Analysis

CHAPTER 5 - Unpaved Road Gravel Loss Analysis

CHAPTER 6 - Unpaved Road Rut Depth Analysis

CHAPTER 7 - Conclusions and Recommendations

5.7.2 *Summary of Volume 7*

The primary objective of the Pavement and Maintenance Studies was to develop models to describe pavement performance and behavior for Brazilian paved and unpaved roads. The models are needed to relate road user costs and road maintenance costs to roadway conditions in order to predict total highway transport costs.

The experimental design sampling matrix addresses the major factors thought to influence pavement performance and behavior. Existing road sections were selected and used to satisfy the requirements of the sampling matrix. Detailed information on traffic, vehicle weights and material characteristics was collected for each section. The same data were collected on unpaved roads as well as information related to blading and regravelling. On paved roads, the dependent variables measured were roughness, rut depth, cracking and patching. The dependent variables studied on unpaved roads included roughness, rut depth, and gravel loss.

The results presented in this report are based on data files completed in 1981. The data collection effort will continue and future analyses of the expanded data base are expected to change some of the equations. Because of the preliminary nature of the relationships presented, no consideration was given to modifying the equations so that they could be directly implemented. Therefore, engineering judgement and experience should be used in any application of the equations. Finally, the application of the models is defined by factor ranges and the study environment. Extreme care should be taken in extrapolating the models beyond these limits.

5.8 VOLUME 8 - HIGHWAY COSTS MODEL (MICR)

5.8.1 Structure of Volume 8

CHAPTER 1 - Introduction

CHAPTER 2 - Objectives and Major Characteristics of the MICR

CHAPTER 3 - Considerations Regarding the Model

5.8.2 *Summary of Volume 8*

Volume 8 describes the major characteristics of the Highway Costs Model (MICR), which constitutes one of the products of the Research on the Interrelationships Between Costs of Highway Construction, Maintenance and Utilization (PICR), carried out in Brazil.

Chapter 1 presents the background of the MICR, in order to inform the reader about the history of its development. There is also a brief presentation of the beginning, objectives and development of PICR studies.

Chapter 2 describes the objectives and major characteristics of the Model. Finally, Chapter 3 contains a number of considerations regarding the Model, describing its limitations, analyzing its fundamental variables, suggesting improvements and commenting on the validity of its application by Brazilian highway authorities.

The MICR *User's Manual* is bound separately in a limited edition. Information on the program is also available (in the Portuguese version).

5.9 VOLUME 9 - MODEL OF TIME AND FUEL CONSUMPTION (MTC)

5.9.1 Structure of Volume 9

CHAPTER 1 - Introduction

CHAPTER 2 - Logic and Basic Conceptions of the MTC

CHAPTER 3 - Equations Used in the MTC Program

CHAPTER 4 - MTC Limitations and Outlook

CHAPTER 5 - Applications and Examples

5.9.2 *Summary of Volume 9*

The Model of Time and Fuel Consumption (MTC) is presented with all the information and elements needed for immediate utilization by the nation's highway transportation planners.

Chapter 1 explains the purpose of the Model and presents to the reader interested in evaluating the potentialities and limitations of the MTC the necessity of familiarizing himself with the tests on which the Model is based. Although this requires examination of other ICR Research publications, this Chapter contains figures and schematic drawings which, in a simplified manner, indicate how these tests were utilized and associated in the elaboration of the MTC.

Chapter 2 contains the primary objective of the document, a detailed description of the fundamental concepts and the logic of the MTC. Chapter 3 presents the speed and fuel consumption equations utilized in the MTC, together with the tests which gave rise to these equations and the respective mnemonics utilized in the MTC program. Chapter 4 demonstrates the major limitations of the present version of the Model, and suggests how to correct or by-pass them in the near future.

