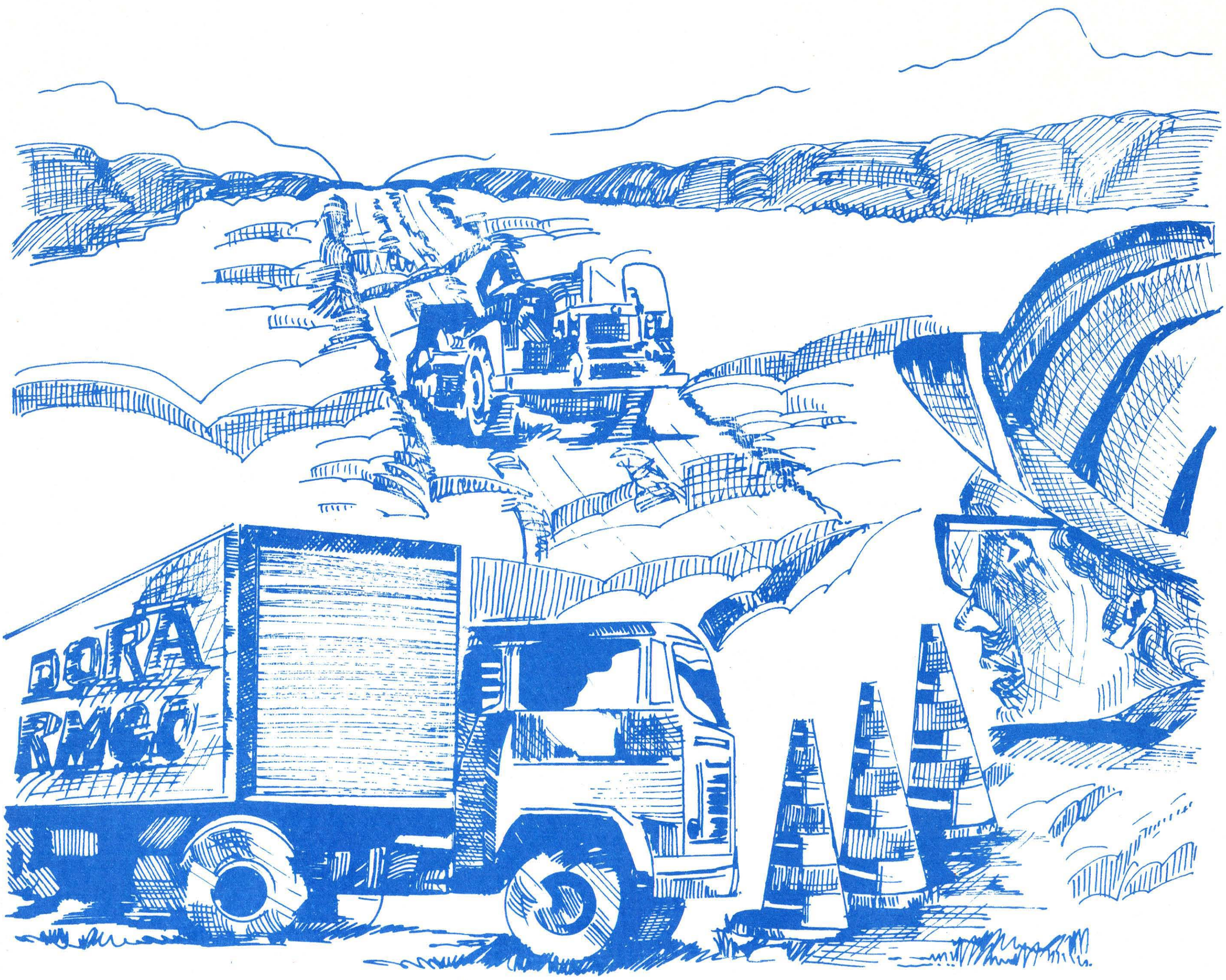
REPÚBLICA FEDERATIVA DO BRASIL

MINISTÉRIO DOS TRANSPORTES

United Nations Development Programme (UNDP)

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

Final Report - 1981



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

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PREPARED BY:

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UNITED NATIONS DEVELOPMENT PROGRAMME (UNDP)
International Bank for Reconstruction and Development (IBRD)
Texas Research and Development Foundation - TRDF

WITH THE PARTICIPATION OF:

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

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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.

1. Rodovias - custos - Brasil 2. Rodovias conservação - Brasil 3. Rodovias - utilização - Brasil - I. Título.

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 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 to 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

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

Aside from explaining the purpose of the Model, Chapter 1 also presents the reader interested in evaluating the potentialities and limitations of the MTC with some considerations on the necessity of familiarizing himself with the tests in which the Model originated. This should be done through examination of the other *ICR Research* publications. However, this Chapter contains figures and schematic drawings which, in a simplified manner, have the objective of indicating just 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 of independent usage 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.

Appendix I (bound separately) 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.

Appendix II (also bound separately) presents the *MTC Programmer's Manual*, with additional information on the MTC, including the definition of all program variables and a complete flowchart and program listing.

CHAPTER 1
INTRODUCTION

Among the most important of the different experiments and surveys carried out by the *Research on the Interrelationships Between Costs of Highway Construction, Maintenance and Utilization* (*ICR Research*) are the surveys on the free speed of the vehicle population and the fuel consumption experiments conducted with the Project's vehicle test fleet.

The results of these experiments, carried out in various Brazilian States during a period of nearly five years, made it possible to produce, for computer use, a mathematical algorithm that predicts the free speed and the fuel consumption of a given fleet of vehicles trafficking on a road of known characteristics.

This algorithm - initially designed just to generate aggregate equations to be used in speed and fuel consumption predictions for global models of highway-investments evaluation - showed, after conclusion of its initial version, a potential for isolated and independent use not foreseen in its initial conception. Consequently, though still used to perform auxiliary functions in the elaboration of the aforementioned models of highway-investments evaluation, it came to be considered as a final product of the *ICR Research*, and was designated the *Model of Time and Fuel Consumption* (*MTC*).

Therefore, correct evaluation of the MTC, whether as an independent model, or an auxiliary model for developing the *Model of the Interrelation of Highway Costs* (*MICR*), requires familiarization with the project, including its implementation and the analysis of the experiments which originated it. Only then will the reader be able to evaluate both the potentialities of the model, derived from its solid experimental foundation, and its limitations, the latter being, to a certain extent, transitory consequences of the new applications envisioned for the MTC.

Such familiarity with the speed and fuel consumption experiments should be gained through the reading of other volumes of this series of *ICR Research* publications, particularly Volume 6. The present Volume, which has the purpose of describing and explaining the basic conceptions and the logic of the Model, contains only a simplified presentation as to how the results of those experiments were organized and utilized in designing the MTC. Figures 1.1 to 1.4, presented below, were conceived with this objective in mind.

Figure 1.1 illustrates that, once the horizontal geometry of the road is known, the MTC, based on the results of Experiment TB-4 (Free Speed on Curves), defines and limits the free speed on all curves of a given road on the basis of radius, roughness, class of vehicle, and so forth. Once this is done, the MTC program considers the road as if it were entirely straight, with sections in which the speed is limited.

Figure 1.2 does not refer to any experiment but illustrates, just as the previous figure, sections of the road where (for legal or safety reasons) speed is also limited. These sections were called *speed-control sections*, and represent stretches where vehicles should travel at a restricted speed that is probably below its capacity. Such stretches include those passing through villages or by Highway Patrol or Inspection Stations, etc. When a speed-control section coincides with a curve, either the curve itself or the restriction imposed by legal or safety reasons may limit speed. In this case, maximum speed will be the lowest of the two, whether imposed legally or by the existence of the curve.

In those road locations where speed is limited neither by speed limits, nor by the curvature itself (Experiment TB-4), the MTC uses a *default* speed limit of 150 km/h. Consequently, the Model then works with one speed-limit profile for the entire road.

Figure 1.3 shows how Experiments TB-1 (Free Speed on Positive Grades), TB-2 (Free Speed on Negative Grades), TB-3 (Acceleration), TBS-3 (Deceleration) and TB-6 (Calibration) were utilized to determine the performance of vehicles in highly varied grade situations, roughness, speed mode (constant/acceleration/deceleration), etc. It should be noted that the final free-speed profile of Figure 1.3 was established after having taken the speed-limit profile into consideration.

Figure 1.4 shows how Experiments FC-1 (Consumption at Constant Speed), FC-2 (Consumption During Deceleration by Gravity), FC-3 (Consumption on Curves), FCS-4 (Consumption During Acceleration), TBS-6 (Consumption During Deceleration by Braking) and FC-4 (Calibration) were utilized to determine fuel consumption in highly varied situations of grade, roughness, speed mode, etc. One should note that the variable *fuel consumption* has volume and time as its units (m*ℓ*/sec).

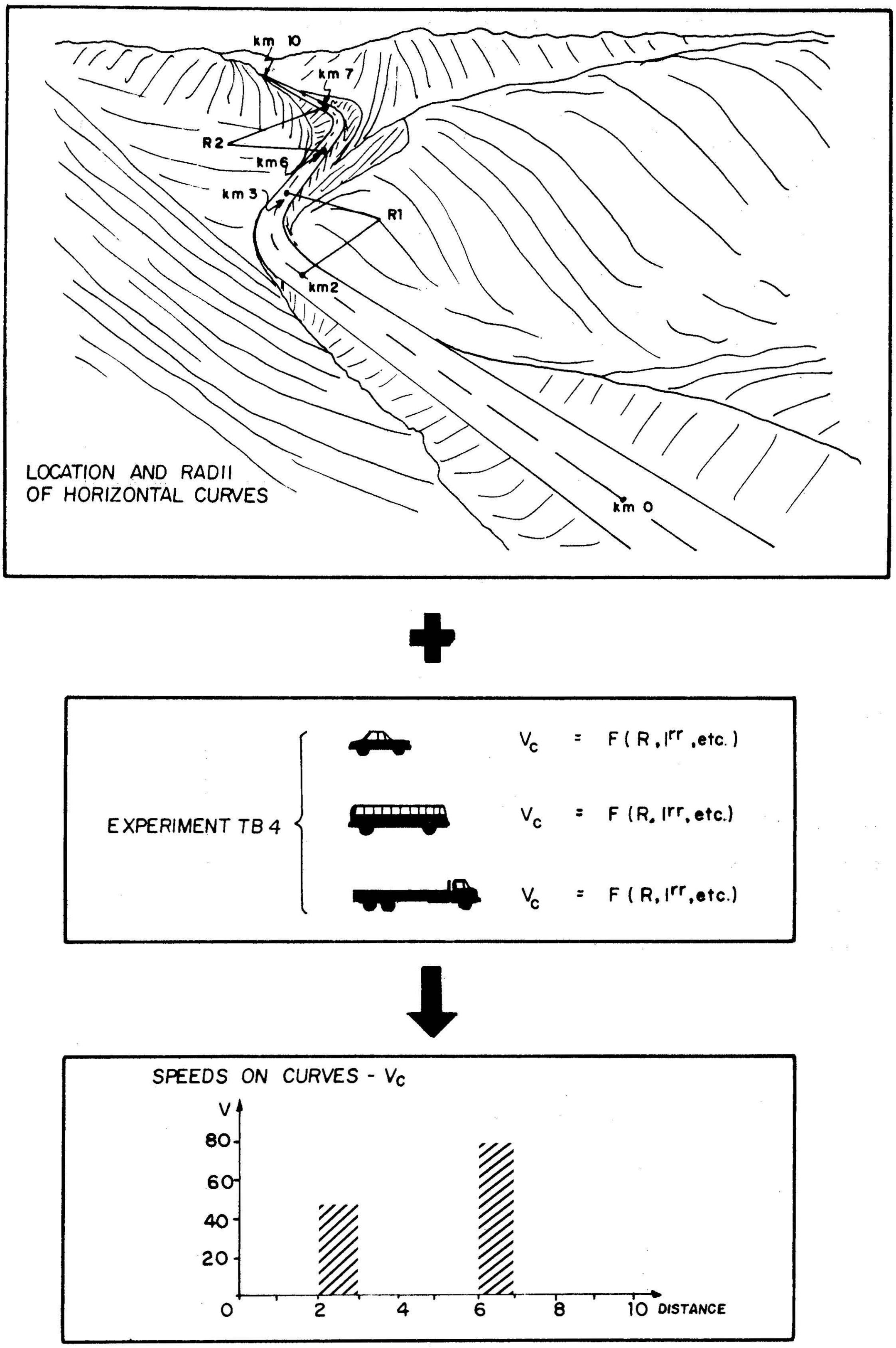


Figure 1.1 - INTEGRATION OF SPEED AND FUEL CONSUMPTION EXPERIMENTS IN MTC DESIGN. DETERMINATION OF SPEED ON CURVES.

