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.