MTC application possibilities are analyzed in the final chapter. It initially evaluates the MTC as a model for independent use in forecasting the speed and fuel consumption of vehicles on specific road segments, whose geometric and road surface characteristics are already known, at the project scale level. This is followed by a discussion of the applications of the MTC as an auxiliary model for generating equations for forecasting speed and consumption, through the utilization of more aggregate road description and geometry variables.

Working Document No. 18 (bound separately in a limited edition) contains the *MTC User's Manual*. It supplies conventional instructions on roads, and diverse Model application examples, along with a number of explanations on certain aspects of the MTC program. These clarifications are aimed at avoiding most of the doubts which can occur to those who, for the first time, prepare and codify the entries of the MTC program.

Working Document No. 18 also presents the *MTC Programmer's Manual*, with additional information on the MTC, including the definition of all program variables and a complete flow-chart and program listing.

5.10 VOLUME 10 - MODEL FOR SIMULATING TRAFFIC (MST)

5.10.1 Structure of Volume 10

CHAPTER 1 - Introduction

CHAPTER 2 - Concepts Inherent to Traffic Simulation

CHAPTER 3 - Generation of Free-Speed Profile

CHAPTER 4 - Vehicle-Travel Simulation

CHAPTER 5 - Operation of the Model

CHAPTER 6 - Calibration and Validation of the Model

CHAPTER 7 - Applications of the Model

CHAPTER 8 - Summary, Conclusions and Recommendations

APPENDIX - MST Computer Output

5.10.2 *Summary of Volume 10*

The Model for Simulating Traffic (MST) is one of the products of the Research on the Interrelationships Between Costs of Highway Construction, Maintenance and Utilization (PICR). The Model simulates traffic flow on two-lane highway sections of any vertical and horizontal alignment complexity. This makes it possible to evaluate the impact of transportation policies and strategies, such as construction of a third (climbing) lane, construction of a highway intersection, or the introduction of new transportation technologies, such as that represented by the multitrailer ("road train"). The MST also makes it possible to compute travel times, operating speeds, fuel consumption and other data that can be used by the transportation planner in analyzing the effects of transportation policies and strategies.

The major purpose of the Model is to specify the relationships between both operating speed and fuel consumption, on one hand, and highway geometry, type of surface and roughness, on the other. This relationship may also be used in the Highway Planning Model, now being prepared by GEIPOT for the Ministry of Transportation, which seeks to define the relationships between the three components of highway transportation costs: highway construction, maintenance and utilization.

This document presents the second version of the MST, which is both more efficient and more complete than the first one. A third version of the MST, describing input data in greater detail, is expected to be completed soon.

The MST *User's Manual* is also available (bound separately in a limited number of copies). This manual presents complete instructions for the codification of the input data and Model parameters, together with four examples of applications (present situation of the highway, introduction of a third lane, introduction of a transversal highway with a STOP sign, and the effect on traffic of the application of new technologies or vehicles, such as the multitrailer).

Finally, the *Programmer's Manual* (bound separately in a limited number of copies) furnishes the complete MST flow chart and the listing of the computer program.

5.11 VOLUME 11 - FUNDAMENTAL EQUATIONS

5.11.1 Structure of Volume 11

CHAPTER 1 - Introduction

CHAPTER 2 - Parameters and Statistical Models

CHAPTER 3 - Program

CHAPTER 4 - Concept and Subjective Scales of the Main Variable

CHAPTER 5 - Examples of Application

APPENDIX I- Definition of Variables

5.11.2 *Summary of Volume 11*

The Research on the Interrelationships Between the Costs of Highway Construction, Maintenance and Utilization (PICR) is a continuation of efforts made throughout the world to obtain parameters and statistical equations designed to estimate the rate of deterioration of a given road surface and the operating costs of the vehicles that travel on the road.

This research explains the rate of pavement deterioration on the basis of such characteristics as highway design, traffic and maintenance practices adopted, while vehicle operating costs are quantified on the basis of the type and volume of the vehicles that make up the traffic flow, the highway design and the level of road maintenance.