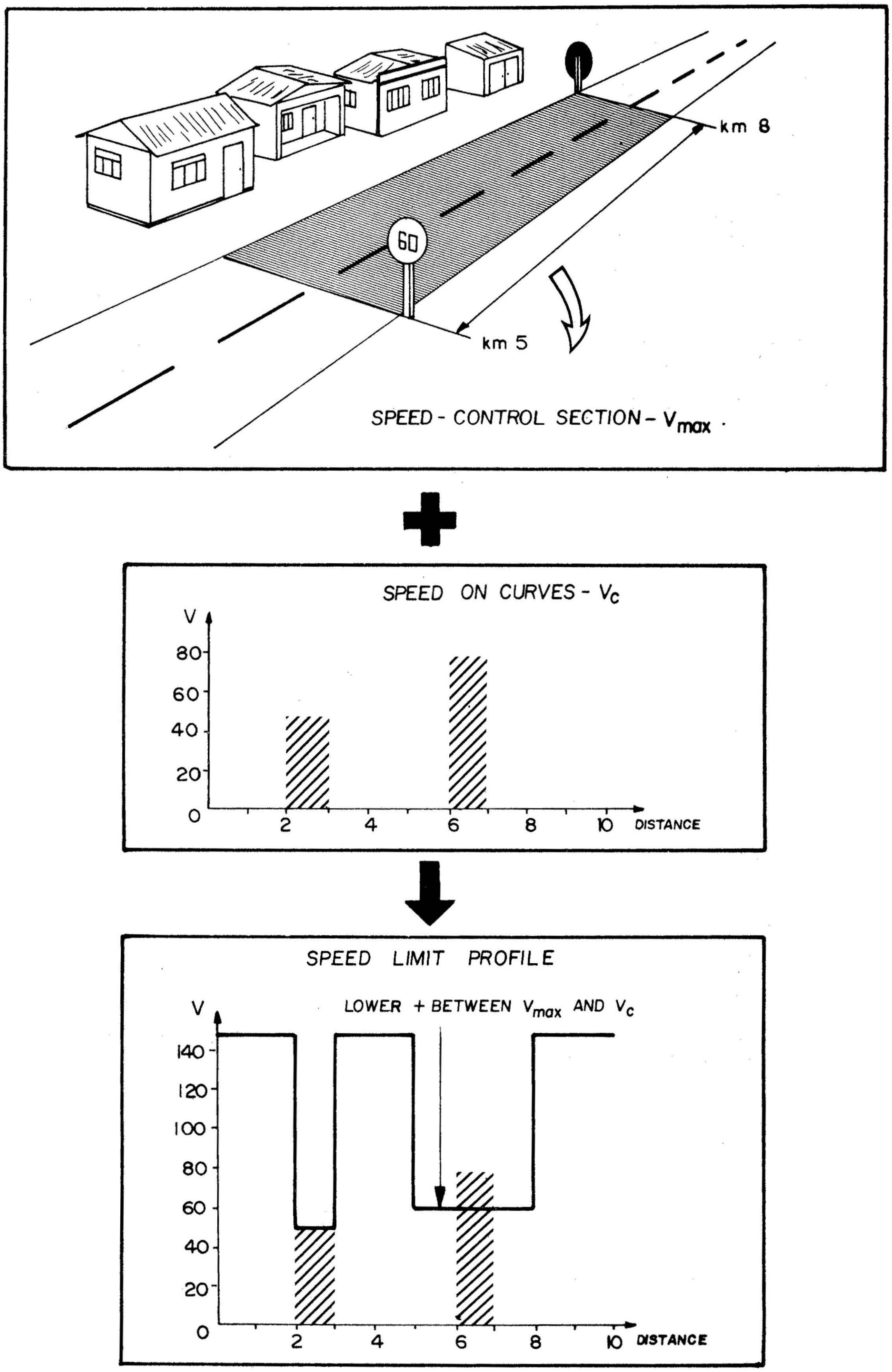


Figure 1.2- INTEGRATION OF SPEED AND FUEL CONSUMPTION EXPERIMENTS IN MTC DESIGN. DETERMINATION OF SPEED LIMIT PROFILE.

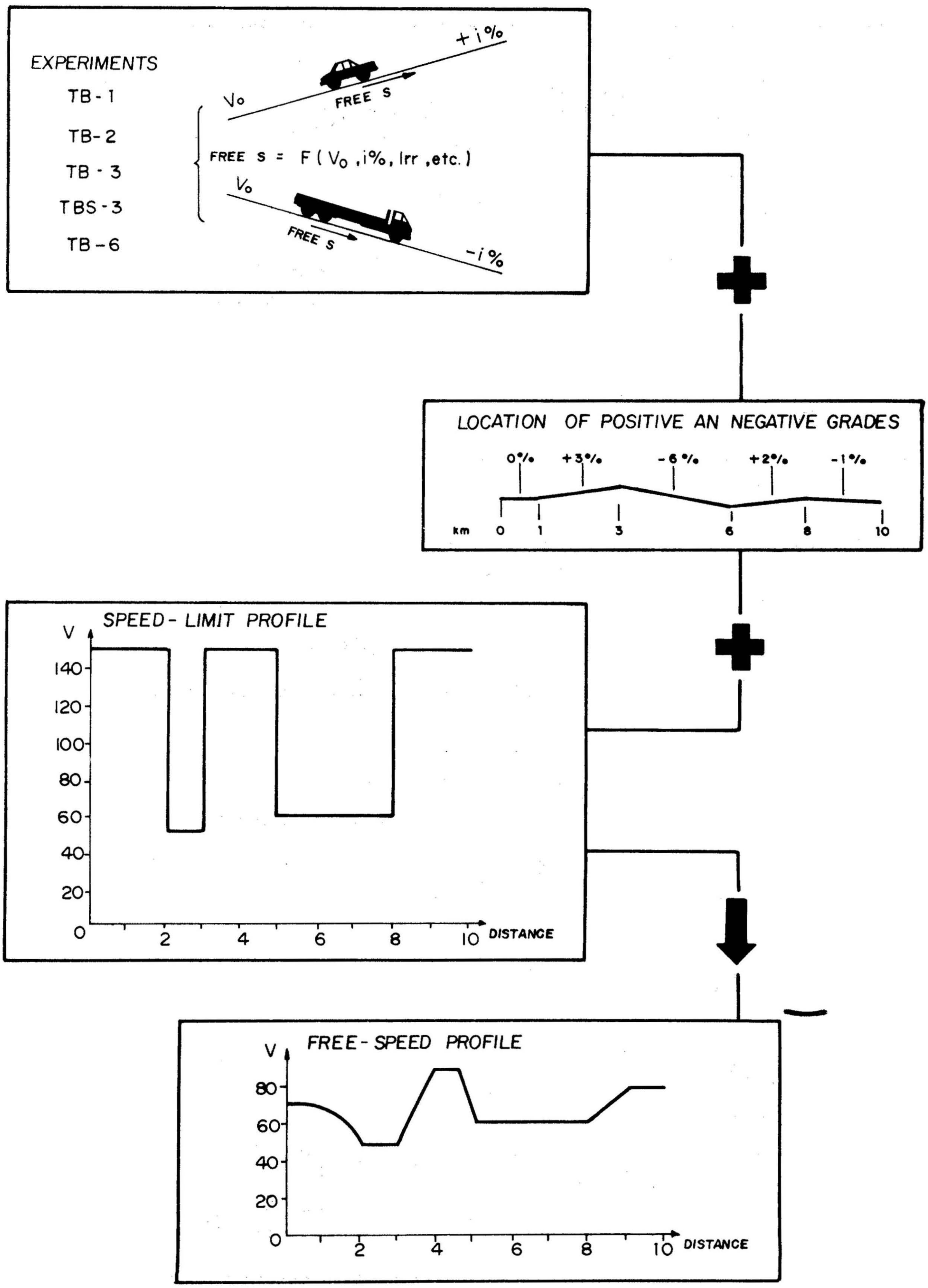


Figure : 1.3 - INTEGRATION OF SPEED AND FUEL CONSUMPTION EXPERIMENTS IN MTC DESIGN. DETERMINATION OF FREE-SPEED PROFILE.

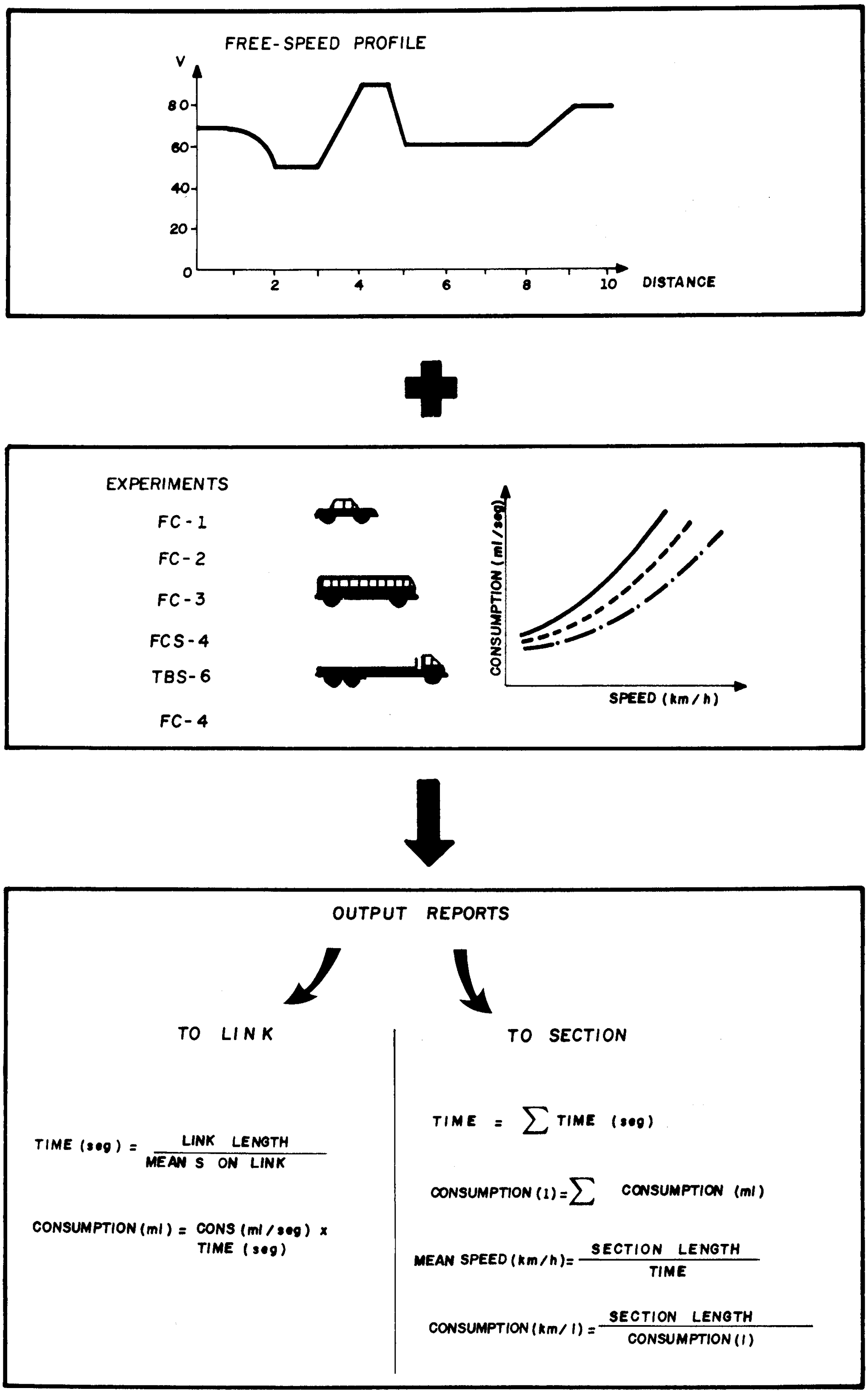


Figure 1.4 - INTEGRATION OF SPEED AND FUEL CONSUMPTION EXPERIMENTS IN MTC DESIGN. OBTAINING OF OUTPUT REPORTS.

Consumption on a link (subdivision of the section) is calculated by multiplying the time spent to cover its length by the rate of consumption. The consumption on the section will be the sum of that on the links which compose it.

The user should note that the result indicated in Figure 1.1 (Speed on Curves) is used in Figure 1.2, with the additional information on sections with speed control, to produce the speed-limit profile in Figure 1.2.

The speed-limit profile in Figure 1.2 is then used in Figure 1.3, together with additional information on the locations of positive and negative grades, to produce the free-speed profile, through the utilization of equations derived from Experiments TB-1, TB-2, TBS-3 and TB-6.

As shown in Figure 1.4, the free-speed profile is associated to the fuel-consumption experiments (FC-1, FC-2, FC-3, FCS-4, TBS-6 and FC-4), to produce the output reports of the model at two levels: detailed report, which will include results of fuel consumption and travel time for each link, and the summarized report, containing the same results for the section as a whole.

This overall view of the utilization of experiments results by the Model, permits detailing the process by which the MTC calculates free speed and fuel consumption for each link and for each section of the road under analysis.

CHAPTER 2
LOGIC AND BASIC CONCEPTIONS OF THE MTC

2.1 CALCULATION OF FREE SPEED

The MTC version presented here uses a series of equations which make it possible to calculate the free speed of six different classes of vehicles for an entire range of situations which may be encountered while traveling on a given road.

These series of equations was obtained from the experiments described in Volume 6. The choice of one or the other equation for the calculation of free speed will be discussed after the following terminology is explained:

- Road Connection - the road (or part of it) that one intends to analyse;
- Section - any subdivision of the road connection; and
- Nodes - points along each section at which the program calculates speeds. At the start of the analysis, these points correspond to the beginning of each grade variation, to the beginning of each curve or straight line, to the start of each change in the type or level of surface roughness and to the beginning and end of each speed-control section. Later, during the process of analysis, the program defines additional nodes for each change in vehicle speed mode(constant/acceleration/deceleration);
- Speed-Control Sections - locations along the road where, for legal or safety reasons, traffic speed is limited to a value independent of the capacity of the vehicles;
- Link - the connection between two consecutive nodes. Therefore, on a given link, the value of the grade, the alignment, the speed control, the type of road surface, the roughness, and the vehicle speed mode are all constant.

For the user to understand the process of calculating free speed, it is necessary to begin with the definition adopted for *steady-state speed.*

Suppose that a link (homogeneous characteristics as to roughness, alignment, profile, etc.) is sufficiently long to permit a vehicle to reach a certain speed at a given point of the segment, and that from this point on it will maintain the same speed till the end of the segment. For example, if the link is a positive grade, it can be expected that the speed of the vehicle will gradually diminish until achieving stability at a certain point. It is just as if, for each class of vehicles on the segment, there existed a speed that would be reached and maintained, should the segment be of sufficient length. Thus, on a given segment, each class of vehicle tends to reach and maintain a certain speed, defined as its *steady-state-speed*.

Therefore, it is possible to associate to a given road segment a single steady-state speed for each class of vehicles.

