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 6 – Study of Vehicle Behavior and Performance

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VOLUME 6 – Study of Vehicle Behavior and Performance

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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 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.

CONTENTS OF THIS VOLUME

LIST OF FIGURES

LIST OF TABLES

SUMMARY

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. This Volume 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 ± 8%) and curves (radii from 20 m to 3,000 m).

CHAPTER 1
INTRODUCTION

In the composition of the total costs incurred by the users of Brazil's road system for the transport of passengers and freight, almost all the components are, in one way or another, dependent on vehicle operation modes and on standards of road construction and maintenance. Taking components such as spare parts, tyres and labour for repairs into consideration, this dependence may be less important. However, fuel consumption and travel time are responsible for a considerable part of the total cost of transportation, where both vehicle operation modes and standards of road construction and maintenance are factors of significant influence.

Because of this, it has become imperative to define the different modes of vehicle operations as a function of the physical characteristics of the roads, and measure the fuel consumption in each situation, in order to establish the functions of dependence between fuel consumption,on one hand, and operation modes and standards of quality of riding surfaces,on the other. These functions are used in the Model of Time and Fuel Consumption (MTC) which is primarily designed to determine the travel time and the total fuel consumption of a vehicle running in free-flow conditions on a highway with defined characteristics. For this purpose, typical sections were selected which constituted segments homogeneous in geometry and traffic conditions, long enough for the performance of the vehicles to reflect the influence of these parameters. On these road sections, a number of surveys were performed to define vehicle operation modes, as well as fuel consumption measurements under different conditions of weight and speed.

To define the characteristics of the test sections, the following factors were selected: type of road surface (paved, unpaved), vertical and horizontal geometry, and state of maintenance (high and low roughness). These factors varied between limits ample enough to form a sampling matrix that would satisfactorily represent the conditions of traffic on Brazil's highway network (GEIPOT, 1976).

On these test sections, observations of traffic behaviour and experiments of fuel consumption were carried out (described in Vol. 2, Chapter 4 of this Report). These observations and experiments were designed to determine the steady-state speeds of vehicles on straight sections (grades of 0% to 8%), on curves (radius of 20 m to 3000 m), and in acceleration and deceleration modes (Table 1.1), as well as fuel consumption in each of these situations (Table 1.2).

In this way, correspondence was established between the speed observations of the vehicle population and the experiments on fuel consumption measurement carried out with the PICR test fleet. This correspondence permitted establishing consumption functions for the different modes of vehicle operation, so that for each operational mode (steady-state speed, acceleration or deceleration), determined by the variations in road characteristics, there would be a corresponding consumption function that would establish relationships among the variables that affect the fuel consumption and the travel time of a vehicle on a given route.

The following traffic surveys are described and analyzed in this Volume (Table 1.1): free-flow speeds on positive and negative grades and curves (TB-1, TB-2 and TB-4, respectively), effect of radar (TB-7), and approaches to curves (TBS-3). The experiments on speed calibration (TB-6), speed/capacity (TB-8) and calibration of operating speed (TB-9) provided independent data for the validation of speed-simulation models developed from previous surveys. The remainder was filed for further analysis.

The fuel consumption experiments are also discussed (Table 1.2), with the exception of the experiment which had the specific objective of collecting data for the validation of the Model of Time and Fuel Consumption (FC-4), which is commented in Volume 9 of this report.

Chapter 2 describes the effect of policing the speed limit on driver behaviour. Chapter 3 describes the influence of road roughness on vehicle performance. Chapters 4 to 6 present the traffic behaviour surveys, while Chapters 7 to 11 discuss the fuel consumption experiments. Chapter 12 presents the conclusions of these experiments. The use of the equations derived from these experiments in the Model of Time and Fuel Consumption is described in Volume 8 of this Report.

TABLE 1.1 - SURVEYS FOR THE STUDY OF TRAFFIC BEHAVIOUR

MAIN SURVEYS

NUMBER	TITLE	OBJECTIVE
TB-1	Free-flow speeds on positive grades	To determine the mode of free-flow speed on positive grades for each class of vehicles
TB-2	Free-flow speeds on negative grades	To determine the mode of free-flow speed on negative grades for each class of vehicles
TB-4	Free-flow speeds on curves	To determine the mode of free-flow speed on horizontal curves for each class of vehicles
TB-6	Speed Calibration	To collect independent data to verify and calibrate the models based on the experiments TB-1 to TB-4
TB-7	Effect of Radar	To determine whether the data on speed are being influenced by the presence of radar equipment on road shoulders
TB-8	Speed/Capacity	To collect data for the development of the relationship between speed and the volume of traffic
TB-9	Calibration of Operational Speed	To collect independent data to verify and calibrate the models of the TB-8 experiment