Once the parameters and statistical equations are logically organized into a computational model, it becomes possible to simulate, in an integrated manner, for the entire life span of a highway or for a given period of analysis, the quantities of materials and services required for maintaining the road, as well as the parts and services necessary for operating the vehicles (road maintenance cost and vehicle operating cost).

The computational model designed to perform the aforementioned functions, in a dynamic and iterative manner, was termed the Highway Costs Model (MICR), and is presented in Volume 8 of this Report.

However, highway planners and analysts do not always need complete simulations (dynamic and iteractive simulations). For example, sometimes they will desire only to calculate the cost of operating a specific type of vehicle under a given set of highway conditions.

The equations presented herein make it possible to determine the operating costs of vehicles according to the method developed by the ICR Research.

The primary objectives of Volume 11 are: (1) to illustrate the utilization of a series of programs for hand calculators (the *Hewlett-Packard HP-97* is used) and microcomputers (*Basic Language*) and (2) to facilitate a number of cost calculations which would otherwise have to be performed by the MICR. For the most part, this volume was prepared before the equations presented in Volume 5 of this report became

available. Therefore, it should be kept in mind that the equations presented herein are based on 1979 data and correspond to those utilized by the MICR in December 1981. These data should be updated as new equations are introduced into the MICR or as the need occurs to use those of Volume 5.

5.12 VOLUME 12 - INDEX TO PICR DOCUMENTS

5.12.1 Structure of Volume 12

CHAPTER 1 - Introduction

CHAPTER 2 - List of Documents Produced by PICR

CHAPTER 3 - Bibliography Consulted

CHAPTER 4 - List of Manufacturers

CHAPTER 5 - List of Authors

CHAPTER 6 - Index of Titles

CHAPTER 7 - Subject Index

5.12.2 *Summary of Volume 12*

The *Index to PICR Documents* permits one to locate the subjects discussed in the Final Report and in the other documents produced by the ICR Research.

The *List of Documents Produced by the PICR* enumerates all the documents produced by the PICR under the format of bibliographical references and are chronologically arranged.

The *Bibliography Consulted* contains the bibliographical references (alphabetically arranged) cited by PICR technicians in their work.

The *List of Manufacturers* is alphabetized according to the name of the manufacturer and includes the company's address. A number refers the reader to the *List of Documents Produced by the PICR* .

The *List of Authors* contains the name of each author, in alphabetical order, followed by a number or numbers which indicate the documents which he or she produced and their location in the *List of Documents Produced by the PICR.*

The *Index of Titles* lists the titles of all documents in alphabetical order, followed by a number or numbers which refer the reader to the *List of Documents Produced by the PICR.*

The *Subject Index* presents, in alphabetical order, "word by word", all the topics discussed in the Final Report and in the other documents produced by PICR.

5.13 WORKING DOCUMENTS

5.13.1 Working Document No. 1

Project Background Documents for the EWG - This volume contains documents submitted by the project's technical team at the first meeting of the Expert Working Group (EWG), to assist in defining the methods and techniques to be followed during data collection.

5.13.2 Working Document No. 2

Summary of Findings - EWG Meeting - This document contains a summary of the conclusions and recommendations which resulted from the meeting between the project team and the EWG.

5.13.3 Working Document No. 3

Appendix to the Project Inception Report - Research Concepts and Procedures - This appendix contains documents that complement the English version of the Inception Report - Concepts and Methodology.

5.13.4 Working Document No. 4

Project Technical Memos 1976 - This is a collection of technical memos produced by the project's technical staff during 1976.

5.13.5 Working Document No. 5

Project Technical Memos 1977 - This is a collection of technical memos produced by the project's technical staff during 1977.

5.13.6 Working Document No. 6

Project Instrumentation Memos - This consists of a description of the measuring instruments used by the PICR.