The calculation of the free speed through the use of the MTC is based on the supposition that, on each link, the vehicles will accelerate, decelerate or maintain their present speed, depending on whether the speed of entry into the segment is below, above or equal to its respective steady-state speed. Thus, the choice of the speed equation will be subordinated to the conception of the model, which attempts to take the vehicle from entry speed to the steady-state speed of the segment. To do this, the MTC has six speed functions.

The general forms of these speed functions are presented in Figure 2.1. The mnemonics of the functions used in the program are composed of four letters. The first two letters indicate that its use is for positive grades (PG) or negative grades (NG). The third letter indicates either acceleration (A), deceleration (D) or steady-state speed (S). When the fourth letter is B, it indicates that the function is used for forced deceleration, which occurs when the vehicle tries to enter a speed-control link at a speed higher than that permitted. The letter (E) is used only to complete the fourth position, and has no meaning in itself. The single exception to the composition of these mnemonics is the function LACC, used to accelerate vehicles on positive grades.

Summarizing, the functions are as follows:

- PGSE - steady-state speed on positive grades;
- LACC - acceleration on positive grades;
- PGDB - forced deceleration on positive grades;
- NGSE - steady-state speed on negative grades;
- NGAE - acceleration on negative grades; and
- NGDB - forced deceleration on negative grades.

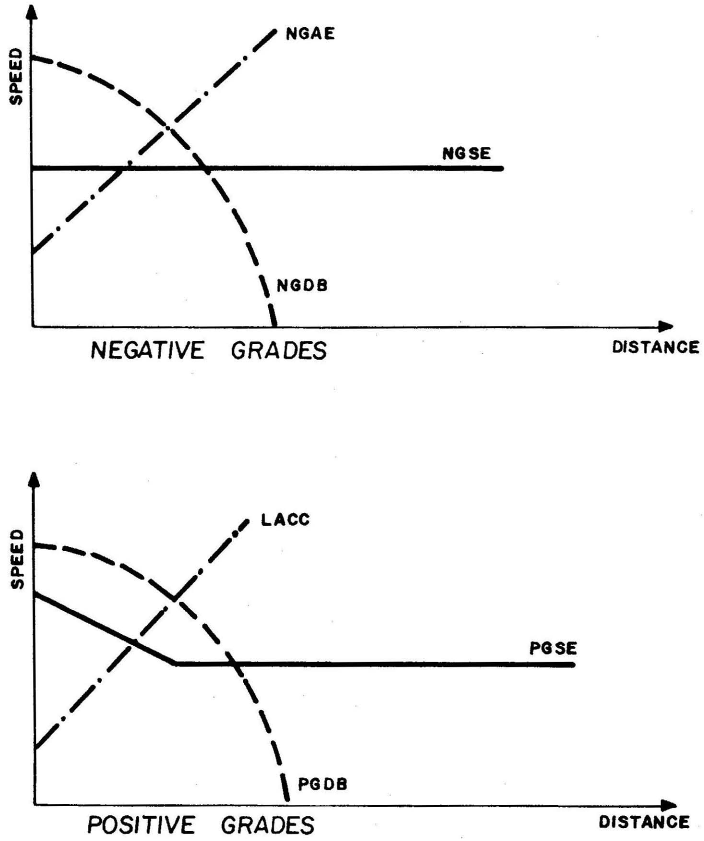


Figure 2.1 - GENERAL FORM OF SPEED FUNCTIONS.

A final observation should be made with relation to function PGSE (steady-state speed on positive grades). Figure 2.1 shows that this function can be utilized to decelerate vehicles. This occurs when the vehicle enters a positive grade at a speed higher than the steady-state speed of the grade. It is as if the vehicle loses speed until reaching the level of steady-state speed. This situation thus differs from that of forced deceleration. In the latter situation, the vehicle is below its capacity. In the former, it loses speed not due to speed controls because it is running at a speed higher than the steady-state speed of the positive grade.

2.2 *CALCULATION OF FUEL CONSUMPTION*

Six functions are used to calculate the rate of fuel consumption (volume per time unit). To obtain the volume of fuel consumed on each link, the rate of consumption is multiplied by the time spent to cover it. Time is calculated as the distance divided by the average speed on the link, the latter being obtained on the basis of speed at the start and at the end of the link. The consumption function chosen for each link depends on the speed function utilized in the description of vehicle behavior. As independent variables, the consumption functions use grade, roughness, surface type, vehicle class, type and gross weight, though not all the functions utilize all these factors.

The final letter of the mnemonics of the fuel-consumption functions indicates whether the function should be used for positive (P) or negative (N) grades. With the exception of functions FCDP (consumption during forced deceleration on positive grades) and FCDN (consumption during forced deceleration on negative grades), the letters and the preceding numbers show which experiment was performed to produce the respective equation (vide Volume 6). For the two exceptions specified above, the average rates of fuel consumption were estimated on the basis of the data gathered during Experiment TBS-6 (forced deceleration).

Fuel consumption is calculated according to vehicle class and type. In the case of gasoline-powered automobiles, utilities and light trucks (empty and loaded), the rate is given in units of milliliters per second of the gasoline mixture with 20% alcohol (as explained in Volume 6), whereas for the remaining classes and types of vehicles units of milliliters of diesel fuel per second are used.

Summarizing, the functions are as follows:

- FC1P - consumption at steady-state speed on positive grades;
- FCS4P- consumption during acceleration on positive grades;
- FCDP - consumption during forced deceleration on positive grades;
- FC2P - consumption during deceleration by gravity on positive grades;
- FC1N - consumption at steady-state speed on negative grades;
- FCS4N- consumption during acceleration on negative grades; and
- FCDN - consumption during forced deceleration on negative grades.

2.3 *SELECTION OF SPEED AND FUEL-CONSUMPTION EQUATIONS*

The process of selecting equations for the calculation of speed (or travel time) and fuel consumption will be shown under this item.

The choice of the fuel-consumption equation is based on the speed equation chosen to describe a vehicle's behavior on a specific link or, in other words, a consumption equation will be associated to each speed equation. Consequently, once the speed equation is determined, the consumption equation will be automatically determined.

Speed is calculated at each node (already defined) of a section of the road. Therefore, before calculating speed it is necessary that the section be divided into links, composed of the stretches between two consecutive nodes. As already stated, the physical characteristics of a given link (grade, alignment, roughness, etc.) are constant. Consequently, it is possible to determine the constant speed for each vehicle class on the segment in question. The result of the comparison between the speed of the vehicle at the entry node of the segment (or, simply, entry speed) and the steady-state speed on the segment will determine the choice of the speed equation. This occurs since the MTC is designed in such a way that the vehicle always tends to steady-state speed. If the speed is lower than the steady-state speed, the vehicle should be accelerated, if higher, it should be decelerated; if speed is equal to steady-state speed, it should be maintained. It is with this in mind that one utilizes the acceleration, deceleration or steady-state speed equation, respectively. Before choosing one of these equations, however, the program will determine if the grade of the link is positive or negative[1], since the equations and vehicle behavior will be different in each situation.

The following terminology is now considered:

- V1 - vehicle speed at the entry node of the link or, simply, entry speed;
- V2 - vehicle speed at the exit node of the link or, simply, exit speed; and
- SSS - steady-state speed.

Suppose that a vehicle is on a positive-grade link. Figure 2.2 shows the possible behaviors of the vehicle on this link. For those cases in which the vehicle reaches the steady-state speed on the link, should the vehicle be above (or below) the steady-state speed, it will be accelerated (or decelerated) and, once steady-state speed has been reached, the MTC program creates an additional node at this point and maintains speed until the end of the link (cases 2 and 4 of Figure 2.2). The user should observe that the original segment was divided into two smaller segments, both of which possess the same physical characteristics. However, the new segment is created due to change in vehicle behavior (from deceleration to steady-state speed, in case 2, and from acceleration to steady-state speed, in case 4 of Figure 2.2).

Figure 2.3 shows possible vehicle behaviors on negative-grade links. The speed equations will be chosen through a comparison between entry speed (V1) and steady-state speed (SSS), just as was done previously, the only difference being that, when entry speed is higher than steady-state speed, the vehicle should be decelerated on negative

[1] If the grade is neutral, the results will be the same, independently of whether one uses the positive or negative grade equations. However, the program deals with neutral grades as if they were negative grades.

grades, maintaining the same speed over the entire segment (case 1 of Figure 2.3).

The equations of forced deceleration on positive (PGDB) and negative (NGDB) grades will only be utilized in those cases in which the vehicle attempts to enter a speed-control link at a speed higher than permitted (Figures 2.4 and 2.5).

Figure 2.4 shows the original speed profile on two consecutive links, assuming a random situation for the first (for example, steady-state speed) and a speed-control situation for the second. Clearly, the entry speed (V1) of a link should be the same as the exit speed (V2) of the previous link, or the speed profile will experience a lack of continuity.

To avoid discontinuity, the MTC utilizes the maximum speed permitted on the second segment as the exit speed (V2) of the first link (Figure 2.5). Consequently, the speeds should be calculated backwards along the road until reaching the point where the vehicle should begin deceleration to reach the required exit speed. This is shown in Figure 2.5.

The additional node created in the first segment is the point at which the vehicle begins deceleration. In this way, the first segment is divided into two smaller segments, both possessing the same physical characteristics. The new segment, however, is created as a result of a change in vehicle behavior (from steady-state speed to deceleration). Figure 2.6 shows the new links with the final speed profile.

If the grade of the second link of Figure 2.6 is positive, the equation to use will be PGDB - forced deceleration on positive grades. If negative, the equation will be NGDB - forced deceleration on negative grades. Once the two final possible situations for vehicle behavior have been discussed, the description of the process of choosing the speed equations and, consequently, the fuel-consumption equations, is completed.

2.4 COMPUTATIONAL LOGIC

This item presents an explanation of the logic of the MTC

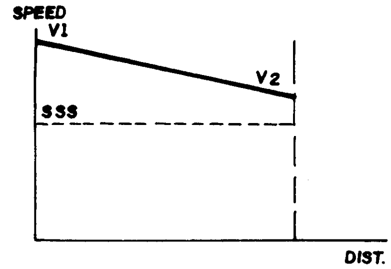
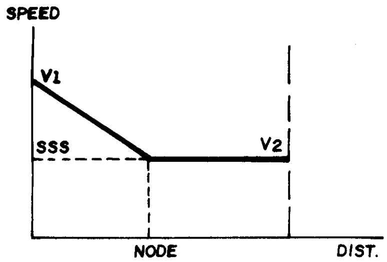
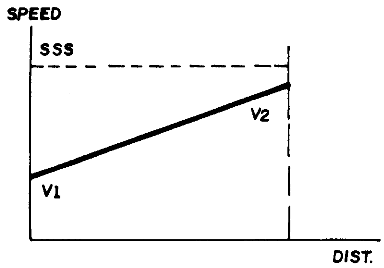
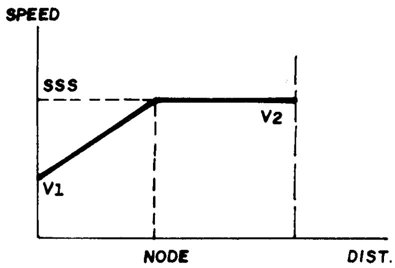
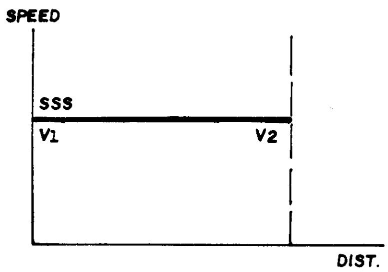
CASE	SPEED PROFILE	SPEED FUNCTION(s) USED
1		PGSE - DECELERATION BY GRAVITY
2		1st LINK : DECELERATION BY GRAVITY 2nd LINK : STEADY - STATE SPEED
3		LACC - ACCELERATION
4		1st LINK : LACC - ACCELERATION 2nd LINK : STEADY - STATE SPEED
5		PGSE - STEADY - STATE SPEED

Figure 2.2 - POSSIBLE PERFORMANCES OF VEHICHES ON POSITIVE GRADES.

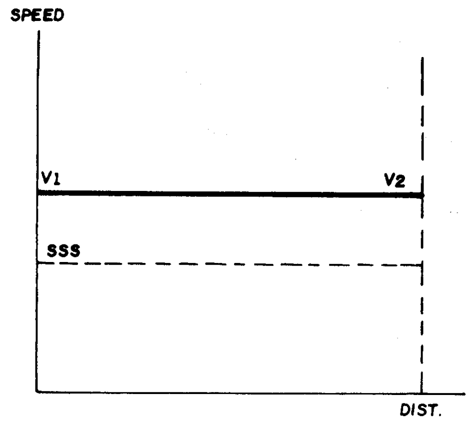
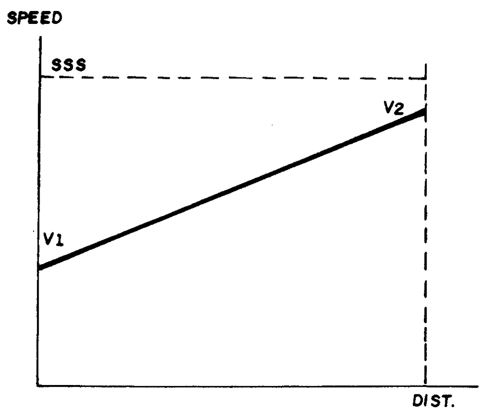
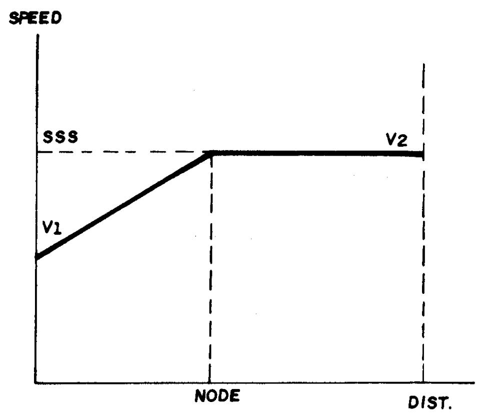
CASE	SPEED PROFILE	SPEED FUNCTION(s) USED
1		NGSE - STEADY - STATE SPEED
2		NGAE - ACCELERATION
3		1st LINK : ACCELERATION 2nd LINK : STEADY - STATE SPEED

Figure 2.3 - POSSIBLE PERFORMANCES OF VEHICLES ON NEGATIVE GRADES.