SATELLITE SURVEYS

TBS-1	Wet/Dry	To define differences in vehicle performance due to rain and wet surfaces
TBS-2	Types of Surfacing	To define differences in vehicle performance due to different types of gravel surfacing
TBS-3	Approaches to Curves	To collect data on deceleration occurring on approaches to horizontal curves
TBS-5	Night Traffic	To determine free-flow speeds at night time

TABLE 1.2 - TRAFFIC EXPERIMENTS PERFORMED WITH THE TEST FLEET

CATEGORY	IDENTIFICATION	OBJECTIVE
MAIN EXPERIMENTS ON FUEL CONSUMPTION	FC-1	To measure fuel consumption in mode of steady-state speed on grades
	FC-2	To verify fuel consumption and mode of deceleration of vehicles on positive grades preceeded by steep negative grades
	FC-3	To investigate the influence of small-radius curves on fuel consumption by vehicles
	FC-4	To measure fuel consumption on long sections to validate the Model of Time and Fuel Consumption (MTC)
SATELLITE EXPERIMENTS ON FUEL CONSUMPTION	FCS-5	To measure fuel consumption by large vehicles
	FCS-4 and TB-3	To measure fuel consumption in acceleration mode
	TBS-6	To measure fuel consumption in deceleration mode
	FCS-6	To investigate the effect of adding alcohol to gasoline

CHAPTER 2

INFLUENCE OF SPEED LIMIT ON DATA COLLECTED

In November 1976, a governmental order reactivated policing of speeds on highways, using radar, to make effective the legal speed limit of 80 km/h. Up to that date, approximately 100.000 data had already been collected on speeds developed by vehicles on tangents and curves, using the same type of radar as that used for policing roads, ostensibly placed on road shoulders.

As a result, it became necessary to verify whether, because of the greatly increased policing, the presence of radar on road shoulders was affecting the speed patterns of the vehicles. But the surveys carried out with radar camouflaged showed no significant difference between the speeds observed before November 1976, with radar exposed, and those observed after that date, with radar camouflaged, except in the case of buses and loaded trucks.

The data on loaded trucks showed that the exposed radar inhibited the drivers from accelerating on negative grades. Since the observation of this acceleration was one of the objectives of the survey on free-flow speeds occurring on negative grades (TB-2), all data on loaded trucks obtained with exposed radar were rejected.

With relation to buses, after November 1976, even with radar camouflaged, a significant decrease in speed at the end of negative grades was observed. In this case, the change in drivers' behaviour was attributed to the obligation imposed about this same time on bus companies of using tachographs in their vehicles and maintaining speed readings filed for inspection by DNER. As a result, all bus data obtained on negative grades before November 1976 were also rejected.

CHAPTER 3
INFLUENCE OF ROAD RIDING QUALITY

The Maysmeter, described in Volume 3 of this report, was adopted to measure the different states of maintenance of paved or unpaved roads. This instrument was used to measure road roughness, defined by a statistic called *roughness index*, or QI.

Based on the analysis of the results of the roughness measurements taken since 1976 by the Pavement Performance and Maintenance Study Team on 48 test sections with gravel and on 74 with asphaltic surfacing, located on the highway network of São Paulo, Minas Gerais, Goiás and the Federal District, the QI values for different levels of maintenance were established, as presented in Table 3.1 (Gontijo, 27/06/80).

However, it is necessary to emphasize that recent studies carried out in the United States by Gillespie, Sayers and Segel(12/80), and studies carried out in Brazil by the ICR Research (Alckmin, et al., 10/81), have raised doubts about the capability of this equipment for discriminating among highways as to their state of maintenance and type of surfacing. These studies show that highways with the same type of surfacing and submitted to the same maintenance standard can present different QI values, depending on a number of not fully explained factors which can occur during roughness measurements.

The ICR Research continues to study the problem, both theoretically and empirically, and it is possible that in a short time the PICR will have a satisfactory answer to this question. However, in the meantime it is necessary to be extremely careful, when measuring roughness, to avoid using QI values not correlated to those obtained at the time of the tests in the prediction equations for vehicle speed and fuel consumption.