5.13.7 *Working Document No. 7*

Project Instrumentation - Operational Memos - This is a series of technical memos with instructions on the operation and maintenance of the measuring equipment used by the PICR.

5.13.8 *Working Document No. 8*

User Survey Route Inventory - This document contains a description of a survey of users' routes, whose cost data served as basis for the study. Here a schematic presentation of the distribution of nodes is offered, together with the establishment of the links and routes.

5.13.9 *Working Document No. 9*

Details of Pavement and Maintenance Sections - Here the characteristics of the sections included in the Pavement Deterioration studies are documented.

5.13.10 *Working Document No. 10*

Roughness Measurement Systems - This document describes the various pieces of equipment used for measuring road surface roughness, and a first attempt to correlate the measures generated by the various instruments.

5.13.11 *Working Document No. 11*

Project Technical Memos 1978 and 1979 - This is a collection of technical memos written during 1978 and 1979.

5.13.12 *Working Document No. 12*

Vehicle Weight Data - This document contains data on vehicle weight obtained on Brazilian roads. These data were obtained in order to permit an identification of the loading habit of users.

5.13.13 *Working Document No. 13*

Traffic Flow Information - This document contains information on the traffic countings carried out by the PICR with the objective of studying road deterioration.

5.13.14 *Working Document No. 14*

Material Characteristics of Pavement Study Sections - This document presents the results of the tests made to characterize pavement layers for the sections included in the pavement deterioration study.

5.13.15 *Working Document No. 15*

Paved and Unpaved Road Performance Parameters - This document characterizes the parameters which indicate the deterioration of paved and unpaved roads.

5.13.16 *Working Document No. 16*

Data Collection Procedures for the Fuel and Speed Experiments - This paper includes the methods and techniques of the experiments which involve both vehicle operation simulations and fuel consumption measurements.

5.13.17 *Working Document No. 17*

Test Section for the Fuel and Speed Experiment - This paper documents the characteristics of the several sections selected to make it possible to simulate vehicle operation and measure fuel consumption.

5.13.18 *Working Document No. 18*

Time and Fuel Algorithm - This is the first version of the Model of Time and Fuel Consumption (MTC), which was then called the Time and Fuel Algorithm (TAFA). This topic is presented in Volume 9 of the Final Report in a more finished form.

5.13.19 *Working Document No. 19*

User Survey Methodology and Documents - This document presents the methods and techniques (standardized forms, etc.) used by the User Costs Group in data collection.

5.13.20 *Working Document No. 20-I*

Documentation of the Pavement Studies Data Files - This volume presents the documentation of the Pavement Deterioration Study Group.

5.13.21 *Working Document No. 20-II*

Documentation of the Traffic Experiments Data Files - This volume presents the documentation of the Traffic Study Group's files.

5.13.22 *Working Document No. 20-III*

Documentation of the User Cost Surveys Data Files - This volume presents the documentation pertaining to the User Cost Surveys files.

5.13.23 *Working Document No. 21*

Resultados de Deflexões Medidas com Viga Benkelman - This document consolidates the results of pavement-deflection measurements obtained with the use of the Benkelman Beam on PICR test sections.

5.13.24 *Working Document No. 22*

A Procedure for Obtaining a Stable Roughness Scale from Rod Level Profiles - This is part of the Ph.D. Thesis submitted to the University of Texas at Austin, by César Augusto Vieira de Queiroz. It discusses an attempt to establish the roughness level of a road surface through conventional topographic measurements.

5.13.25 *Working Document No. 23*

An Evaluation of Unpaved Road Performance and Maintenance - This is a Ph.D. Thesis submitted to the University of Texas at Austin, by Alex T. Visser. The data from which the models and equations were developed were obtained by the PICR.

5.13.26 *Working Document No. 24*

User Cost Analysis Memos - 1980 - This volume contains the technical memos which document the analysis of the users costs files carried out during 1980.