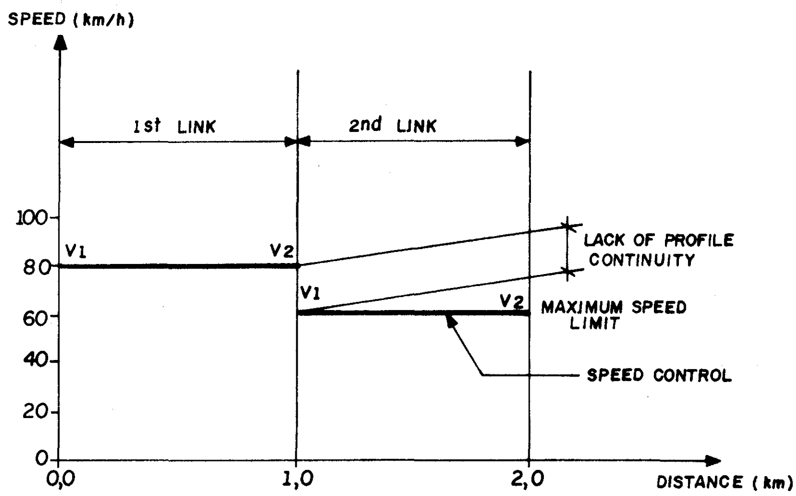


Figure 2.4 - ORIGINAL SPEED PROFILE.

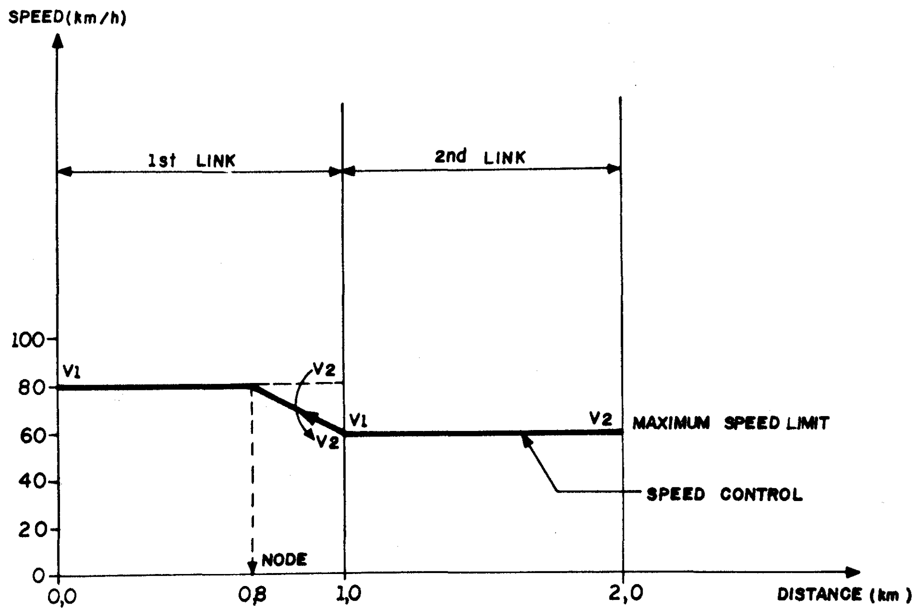


Figure 2.5 - FINAL SPEED PROFILE.

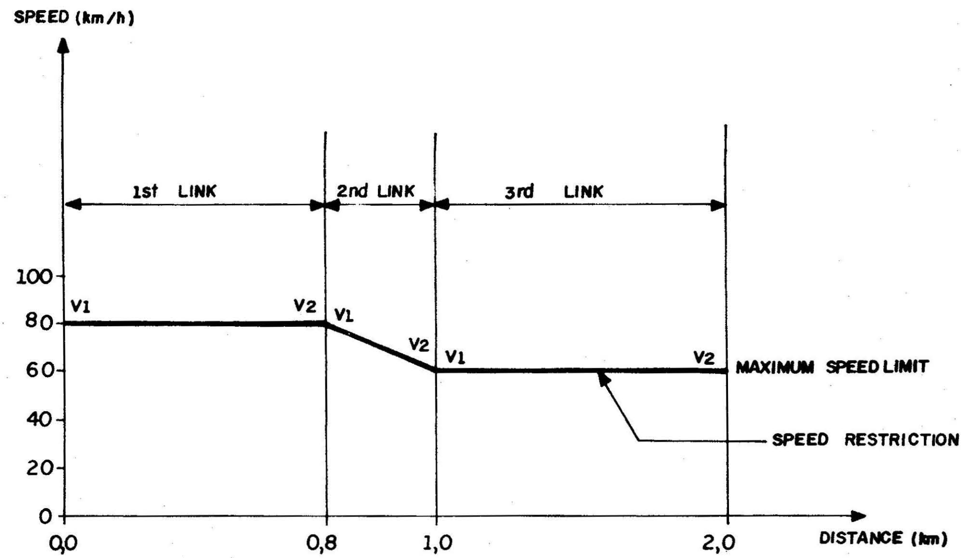


Figure 2.6 - CREATION OF NEW LINK.

computer program, coded in FORTRAN IV. In the MTC, the physical characteristics of the road are analysed consecutively, as nodes are established at the transitions between sections with different characteristics. The flowchart of the major aspects of the model is presented in Figure 2.7.

As shown in Figure 2.7, the MTC executes interactions at three levels: direction, vehicle class and link. The direction loop makes it possible to analyse the road in both traffic directions. The vehicle-class loop repeats the logic of the program for each of the vehicle classes specified by the user. Finally, speed, time and fuel consumption are calculated in each link.

There are three major execution phases in the MTC: establishment of analysis arrays, calculation of forward speed and calculation of backward speed. The establishment of analysis arrays consists of converting the input data to the form required by speed calculations: the program creates the links where the physical characteristics (grade, alignment, roughness, etc.) are constant, thus permitting the speed calculations. The forward-speed calculation gives the speed that the vehicle reaches at the end of the link (exit speed). The backward speed must be calculated when the entry speed on a speed-control link is greater than the maximum speed permitted. It should be recalled that, when this occurs, speeds must be calculated backwards along the road, until one finds the point at which the vehicle should begin decelerating to reach the entry speed required on the speed-control link.

Figures 2.9, 2.10 and 2.11 provide greater details as to the three functional parts of the MTC. The small graphs shown in Figures 2.10 and 2.11 represent speed profiles on a link. The only symbol still not defined that appears in the figures is ESPM. It appears when it is necessary to calculate backward speed (Figure 2.11).

ESPM is the greatest speed at which the vehicle can enter the segment previous to the speed-control link and still manage to decelerate to the required speed. If the original entry speed is greater than ESPM, this means that the vehicle cannot decelerate to the required speed on this link. In this case, it will be necessary to move backwards one or more links until reaching a point at which ESPM is greater than the original entry speed, as shown in Figure 2.8.

In Figure 2.8, the original entry speed in the second segment

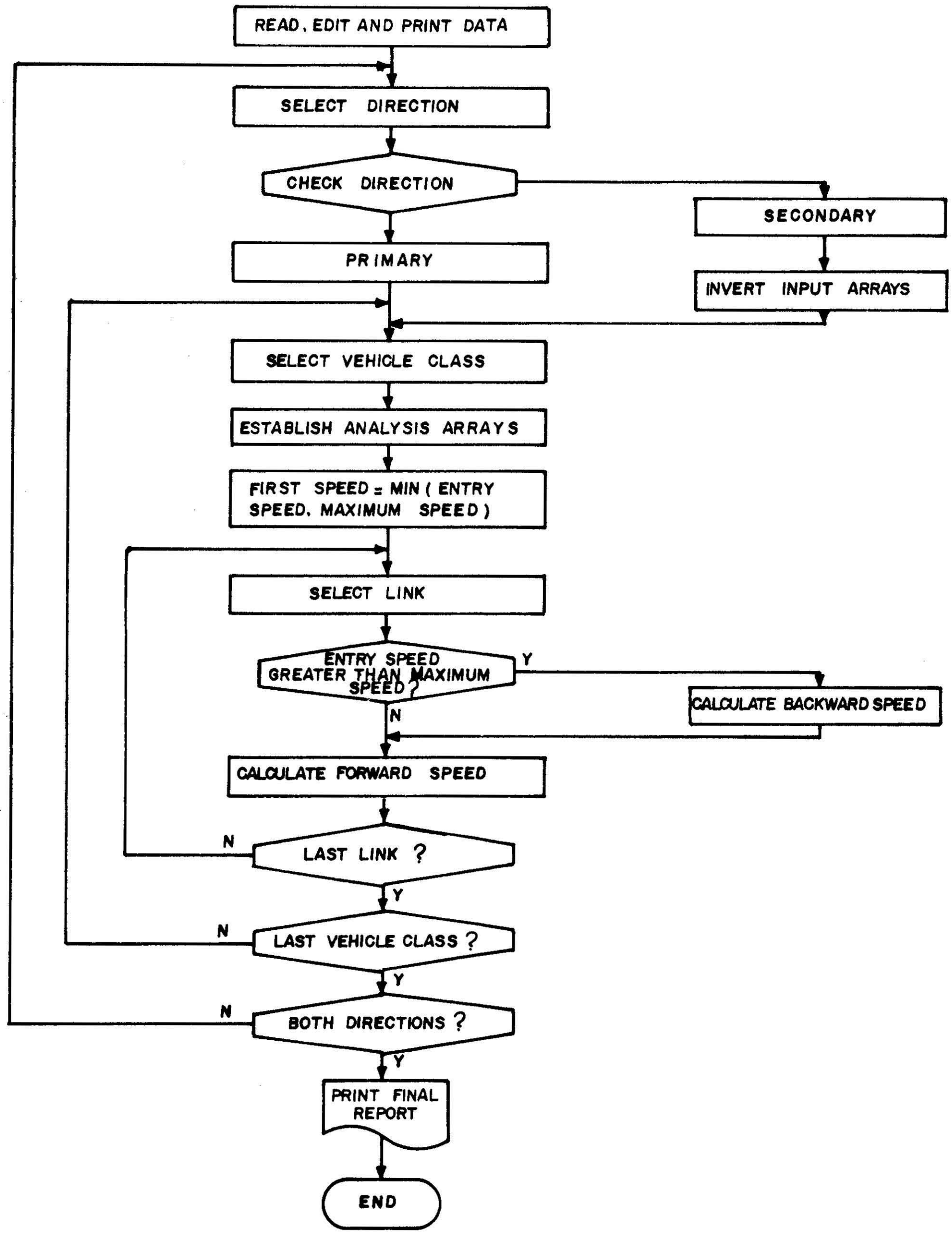


Figure 2.7 - BASIC LOGIC OF THE MTC.

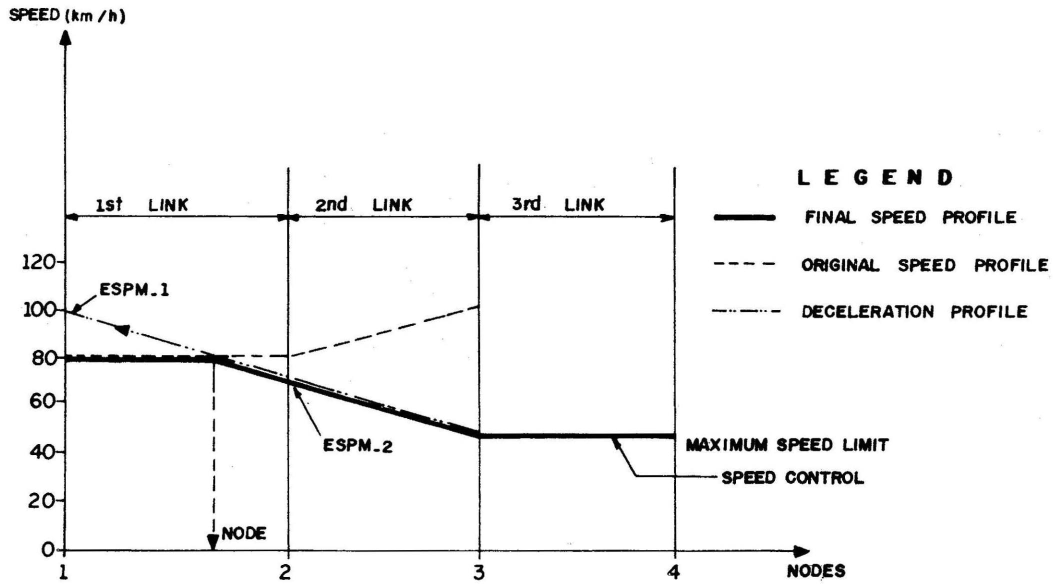


Figure 2.8 – CALCULATION OF BACKWARD SPEED.

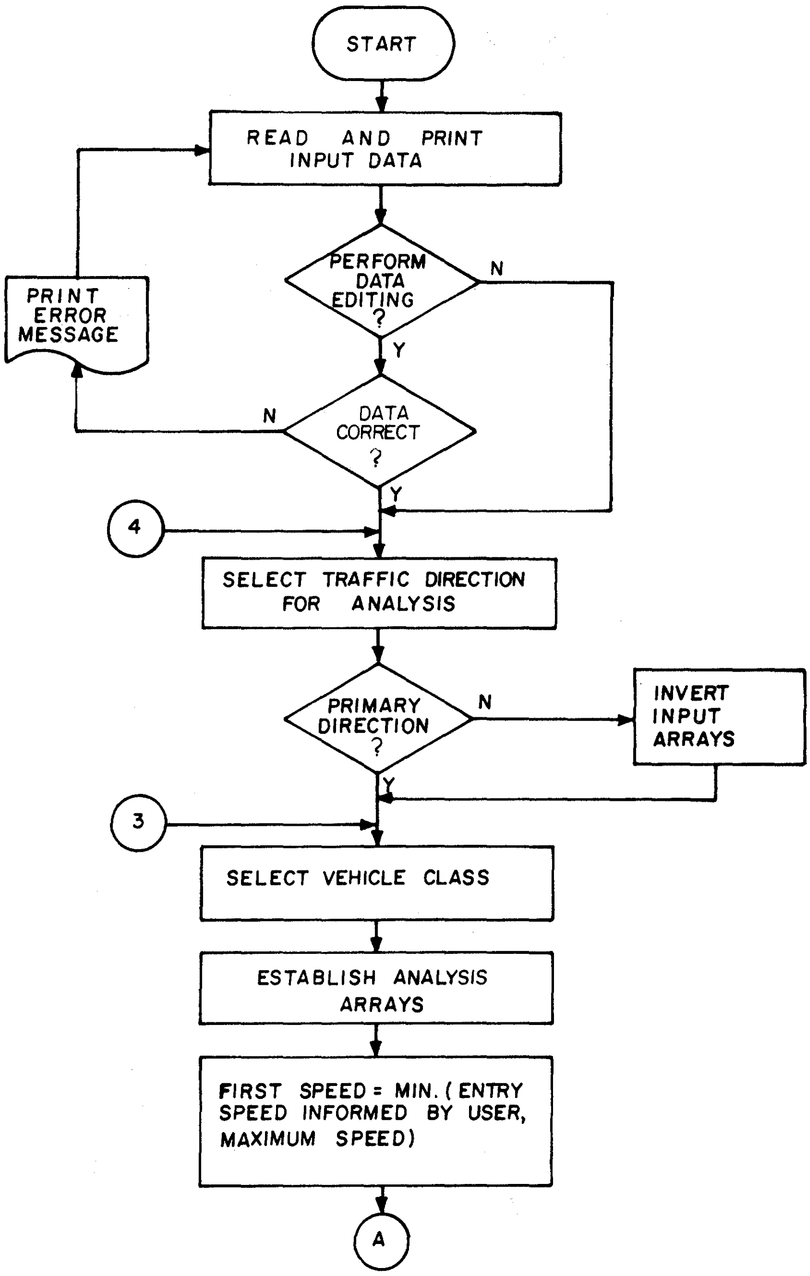


Figure 2.9 - LOGIC OF THE MTC – ESTABLISHMENT OF ANALYSIS ARRAYS.

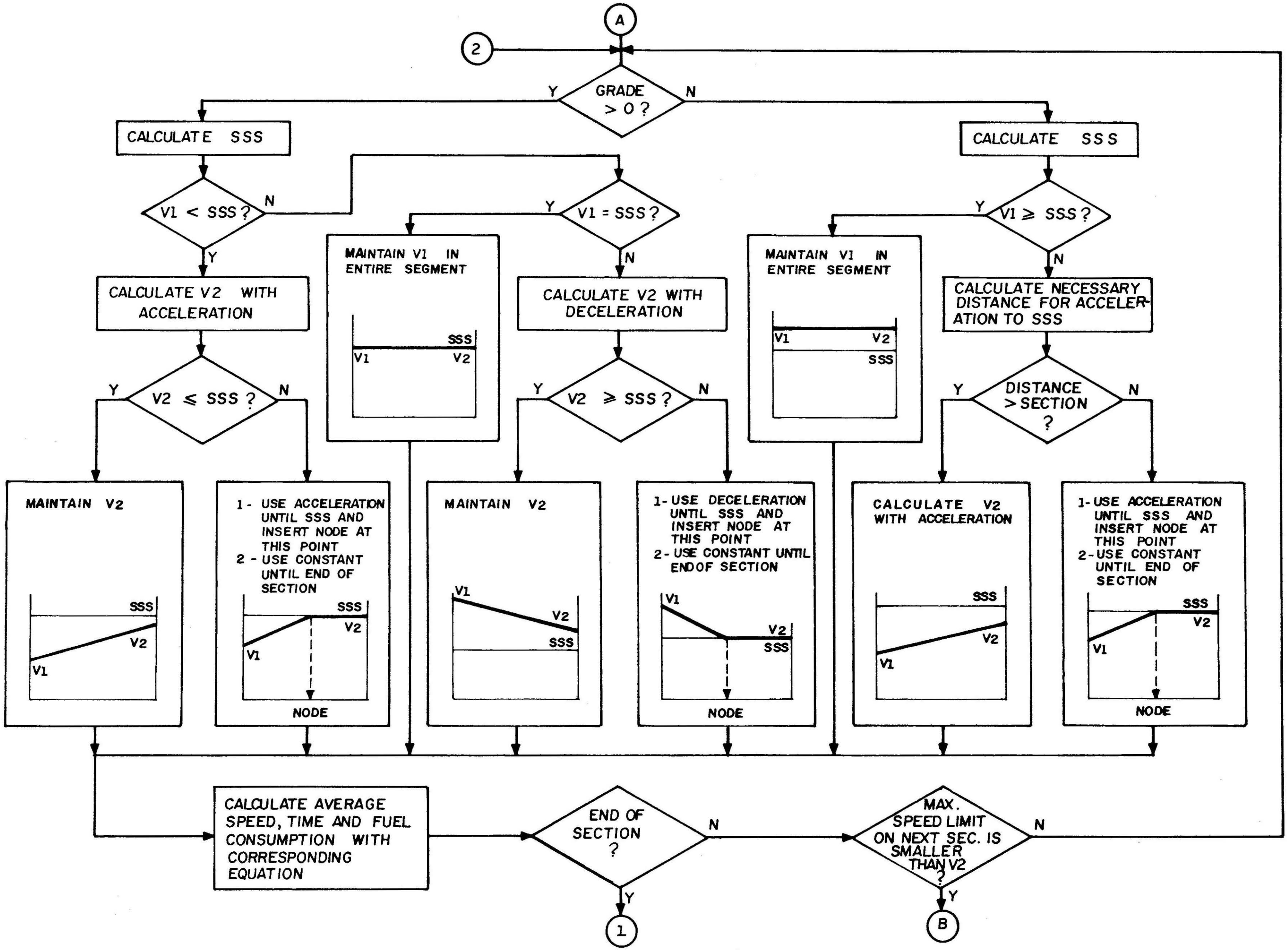


Figure 2.10 – LOGIC OF THE MTC – CALCULATION OF FORWARD SPEED.

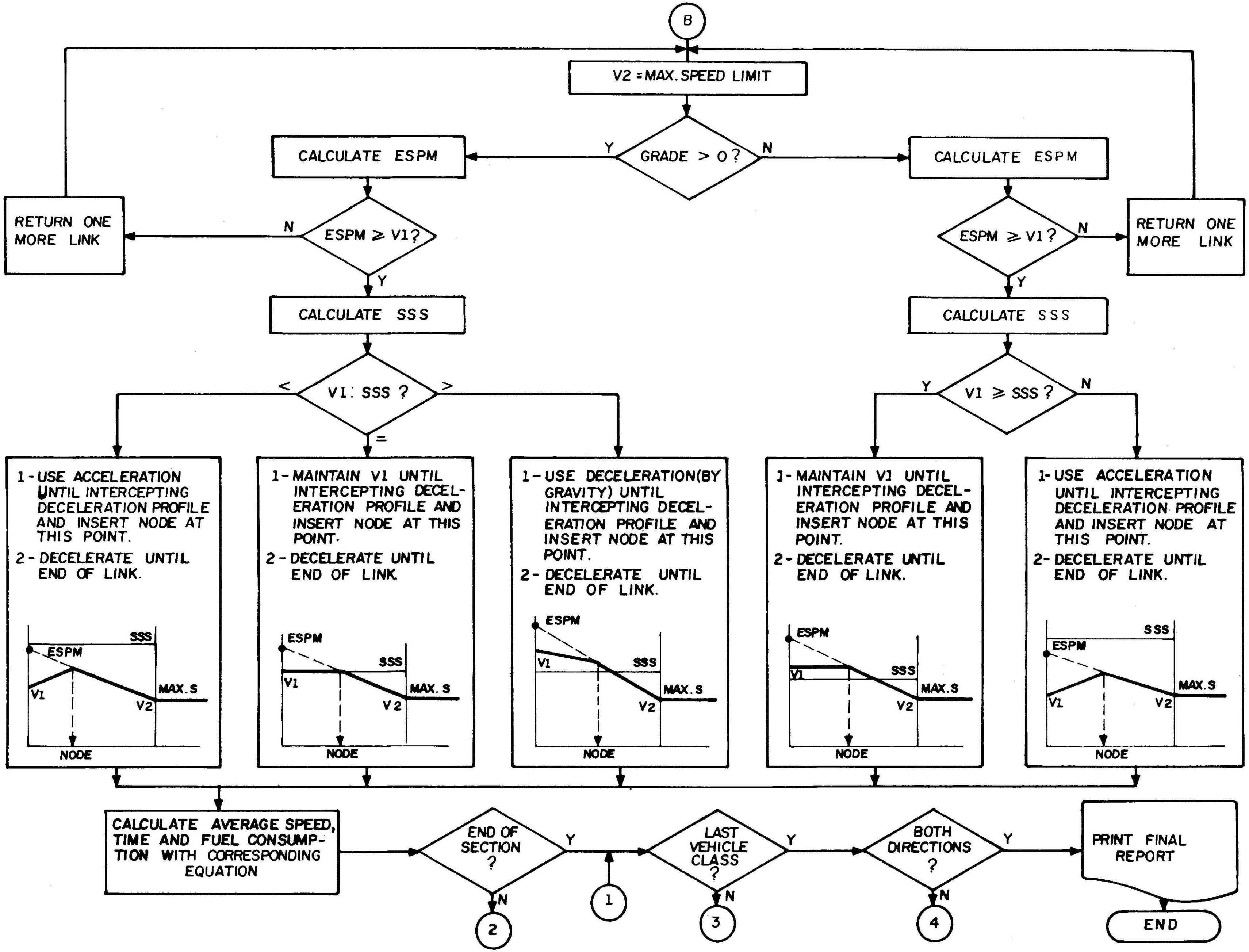


Figure 2.11- LOGIC OF THE MTC - CALCULATION OF BACKWARD SPEED.

is greater than ESPM-2. Since the vehicle cannot, therefore, decelerate on this link, it is necessary to move backwards one or more links to the point at which ESPM is greater than the original entry speed. In Figure 2.8, this occurs in the first link, where ESPM-1 is greater than the original entry speed. This, makes it possible for the vehicle to decelerate to the speed required on the third link.

Finally, in Figure 2.9, the user will note that, should there be a speed control on the first link of a section, vehicle speed at the first node will be either the entry speed supplied by the user himself or the maximum speed permitted. The program will choose that which is the lowest.

CHAPTER 3
EQUATIONS USED IN THE MTC PROGRAM

3.1 INTRODUCTION

The equations used in the *Model of Time and Fuel Consumption* (*MTC*) are derived from specific experiments. The speed equations were determined on the basis of the following experiments:

- TB-1 - Free speed on positive grades;
- TB-2 - Free speed on negative grades;
- TB-3 - Acceleration;
- TB-4 - Free speed on curves;
- TB-6 - Calibration; and
- TBS-3- Deceleration.

The fuel consumption equations were determined on the basis of other experiments, which are listed below:

- FC-1 - Consumption at steady-state speed on positive and negative grades;
- FC-2 - Consumption at start of positive grades preceded by negative grades;
- FC-3 - Influence of horizontal curvature on consumption;
- FC-4 - Calibration;
- FCS-4- Consumption during acceleration; and
- TBS-6- Consumption during deceleration.

As discussed in previous chapters, a given fuel-consumption equation is associated with a given speed equation in the MTC. Table 3.1 shows the relations among the equations (together with the mnemonics utilized in the program), the tests which led to these equations, and the correspondence between speed and consumption equations.

Fuel consumption is calculated by vehicle class and type. For gasoline-powered automobiles, utilities and light trucks (empty and loaded), the rate is given in milliliters/second of a gasoline-plus--20%-alcohol mixture, while in the other vehicle classes and types the units used are milliliters/second of diesel oil.

As was explained in Volume 6, when some experiments were being carried out the fuel available as a substitute for pure gasoline was the gasoline/alcohol mixture.

TABLE 3.1 - CORRESPONDENCE BETWEEN MTC EQUATIONS AND THE EXPERIMENTS

GRADE	SPEED EQUATION	EXPERIMENT	CORRESPONDING CONSUMPTION EQUATION	EXPERIMENT
POSITIVE	PGSE - steady-state	TB-1	FC1P	FC-1
	PGSE - deceleration	TB-1	FC2P	FC-2
	PGDB - deceleration	TBS-3	FCDP	TBS-6
	LACC - acceleration	TB-6	FCS4P	FCS-4
NEGATIVE	NGSE - steady-state	TB-2	FC1N	FC-1
	NGDB - deceleration	TBS-3	FCDN	TBS-6
	NGAE - acceleration	TB-3/TB-6	FCS4N	FCS-4/FC-1

Consequently, Experiment FCS-6 was carried out to make all fuel-consumption results uniform, since some of the experiments had been performed with the use of pure gasoline and others with the gasoline/alcohol mixture. The adjustment factors were as follows: 1.09 for the VW 1300 model; 1.05 for the Kombi (utility); and 1.02 for the F-400. It should be emphasized that these factors apply only to those experiments carried out with pure gasoline and, consequently, cannot be applied externally to the results of the model, since the factors do not apply to those equations designed to predict consumption in terms of the gasoline/alcohol mixture.

In practice, however, considering that the differences in consumption observed in Experiment FCS-6 were small, and perhaps even below other imprecisions of the model, the MTC results can be accepted as valid for pure gasoline.