5.13.27 *Working Document No. 25*

Performance Prediction Models for Pavement Management in Brazil - This is the Ph.D. Thesis of César Augusto V. de Queiroz, submitted to the University of Texas at Austin. The data used for developing the models contained therein are from the PICR.

5.13.28 *Working Document No. 26*

Boletins Técnicos Nº 1 to 11 - This is a collection of Technical Bulletins written and distributed by technicians directly involved in the collection of data for the Study of Pavement, Maintenance and Deterioration.

5.13.29 *Working Document No. 27*

Resultados dos Levantamentos da Condição dos Pavimentos - This volume contains the results of the survey of the condition of pavements carried out on the test sections included in the Study of Pavement, Maintenance and Deterioration.

5.13.30 *Working Document No. 28*

User Cost Analysis Memos - 1981 - This volume contains the

technical memos which documented the statistical analysis of the User Cost Files carried out during 1981.

5.13.31 *Working Document No. 29*

Resultados de Deflexões Medidas com Dynaflect - This volume contains the results of deflection measurements obtained with the Dynaflect. This instrument induces an elastic deformation in the pavement by applying a small load at 8 cycles per second.

5.13.32 *Working Document No. 30*

Estudo Sobre a Validade dos Dados de Irregularidade da PICR - This volume presents an evaluation of the roughness measurements regarding factors that can distort the results.

5.13.33 *Working Document No. 31*

Road User Cost Surveys (Report III)

Working Document No. 32

Road User Cost on Traffic Experiments (Report IV)

Working Document No. 33

Pavement and Maintenance Studies (Report V)

Working Document No. 34

Instrumentation Report (Report VI) - This is the final report submitted by the Texas Research and Development Foundation (TRDF) to the World Bank at the termination of the TRDF's contract. It shows the ICR Research in December 1979. This report was submitted to the World Bank in June 1980 and its circulation was restricted to the institutions involved in the project.

5.13.34 *Working Document No. 35*

Manual de Recuperação de Informações e Procedimentos de Aná-

lise Estatística - This manual permits the retrieval of any information associated with the statistical procedures adopted by the PICR through December 1979. Data entry for information retrieval is made through key-words or subject matter.

5.13.35 *Working Document No. 36*

Quarterly Progress Report No. 1

Working Document No. 37

Quarterly Progress Report No. 2

Working Document No. 38

Quarterly Progress Report No. 3

Working Document No. 39

Quarterly Progress Report No. 4

Working Document No. 40

Quarterly Progress Report No. 5

Working Document No. 41

Quarterly Progress Report No. 6

Working Document No. 42

Quarterly Progress Report No. 7

Working Document No. 43

Quarterly Progress Report No. 8

Working Document No. 44

Quarterly Progress Report No. 9

Working Document No. 45

Quarterly Progress Report No. 10

Working Document No. 46

Quarterly Progress Report No. 11

Working Document No. 47

Quarterly Progress Report No. 12

Working Document No. 48

Quarterly Progress Report No. 13

Working Document No. 49

Quarterly Progress Report No. 14 - This selection of working documents is a series of quarterly reports written by TRDF for the World Bank as a contract requirement. They explain the progress made, the variations in staff, the difficulties encountered, and the solutions adopted. These reports also contain copies of technical memos written during the period from July 1976 to October 1979.

5.13.36 *Working Document No. 50*

Report I - Inception Report - This is the English version of the *Relatório Preliminar*, which basically describes the organization of the PICR, and the methods and techniques which would be utilized.

5.13.37 *Working Document No. 51*

Report I - Midterm Report - This is the English version of the *Relatório Intermediário*, where a number of preliminary results obtained by PICR are presented.

5.13.38 *Working Document No. 52*

Relatório Preliminar - This is the Portuguese version of the *Inception Report* (Working Document No. 50).

5.13.39 *Working Document No. 53*

Relatório Intermediário - This is the Portuguese version of the *Midterm Report* (Working Document No. 51).