3.2 *LIST OF EQUATIONS*

Tables 3.2 to 3.12 show the equations for predicting free speed and fuel consumption used in the MTC.

TABLE 3.2 - STEADY-STATE SPEED ON POSITIVE (PGSE - CONST.) AND NEGATIVE (NGSE) GRADES

Automobiles	$V=S1\ (91.9-2.7G_P-0.154QI)+S2(99.6-3.7G_P+0.6G_{N1}-0.214QI)$
Buses	$V=S1\ (84.3-0.5G_N-10.8G_{P1}-5.1G_{P2}-0.154QI)+S2(67-6.8G_{N1}-6.2G_P-0.93G_{P3}QI)$
Empty Utilities	$V=S1\ (84.3-2.4G_P-0154QI)+S2(89.4-3.7G_P+0.6G_{N1}-0.177QI)$
Full Utilities	$V=S1\ (84.3-3.7G_P-0.154QI)+S2(83.9-37G_P+0.6G_N-0.177QI)$
Light Trucks	$V=S1\ (74.6-3.0G_N-3.7G_P-0.154QI)+S2(80\ 9-3.7G_P+0.6G_{N1}-0.177QI)$
Full Trucks	$V=S1\ (74.6-3.0G_N-12G_{P1}-3.5G_{P2}-0.154QI)+S2(67-3.7G_P-6.8G_{N1}-0.177QI)$

$S1$ = {1 if paved
{0 otherwise

$S2$ = {1 if unpaved
{0 otherwise

G_N = {Grade (%) if Grade $< 0\%$
{0 otherwise

G_{N1} = {Grade (%) if $-3.6\% <$ Grade $< 0\%$
{-3.6% otherwise

G_P = {Grade (%) if Grade $> 0\%$
{0 otherwise

G_{P1} = {Grade (%) if $0\% <$ Grade $\leqslant 3\%$
{3% if Grade $> 3\%$

G_{P2} = {Grade -3% if Grade $> 3\%$
{0 otherwise

G_{P3} = {(6%-Grade)/6 if $0\% <$ Grade $< 6\%$
{0 otherwise

QI = roughness (count/km)

V = Speed (km/h)

TABLE 3.3 - DECELERATION ON POSITIVE GRADES PRECEDED BY NEGATIVE GRADES (PGSE - DECEL.)

Automobiles	$\Delta V = D\,(-0.0001G1-0.008G2-0.0158G3)S1+DS2GA$
Buses	$\Delta V = D\,(-0.0003G1-0.167G2-0.0312G3)S1-0.006DS2G$
Empty Utilities	$\Delta V = D\,(-0.0003G1-0.008G2-0.01G3)S1+DS2GA$
Full Utilities	$\Delta V = D\,(-0.0003G1-0.008G2-0.0152G3)S1+DS2GA$
Empty Trucks	$\Delta V = D\,(-0.0016G1-0.008G2-0.0125G3)S1+DS2GA$
Full Trucks	$\Delta V = D\,(-0.0037G1-0.008G2-0.D125G3)S1-0.006DS2G$

D = -distance in meters from start of grade to point at which speed is equal to constant speed or - length of link (meters)

S1 = {1 if paved; {0 otherwise

S2 = {1 if unpaved; {0 otherwise

G1 = Grade (%) if $0 < \text{Grade} < 3\%$; 3% if Grade $\geq$ 3%

G = Grade (%)

G2 = 0 if Grade $\leq$ 3%; Grade-3% if $3\% < \text{Grade} < 5\%$; 2% if Grade $\geq$ 5%

G3 = 0 if Grade $\leq$ 5%; Grade -5% if Grade > 5%

ΔV = Speed loss (km/h)

$$A = \begin{cases} -0,000794 & \text{if Grade} \leq 3\% \\ -0,000794-0,001976\,\left(\frac{G-3}{3}\right) & \text{if } 3\% < \text{Grade} < 6\% \\ -0,00277 & \text{if Grade} \geq 6\% \end{cases}$$

TABLE 3.4 - FORCED DECELERATION ON POSITIVE (PGDB) AND NEGATIVE (NGDB) GRADES

$V_2^2 = V_1^2 - ckax$

V_1 = speed at start of link, in km/h

V_2 = speed at end of link, in km/h

C = conversion factor of units

K = 1,0 if paved
1,1 if unpaved

a = rate of deceleration, in m/sec^2

x = distance covered during deceleration, in meters

Vehicle Class	Rate of Deceleration(m/sec^2)
Automobiles	0.61
Buses	0.61
Empty Utilities	0.61
Full Utilities	0.61
Empth Trucks	0.46
Full Trucks	0.33

TABLE 3.5 - ACCELERATION ON POSITIVE GRADES (LACC)*

$$\Delta V = \frac{VC-VE}{1000m} \times D$$

VC	=	specific constant speed of positive grade, in km/h
VE	=	entry speed on positive grade, in km/h
D	=	distance covered during acceleration, in m
ΔV	=	addition of speed (km/h)

* This equation did not result from any basic tests developed during the ICR Research for use in the MTC. During calibration, it was noted that the acceleration equation derived from the data of TB-3 increased speed on positive grades excessively. Consequently, the equation above (valid for all vehicle classes) was elaborated separately and tested against the calibration data (TB-6).

TABLE 3.6 - ACCELERATION ON NEGATIVE GRADES

PAVED ROADS	
Automobiles	$\Delta V = [0.04444+0.00016(PW-46.1)-0.00238G-0.000038QI]\ D$
Buses	$\Delta V = [0.03903+0.00037(PW-17.1)-0.00109G-0.000038QI]\ D$
Utilities	$\Delta V = [0.04894+0.00037(PW-38.1)-0.00109G-0.000038QI]\ D$
Light Truck (Gas.)	$\Delta V = [0.04538+0.00037(PW-46.5)-0.00109G-0.000038QI]\ D$
Light Truck (Die.)	$\Delta V = [0.03903+0.00022(PW-28.2)-0.00109G-0.000038QI]\ D$
Heavy Truck	$\Delta V = [0.03737+0.00037(PW-11.1)-0.00109G-0.000038QI]\ D$
Half-Trailer	$\Delta V = [0.03903+0.00037(PW-9.6)-0.00109G-0.000038QI]\ D$
UNPAVED ROADS	
Automobiles	$\Delta V = [0.05639+0.00021(PW-46.1)-0.00169G-0.000046QI]\ D$
Buses	$\Delta V = [0.03811+0.00021(PW-17.1)-0.00131G]\ D$
Utilities	$\Delta V = [0.04735+0.00021(PW-38.1)-0.00245G-0.000025QI]\ D$
Light Truck (Gas.)	$\Delta V = [0.04152+0.00021(PW-46.5)-0.00131G]\ D$
Light Truck (Die.)	$\Delta V = [0.03325+0.00021(PW-28.2)-0.00131G]\ D$
Heavy Truck	$\Delta V = [0.03951+0.00021(PW-11.1)-0.00131G]\ D$
Half-Trailer	$\Delta V = [0.03325+0.00021(PW-9.6)-0.00131G]\ D$

G = Grade (%)

QI = roughness (count/km)

PW = Power/Weight Ratio (HP/t)

D = Distance covered during deceleration

ΔV = Addition of speed (m/sec)

TABLE 3.7 - FREE SPEED ON CURVES (FSC)

PAVED ROADS	
Automobile	$V=17.756+0.428xR_{100}+0.12xR_{200}+0.035xR_{400}+0.014xR_{600}-0.71xG-0.010xQI_{75}-0.28xQI_{200}$
Bus	$V=17.756+0.290xR_{100}+0.12xR_{200}+0.035xR_{400}+0.014xR_{600}-0.71xG-0.045xQI_{75}-0.28xQI_{200}$
Empty Utility	$V=17.756+0.390xR_{100}+0.12xR_{200}+0.035xR_{400}+0.014xR_{600}-0.71xG-0.045xQI_{75}-0.28xQI_{200}$
Full Utility	$V=20.906+0.390xR_{100}+o.12xR_{200}+0.035xR_{400}+0.014xR_{600}-0.71xG-0.140xQI_{75}-0.26xQI_{200}$
Empty Truck	$V=24.976+0.390xR_{100}+0.12xR_{200}+0.035xR_{400}+0.014xR_{600}-0.71xG-0.140xQI_{75}-0.28xQI_{200}$
Full Truck	$V=17.756+0.390xR_{100}+0.12xR_{200}+0.035xR_{400}+0.014xR_{600}-0.71xG-0.140xQI_{75}-0.28xQI_{200}$
UNPAVED ROADS	
Automobile	$V=20.87+0.34xR_{100}+0.115xR_{200}-0.21xG-0.042xQI_{140}-0.083xQI_{300}+44.41xSE$
Bus	$V=20.87+0.19xR_{100}+0.115xR_{200}-0.85xG-0.007xQI_{140}-0.083xQI_{300}+44.41xSE$
Empty Utility	$V=30.71+0.19xR_{100}+0.115xR_{200}-0.21xG-0.042xQI_{140}-0.083xQI_{300}+44.41xSE$
Full Utility	$V=20.87+0.19xR_{100}+0.115xR_{200}-0.52xG-0.083xQI_{140}-0.083xQI_{300}+44.41xSE$
Empty Truck	$V=25.87+0.19xR_{100}+0.115xR_{200}-0.52xG-0.042xQI_{140}-0.083xQI_{300}+44.41xSE$
Full Truck	$V=20.87+0.19xR_{100}+0.115xR_{200}-0.52xG-0.042xQI_{140}-0.083xQI_{300}+44.41xSE$

$$R_{100}=\begin{cases}\text{radius, in meters} & \text{if radius} < 100m \\ 100m & \text{if radius} \geq 100m\end{cases}$$

$$R_{200}=\begin{cases}0\ m & \text{if radius} < 100m \\ \text{radius-100m} & \text{if radius} \leq \text{radius}\ \ 200m \\ 100m & \text{if radius} \geq 200m\end{cases}$$

$$R_{400}=\begin{cases}0\ m & \text{if radius} < 200m \\ \text{radius-200m} & \text{if } 200 \leq \text{radius}\ \ 400m \\ 200m & \text{if radius} \geq 400m\end{cases}$$

$$R_{600}=\begin{cases}0\ m & \text{if radius} < 400m \\ \text{radius-400m} & \text{if } 400 \leq \text{radius}\ \ 600m \\ 200m & \text{if radius} \geq 600m\end{cases}$$

G= Grade in %
SE= Superelevation, in decimals

$$QI_{75}=\begin{cases}\text{roughness, in counts/km, if paved and roughness} \leq 75 \text{ counts/km} \\ 75 \text{ counts/km if paved and roughness} > 75 \text{ counts/km}\end{cases}$$

$$QI_{200}=\begin{cases}0 \text{ if paved and roughness} \leq 75 \text{ counts/km} \\ \text{roughness-75 if paved and roughness} > 75 \text{ counts/km}\end{cases}$$

$$QI_{140}=\begin{cases}\text{roughness, in counts/km, if unpaved and roughness} \leq 140 \text{ counts/km} \\ 140 \text{ counts/km if unpaved and roughness} > 140 \text{ counts/km}\end{cases}$$

$$QI_{300}=\begin{cases}0 \text{ if unpaved and roughness} < 140 \text{ counts/km} \\ \text{roughness-140 if unpaved and roughness of} \geq 140 \text{ counts/km}\end{cases}$$

TABLE 3.8 - FUEL CONSUMPTION AT STEADY-STATE SPEED ON POSITIVE (FC1P) AND NEGATIVE (FC1N) GRADES

Automobiles	$C=0.142e^{0.02287S+0.000855(S)GR+0.03782(GR+3)P+0.2695(5-MARC)+0.0001024(QI)(GR+14)}$
Buses	$C=0.195e^{0.0359S+0.0044(S)GR+0.0075(GR+1)P+0.2781(6-MARC)+0.0002088(QI)P}$
Utilities	$C=0.197e^{0.02579S+0.001062(S)GR+0.02932(GR+3)+0.2485(5-MARC)+0.0000785(QI)(GR+14)}$
Light Truck (Gas.)	$C=0.906e^{\left[0.0127+0.00063P+0.00699(5-MARC)+0.0000215(QI)\right]S+0.01234(GR)(MARC)P}$
Light Truck (Die.)	$C=0.1826e^{0.0325S+0.00208(GR)S+0.0254(GR+1)P+0.2333(5-MARC)+0.0014005(QI)}$
Heavy Truck	$C=0.583e^{\left[0.02356+0.000491(GR+1)(P)\right]S+(0.00594P+0.01224GR)(6-MARC)+0.00057(QI)}$
Half-Trailer	$C=\left(2.54/\sqrt{1+G}\right)e^{\left[0.00505+0.00029(GR+1)P+0.00035(QI)\right]S}$

S = Speed (km/h)

GR = Grade (%)

G = $|GR|$ for negative grades; 0 otherwise

P = Gross weight (t)

QI = roughness (counts/km)

MARC = vehicle gear

C = fuel consumption (ml/sec)

TABLE 3.9 - FUEL CONSUMPTION IN DECELERATION ON POSITIVE GRADES PRECEDED BY NEGATIVE GRADES (FC2P)

VEHICLES	Number of Observations	Fuel Consumption (ml/sec)			
		Average	Standard Deviation	Minimum	Maximum
Automobiles	6	2.45	0.164	2.20	2.70
Buses	17	6.10	0.698	4.70	7.30
Utilities	11	3.83	0.380	3.10	4.50
Light Truck (Gas.)	12	10.86	1.072	10.60	14.40
Light Truck (Die.)	5	4.50	0.339	3.90	4.70
Heavy Truck	31	6.77	1.148	5.30	10.10
Half-Trailer	15	12.12	1.012	10.60	14.40

The average rates of consumption are utilized in the model.

TABLE 3.10 - FUEL CONSUMPTION DURING FORCED DECELERATION ON POSITIVE (FCDP) AND NEGATIVE (FCON) GRADES

VEHICLE	Number of Observations	Fuel Consumption (ml/sec)			
		Average	Standard Deviation	Minimum	Maximum
Automobiles	16	0.50	0.19	0.28	0.97
Buses	6	1.57	0.61	1.17	2.68
Utilities	26	0.66	0.18	0.31	1.03
Light Truck (Gas.)	14	4.81	1.74	1.50	6.75
Light Truck (Die.)	14	2.53	0.93	1.21	4.38
Heavy Truck	20	2.04	0.63	0.80	3.25
Half-Trailer	6	2.41	0.18	2.21	2.71

The average rates of consumption are utilized in the model.

TABLE 3.11 - FUEL CONSUMPTION DURING ACCELERATION ON POSITIVE GRADES (FCS4P)

VEHICLE	Number of Observations	Fuel Consumption (ml/sec)			
		Average	Standard Deviation	Minimum	Maximum
Automobiles	69	2.72	0.11	2.50	2.90
Buses	65	5.85	0.46	4.00	7.60
Utilities	143	3.60	0.49	2.10	4.40
Light Truck (Gas.)	66	10.03	0.95	8.40	12.50
Light Truck (Die.)	69	3.78	0.35	2.80	4.60
Heavy Truck	149	5.80	1.01	2.60	8.80
Half-Trailer	92	10.08	1.14	7.00	12.80

The average rates of consumption are utilized in the model.

TABLE 3.12 - FUEL CONSUMPTION DURING ACCELERATION ON NEGATIVE GRADES (FCS4N)

During calibration, it was necessary to adjust forecasts of consumption during acceleration on negative grades. Consequently, the equation FCS4N became a variable between the rates of consumption of the equations FCS4P and the equations FC1N.

If $S < S_1$ $\quad C = \frac{S_1 - S}{S_1} \; A \quad \frac{S}{S_1} \; B$

If $S \geqslant S_1$ $\quad C = B$

C = fuel consumption (ml/sec)
S = speed at start of stage of acceleration
S_1 = constant speed of adjustment calculated for each vehicle according to type of surface and cargo level.
A = fuel consumption forecast by equation FCS4P
B = fuel consumption forecast by equation FC1N

TYPE OF VEHICLE[1]	Constants of Adjustment			
	PAVED		UNPAVED	
	EMPTY	FULL	EMPTY	FULL
Automobiles	120	10000	120	10000
Buses	80	80	80	80
Utilities	100	100	100	100
Light Truck (Die.)	80	100	60	70
Heavy Truck	60	150	60	100
Half-Trailer	150	150	150	150

[1] Field tests with the light gasoline-powered truck (F-400) must be repeated and calibration had not been completed at the time of publication of this report.

CHAPTER 4

MTC LIMITATIONS AND OUTLOOK

As all models, the MTC has its limitations. Some of them originate in attempts to simulate highly complex phenomena in which such factors as driver behavior and environmental influences are important. Others originate in the experiments and analyses which produced the equations and parameters. Finally, there are those of the computer program which expresses the model.

Although the limitations originating in the necessity of simplifying the representation of the behavior of drivers and environmental influences are either explicit or implicit in this and other *ICR Research* reports, attention should be called to the assumption of *free speed*, which dominated the entire conception of the Model. This means that the MTC predictions are only valid for roads on which traffic is so low that there is no interaction among vehicles.

The *ICR Research* team has already gathered the necessary data and formulated the logic of the *Traffic Simulation Model* - *MST* (see Volume 10 of this Report), which will consider the influence of traffic on vehicle speed. Once this influence is modeled and associated to the MTC, one will have a prediction of speed and fuel consumption as a function of the relevant characteristics of the vehicle, road and traffic. In view of reductions in team personnel and the priority given to the ICR and MTC (second version) models, there is no current forecast as to the time it will take to conclude the MST. Until such time, the aforementioned MTC limitation will remain.

As regards the limitations originating in the experiments and analyses, one should note the following:

- Incomplete Calibration

The calibration of the MTC produced good results within the context of the TB-6 and FC-4 calibration experiments, as described in Volume 6. In certain aspects, however, the inference space in these experiments is limited. Consequently, not all of the options permitted by the MTC could be calibrated. In relation to the sections used in both calibration experiments, the most apparent limitation is that of the low degree of road-surface roughness. However, this is not a serious problem, since the inference space in the basic experiments (TB-1, TB-2, FC-1, etc.) is quite ample in terms of the roughness factor. Aside from this, speed-control sections were not considered in the calibration experiments, nor was their effect on the behavior (and fuel consumption) of the vehicles. The use of the MTC on speed-control sections could, therefore, lead to unrealistic predictions. It is probable that calibration experiments will be carried out on sections with a high degree of roughness or on speed-control sections, or both, in 1982.

- Equations of Deceleration and Acceleration

The equations of deceleration were derived exclusively from observations of the behavior of vehicles before horizontal curves (Experiment TBS-3). New analyses and, perhaps, even new experiments are needed (particularly on speed-control sections) in order to improve these equations. With regard to the equations of acceleration, one could consider it to be inconsistent to use the Project's test fleet, and instruct the drivers as to the manner in which they should accelerate, instead of observing the behavior of the vehicle population. New experiments involving deceleration and acceleration have been suggested for 1982.

- Omission of Alcohol-Powered Vehicles

Some alcohol-powered vehicles (including factory vehicles and others converted to use this fuel) have already been tested. According to plans, next year an additional one or two vehicles will be tested, the results analysed, and the computer program modified to also include this type of fuel in the MTC.

- Representativeness of the VW 1300

The present version of the MTC does not distinguish classes among automobiles and seeks to determine the consumption of the various types of this class, based simply on variations in gross weight. In cargo vehicles, there is a clear correlation between admissible gross weight and the power or cylinder capacity of the engine and, consequently, consumption. In automobiles, however, this correlation is not as evident. So, the equations and parameters depend on the representativeness of the Volkswagen 1300 sedan, in relation to the automobile population of the country, since this was the only automobile in the *ICR Research* test fleet. Tests using medium and/or large automobiles are being proposed for 1982 or 1983.

As regards the limitations of the MTC program, it is very important to consider the fact that, when the program was conceived, there was no intention of using it in direct and isolated applications (see description in the next chapter). This type of application became apparent only after conclusion of the program. From that moment forward, it became obvious that modifications would have to be introduced into some aspects of the program, as listed below:

• Small capacity for storing analysis data. The maximum number of positive and negative grades, curves, etc., that can be considered at a single time is insufficient for the analysis of long and hilly sections (for example, those longer than 20 or 30 km), thus making it necessary to subdivide them into shorter sections. Besides this, due to the unpredictability of the combination of analysis arrays in the creation of the links with which the program works, the user does not have a precise indication of this capacity. However, this limitation will not create any problems for the user who follows the recommendations contained in the appended Manual. In most cases, it is possible to analyse road sections up to 100-km long on a single run without exceeding program capacity, by simply dividing the section into five or six consecutive links. This limitation is scheduled to be totally eliminated by means of a modification in the logic of the program to be introduced in 1982.

• Possible occurrences of lack of continuity in the speed profile between consecutive segments. This is due to the fact that the model assumes that the initial speed of a vehicle on one segment will be the exit speed of the previous segment. For example, if the exit speed of the car class is 80 km/h, this will also be its entry speed into the subsequent segment. Should a speed-control section with a maximum permitted speed of less than 80 km/h be located at the start of the second segment, a lack of continuity will occur in the speed profile, leading consequently to error in speed predictions, since the vehicle would then have two speeds at a single point on the road. The modification to be introduced into the logic and structure of the program, as previously mentioned, should greatly attenuate or even make this limitation irrelevant, since there will then be no need of sectioning the road into segments in the conventional analyses.

• Stratification of vehicle classes. This does not correspond to the conventionally adopted classification in traffic reports such as, for example, those produced on the basis of origin and destination reports (O/D), of the National Highway Department (DNER). The MTC first classifies utility and cargo vehicles as *empty* and *loaded*, only later classifying them by size (three classifications for cargo vehicles). In the O/D reports, the classification begins on the basis of size (four for cargo vehicles) and only later goes on to the question of whether the vehicles are loaded or empty. The model accords great emphasis to utility vehicles, reserving separate classes for those that are loaded and those that are empty. In the standardized O/D output reports, utilities do not exist, though it is possible to obtain them from field reports. These differences cause some degree of difficulty in making the MTC inputs compatible with the conventional reports. Aside from this, in the output reports of the model, consumption of diesel-powered trucks is a weighted mean. For example, if 50% of these trucks are classified as light, with consumption of 3 km/ℓ, and the other 50% are semi-trailers, with consumption of 1 km/ℓ, the result printed on the output report will be 2 km/ℓ. This difficulty, however, can be easily avoided by running the program separately for each type of truck. A modification is scheduled to be introduced into the program inputs in 1982 to make it simple to achieve compatibility between the program and the O/D output reports of the DNER.

In conclusion,is anticipated that the present limitations of the MTC program will be largely liminated or avoided through the elaboration of a new version of the MTC in 1982. Aside from this, the new version of the system will have a modular structure, designed to optimize its operation. The principal purpose here is to make easier both the maintenance of the system and the coupling of new programs.

CHAPTER 5

APPLICATIONS AND EXAMPLES

5.1 INTRODUCTION

Originally, the MTC was not conceived for isolated or independent applications. It was to be only an algorithm of time and fuel and was actually utilized to generate speed and fuel equations for the ICR model, as discussed in Volume 8. After conclusion, it was decided that, should the MTC not be very demanding in terms of computer time, it would be made part of a system of models or routines which, with innumerable advantages, would substitute the ICR model. This system would be designated *Brazilian Models for the Evaluation of Highway Investments* (MOBAIR).

This possibility in fact occurred, since the MTC program can be rapidly executed in any large or medium-size computer. Consequently, it is now considered possible that the MTC will be incorporated into the future MOBAIR system, whose conception is to be outlined by the *ICR Research* team in 1982.

As regards direct and isolated applications, one should consider the fact that the MTC shows a good degree of precision for different levels of planning. However, it has the disadvantage of demanding highly-detailed inputs that are sometimes incompatible with the objectives and with the aggregate-scale prism adopted in some of the highway-planning studies. Inversely, this same degree of detail that is characteristic of its inputs (every grade, every curve, etc.) makes it possible to use the MTC in the comparison of design alternatives or even in the comparison of complete projects, provided that the comparison criteria based solely on fuel economy (and travel time) can be explicitly justified.

Under these conditions, the future MOBAIR system would have to have sufficient flexibility to use the MTC directly, when the inputs it requires at the engineering project level are available, or as an auxiliary model aimed at generating aggregate equations, of the type required by the present ICR model.

Consequently, one should discuss the validity of the MTC applications on two levels: for direct use as a model, isolatedly and independently; or as an auxiliary model of the present ICR Model or the future MOBAIR system.

5.2 ISOLATED AND DIRECT MTC APPLICATIONS

In isolated applications, the MTC predicts travel time and fuel consumption, simultaneously taking into account all of the important characteristics of a road, in the same manner as they are indicated in a project. In this sense, as far as is known, there exists no alternative, either in Brazil or abroad, which permits comparisons with the MTC, at least in terms of the vast experimental foundation on which the development of the MTC was based.

The decision as to the use for the isolated predictions of the MTC are to be put, this is a decision which should be taken by the user. Based on knowledge of the experiments which form the basis of the MTC, the logic and conceptions inherent in the program, and the more critical limitations of the present version - as extensively discussed in Volume 6 and in previous chapters of this Report - the user will be perfectly able to form his own judgement in taking this decision.

Naturally, there are other factors which will make it possible for the user to extend or restrict the use of the MTC in his arsenal of planning models, programs and parameters. Aside from the inexistence of fuel-consumption prediction methods similar to those of the MTC, one should also take into consideration all of the implications attending the current shortage and costs of oil derivatives. In other words, based on the concept of fuel economy, these two factors could well justify the comparison of design alternatives during the engineering-project stage, or of design alternatives during the phase of feasibility studies, with the condition that it be clearly understood and justified that the exclusion of other operational cost items will not invalidate or weaken or even distort the conclusion which one desires to obtain. In the latter case, given the present economic conditions of the country, considerations regarding the *shadow price* of fuel could be used to strengthen the justification of isolated applications of the MTC.

Obviously, there always exists the possibility of utilizing the MTC together with other methods and parameters, in separate operations. In other words, the MTC could be used in an isolated and independent fashion to calculate speed and fuel consumption, while other models or methods would be used separately to calculate the other items of road maintenance or operating costs of vehicles.

An example of an isolated application of the MTC is presented in the MTC *User's Manual* (bound separately).

5.3 MTC APPLICATIONS AS AN AUXILIARY MODEL

As regards the utilization of the MTC as an auxiliary model in the elaboration of other models, it would seem valid to present its application in relation to the ICR Model, by way of example.

The MTC was used to generate equations for predicting speed and fuel consumption on different road sections corresponding to the factorial cells presented in Table 5.1. Varying in length from 3 km to 40 km, these sections were obtained from the route files of the *User Cost Survey Team*, of the *ICR Research*. More than one section were chosen for each factorial cell, so that one would be able to estimate the error variation in speed and fuel consumption. All of the classes and types of vehicle defined in the MTC were simulated on each type of surface and at two levels of roughness:

- Paved: 50 and 100 QI; and
- Unpaved: 70 and 200.

The initial speed in both traffic directions was set at 80 km/h, for all classes of vehicles.

Speed predictions for the following classes of vehicles were then generated with the use of the MTC:

1. Automobile;
2. Bus;
3. Empty Utility;
4. Loaded Utility;
5. Empty Truck; and
6. Loaded Truck.

In the regression analysis which established the aggregate speed equations, the dependent variable V was utilized and defined as:

$$V = \sum_{i=1}^{2} \left[\frac{2L}{\left(\sum_{j=1}^{n_i} t_{ij} \right) \Big/ 3600} \right]$$

TABLE 5.1 - FACTORIAL MATRIX OF SECTIONS CHOSEN FOR GENERATION OF AGGREGATE EQUATIONS WITH THE USE OF THE MTC

RISE PLUS FALL (m/km) \ AVERAGE CENTRAL ANGLE (°/km)	LOWER THAN 100	100 to 180	ABOVE 180
0 to 15	164165 534663 766749	463331 478477 698485	331455 447448 449653
15 to 35	532556 765752	476830 207208A 207208B	158879B 456838B 684685 339863
>35	305303 392399 396395 887886	467468 501500 158879A	452655 456838A 687692

NOTE: The alphanumerals within the cells represent the codes which identify the sections chosen from the route file of the User Cost Survey Team.

Where:

- V = average speed (km/h) of a given class of vehicles in both directions of a given section;
- L = length of the section (km);
- t_{ij} = time spent (in seconds) for the vehicle class to cross the j-th link in direction i of the section under consideration;
- i = 1 primary direction; 2 secondary direction;
- n_1 = number of links in direction i of the section under consideration.

In the case of fuel consumption, MTC predictions were generated for the following types[1] of vehicles:

1. Automobiles;
2. Bus;
3. Empty Utility;
4. Loaded Utility;
5. Light Gasoline-Powered Truck with or without load;
6. Light Diesel-Powered Truck with or without load;
7. Heavy Truck with or without load; and
8. Semi-Trailer with or without load.

In the regression analysis which established the aggregate equations of fuel yield[2], the dependent variable C was used and defined as:

$$C = \sum_{i=1}^{2} \left[\frac{2L}{\left(\sum_{i=1}^{n_i} f_{ij} \right) / 1000} \right]$$

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[1] Observe that a class of vehicles as defined by the MTC can include one or more types (see User's Manual).

[2] Observe that in the greater part of the text, the expression *fuel consumption* has been used in the generic sense, without reference to the unit used. In the case of aggregate equations, however, the need to make this cost item compatible with the other cost items led to the use of the expression *fuel yield* to designate the unit km/ℓ, thus differentiating it from the expression *fuel consumption*, which designates the unit mℓ/sec., which is used principally in the analysis of the experiments.

Where:

C = fuel yield (km/ℓ) of a given vehicle class trafficking in both directions of a given section;

L = length of the section (km);

f_{ij} = fuel consumed (milliliters) by the vehicle class till the point of crossing the j-th link in direction i of the section under consideration;

i = 1 primary direction; 2 secondary direction;

n_1 = number of links in direction i of section under consideration.

In the regression analysis, the following independent variables - representing the geometric characteristics of the sections in aggregate form - were considered:

o Profile - SD = sum in absolute value of rise plus fall (m/km);

o Alignment - ACM = average central angle (degree/km) - (sometimes termed *average degree of curvature* in technical literature).

Table 5.2 presents the values of these variables in relation to the sections chosen and utilized in speed and fuel-yield predictions.

For the aggregate equations of fuel yield, another independent variable was defined:

$$PW = \frac{\text{Power (HP)}}{\text{Gross Weight (t)}}$$

The vehicle specifications utilized in the generation of the aggregate equations for cargo vehicles (classes 5 and 6, types 1, 2, 3 and 4) are presented below:

TYPES OF VEHICLES	POWER (Hp)	GROSS WEIGHT (t)		POWER/WEIGHT RATIO	
		Empty	Loaded	Empty	Loaded
Light Truck (g)	169	2.60	5.90	65.0	24.9
Light Truck (d)	102	2.60	5.90	39.2	17.3
Heavy Truck	147	9.80	21.00	15.0	7.0
Semi-Trailer	285	14.00	40.70	20.4	7.0

TABLE 5.2 - GEOMETRIC CHARACTERISTICS OF SECTIONS CHOSEN FOR GENERATION OF AGGREGATE EQUATIONS WITH THE USE OF THE MTC

SECTION CODE	BEGINNING OF SECTION(km)	END OF SECTION(km)	SUM OF RISES AND FALLS(m/km)	ACM AVERAGE CENTRAL ANGLE(%km)
164165	0.00	14.17	11.5	5.2
305303	0.00	7.94	40.8	47.3
331455	0.00	6.34	13.9	240.6
392399	0.00	13.59	40.2	34.2
396395	0.00	10.26	40.9	30.7
463331	0.00	4.57	9.8	104.0
467468	0.00	11.66	40.5	130.8
476830	0.00	14.53	26.0	138.6
478477	0.00	2.55	6.8	104.9
501500	0.00	13.34	40.9	112.1
532556	0.00	28.32	27.2	16.5
534663	0.00	17.36	11.4	5.3
698485	0.00	8.93	10.0	100.9
765752	0.00	39.99	26.7	17.8
766749	0.00	10.29	11.2	0.0
887886	0.00	5.93	40.9	11.5
158879A	0.00	11.07	40.6	131.4
158879B	17.85	27.04	26.4	191.1
207208A	19.69	27.67	30.4	153.1
207208B	9.84	19.69	25.9	132.3
447448	0.00	12.11	13.7	206.2
449635	27.79	36.43	14.4	240.4
452655	16.05	26.97	39.3	202.0
456838A	8.04	16.33	39.4	412.1
456838B	16.33	22.75	32.3	329.3
684685	10.86	19.45	26.7	198.8
687692	0.00	3.66	38.3	326.3
339863	0.00	8.27	32.1	319.8

Tables 5.3 and 5.4, respectively, present the aggregate equations of speed and fuel yield which were generated by the MTC for the different classes and types of vehicles, utilizing the process described above.

By way of example, the results of the application of the aggregate equations in the prediction of speed for the class of loaded trucks, along with the fuel yield of heavy trucks, are presented in Tables 5.5 and 5.6, respectively, in relation to highway sections with different geometric characteristics and different surface conditions.

5.4 *OBSERVATIONS*

When applied to sections with extreme geometric values (SD and ACM) and roughness (QI*), the equations presented in Tables 5.3 and 5.4 produce excessively-low predictions, including negative values. Even though sections with such extreme combinations are very rare, it is recommended, in order to avoid serious distortions, that one utilizes the following minimum values of fuel yield, when these situations occur:

		In km/ℓ
1.	Automobile	7.05
2.	Bus	2.65
3.	Empty Utility	5.10
4.	Loaded Utility	4.00
5.	Light Truck (gasoline)	1.10
6.	Light Truck (diesel)	2.20
7.	Heavy Truck	1.60
8.	Semi-Trailer	1.00

In determining the aggregate equations of fuel consumption, these values were the smallest predicted by the MTC. It should be noted that the minimum determined for the class *automobile* corresponds to the consumption of the Volkswagen 1300 Sedan. Naturally, the question arises as to whether this automobile and other vehicles in the Project's test fleet are representative of the vehicle population of the country. This question was discussed in Chapter 4.

A further shortcoming in relation to the aggregate equations of speed and fuel is that of the unsuitability of the SD and ACM vari-

TABLE 5.3 - AGGREGATE SPEED EQUATIONS

PAVED SURFACE	
Automobile	V=95.6-0.237xSD-0.266xACM-0.122xQI+K
Bus	V=90.0-0.356xSD-0.246xACM-0.141xQI+K
Empty Utility	V=89.4-0.241xSD-0.261xACM-0.115xQI+K
Loaded Utility	V=87.9-0.290xSD-0.262xACM-0.117xQI+K
Empty Truck	V=86.5-0.276xSD-0.253xACM-0.127xQI+K
Loaded Truck	V=79.8-0.340xSD-0.254xACM-0.140xQI+K
UNPAVED SURFACE	
Automobile	V=81.8-0.163xSD-0.236xACM-0.062xQI+K
Bus	V=71.0-0.282xSD-0.216xACM-0.081xQI+K
Empty Utility	V=79.8-0.167xSD-0.232xACM-0.055xQI+K
Loaded Utility	V=75.1-0.216xSD-0.233xACM-0.057xQI+K
Empty Truck	V=74.2-0.202xSD-0.223xACM-0.067xQI+K
Loaded Truck	V=70.2-0.266xSD-0.224xACM-0.080xQI+K
$K=(0.00058-0.0000137 \times SD) \times ACM^2 + 0.0043 \times SD \times ACM - 0.00123 \times SD \times QI$	

Coefficient of Determination: 0.91

Mean Square Error : 2.89 $(km/h)^2$

Number of Observations : 672

TABLE 5.4 - AGGREGATE FUEL-YIELD EQUATIONS

PAVED SURFACE	
Automobile	C=C1+12.31-0.030xSD+0.01494xACM-0.02401xQI
Bus	C=C1+5.46-0.0301xSD+0.00954xACM-0.00705xQI
Empty Utility	C=C1+7.98-0.0193xSD+0.01424xACM-0.01497xQI
Loaded Utility	C=C1+7.68-0.0293xSD+0.01122xACM-0.01475xQI
Light Truck (g)	C=C1+2.65-0.0079xSD+0.00493xACM-0.00107xQI+0.000059xACMxPW
Light Truck (d)	C=C1+5.49-0.0382xSD+0.00355xACM-0.00705xQI+(0.000059xACM+0.0294+0.0005xSD)xPW
Heavy Truck	C=C1+2.50-0.0364xSD+0.00546xACM+0.00582xQI+(0.000272xACM+0.0728+0.0011xSD-0.00053XQI)xPW
Semi-Trailer	C=C1+1.79-0.0109xSD+0.00156xACM+0.00276xQI+(0.000274xACM+0.0255-0.00034xQI)xPW
UNPAVED SURFACE	
Automobile	C=C2+13.11-0.0199xSD+0.01336xACM-0.02401xQI
Bus	C=C2+ 6.10-0.0197xSD+0.00796xACM-0.00705xQI
Empty Utility	C=C2+ 9.09-0.0089xSD+0.01266xACM-0.01497xQI
Loaded Utility	C=C2+ 8.37-0.0189xSD+0.00964xACM-0.01475xQI
Light Truck (g)	C=C2+ 3.06+0.0025xSD+0.00335xACM-0.00107xQI+0.000059xACMxPW
Light Truck (d)	C=C2+ 6.88-0.0278xSD+0.00197xACM-0.00705xQI+(0.000059xACM+0.0206+0.0005xSD)xPW
Heavy Truck	C=C2+ 2.36-0.0260xSD+0.00388xACM+0.00582xQI+(0.000272xACM+0.1046+0.0011xSD-0.00053xQI)PW
Semi-Trailer	C=C2+ 1.83-0.0005xSD-0.00002xACM+0.00276xQI+(0.000274xACM+0.0459-0.00034xQI)xPW

$C1 = -0.00001225 \times ACM^{2} + K$

$C2 = -0.00001085 \times ACM^{2} + K$

$K = (0.00000011 \times QI \times ACM - 0.00005 \times QI - 0.000113 \times SD) \times ACM$

Coefficient of Determination	:	0.96
Mean Square Error	:	0.31
Number of Observations	:	1344

TABLE 5.5 - SPEED PREDICTIONS (km/h) FOR LOADED TRUCKS OBTAINED THROUGH THE AGGREGATE EQUATIONS

AVERAGE CENTRAL ANGLE (°/km)	RISE AND FALL (m/km)	PAVED, ROUGHNESS (QI*) 30	PAVED, ROUGHNESS (QI*) 100	UNPAVED, ROUGHNESS (QI*) 50	UNPAVED, ROUGHNESS (QI*) 200
50	10	62.4	51.7	55.0	41.1
	25	59.4	47.5	52.8	36.1
	45	55.5	41.8	49.9	29.5
150	10	50.2	39.5	45.8	32.0
	25	49.6	37.6	45.9	29.3
	45	48.8	35.1	46.1	25.8
250	10	46.8	36.1	45.4	31.5
	25	44.4	32.5	43.8	27.1
	45	41.3	27.6	41.6	21.3

TABLE 5.6 - FUEL-YIELD PREDICTIONS (km/ℓ) FOR HEAVY TRUCKS WITH POWER/WEIGHT RATIO = 11 Hp/t

AVERAGE CENTRAL ANGLE (°/km)	RISE AND FALL (m/km)	SURFACE: PAVED, ROUGHNESS (QI*) 30	PAVED, 100	UNPAVED, 50	UNPAVED, 200
50	10	3.33	3.17	3.52	3.18
	25	2.88	2.72	3.23	2.89
	45	2.28	2.12	2.84	2.50
150	10	3.73	3.38	3.74	2.98
	25	3.11	2.76	3.27	2.52
	45	2.29	1.93	2.66	1.90
250	10	3.95	3.56	3.85	3.00
	25	3.17	2.77	3.21	2.37
	45	2.11	1.72	2.37	1.60

ables, utilized to describe the vertical and horizontal geometry of the road, instead of grades and individualized, sequential curves of the MTC.

These variables (SD and ACM) were utilized by the *Transportation and Road Research Laboratory* (TRRL) and by the *Massachusetts Institute of Technology* (MIT) in the Models RTIM and HDM, which, in terms of level of aggregation, are similar to the ICR. However, there is a consensus of opinion that these are rather unsatisfactory and that it is possible to define other variables or indexes that, though possessing the same level of aggregation as the SD and ACM variables, explain and better discriminate the vertical and horizontal geometry of the roads. Work in this area has already been initiated by the *ICR RESEARCH* team.

Finally, a word of caution to those who have contemplated using the equations of the MTC program to obtain predictions of speed and fuel consumption without running the program of the Model. This simply cannot be done. The equations of the MTC were designed for use within the context and inference space of the Model. As was demonstrated in Chapter 2, at each node the Model forms a complete survey of the situation (characteristics of the road, value and mode of previous speed, etc.) before selecting the speed equations and, subsequently, associating the corresponding consumption equations to them. It is entirely incorrect to isolate the phases of this intricate process.

Therefore, should the user, for any reason whatsoever, not be able to run the MTC on a computer, it is recommended that he uses the aggregate equations in Tables 5.3 and 5.4, instead of the MTC equations, independent of the relative unsuitability of the aggregate variables of the geometry presently under consideration.

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