TABLE 3.1 - CHARACTERIZATION OF THE STATE OF MAINTENANCE OF HIGHWAYS

STATE OF ROAD SURFACE	PAVED HIGHWAYS			UNPAVED HIGHWAYS		
	RANGE (QI)	FREQ	%	RANGE (QI)	FREQ	%
VERY GOOD	15 - 29	19	25.7	40 - 79	7	14.6
GOOD	30 - 44	31	42.8	80 - 119	19	39.6
REGULAR	45 - 59	20	27.0	120 - 159	15	31.2
POOR	60 - 74	2	2.7	160 - 199	6	12.5
VERY POOR	> 75	2	2.7	> 200	1	2.1

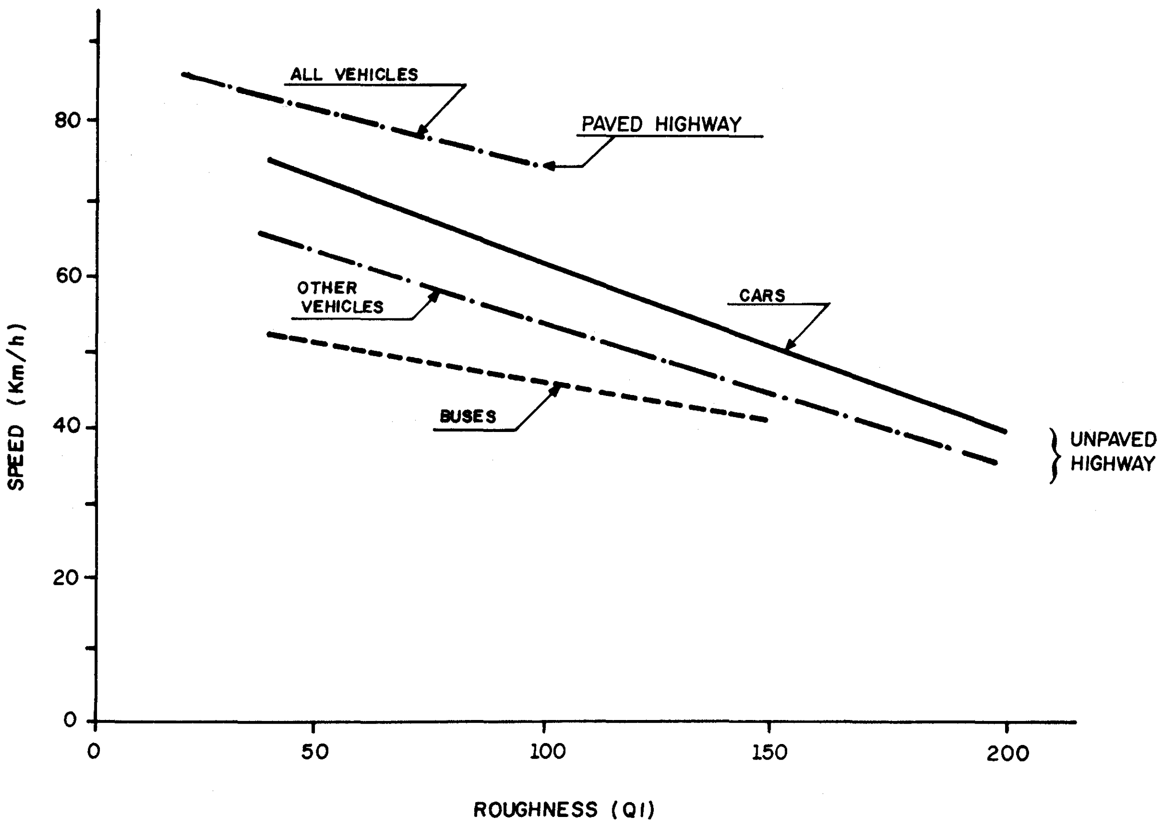


FIGURE 3.1- INFLUENCE OF ROUGHNESS ON FREE - FLOW SPEED (GRADE = 0,2%)

The statistical analysis to verify the influence of roughness on vehicle performance showed that the QI, under the conditions in which it was determined, is a significant variable to explain variations in vehicle speed and fuel consumption.

As to vehicle speed, this influence is translated by the following expressions:

Unpaved Roads

cars	$\Delta V = -0.214\ \Delta QI$	(3.1)
buses	$\Delta V = -0.093\ \Delta QI.Gp3$	(3.2)
others	$\Delta V = -0.177\ \Delta QI$	(3.3)

Paved Roads

all vehicles	$\Delta V = -0.154\ \Delta QI$	(3.4)

where: $Gp3 = \begin{cases} (6-G)/6 & \text{if } 0 < G < 6\% \\ 0 & \text{if otherwise} \end{cases}$

ΔV = decrease in speed (in km/h), for an increase ΔQI in road roughness.

G = grade, in per cent.

As an example, if an automobile on a poorly maintained road (with QI=150) travels at a free-flow speed of 50 km/h, after this same road is bladed (QI=50), its speed would tend to increase by 21.4 km/h:

$V = -0.214\ \Delta QI$ or

$-0.214\ (50-150) = +21.4$ km/h

Therefore, the automobile will run at (50 + 21.4) km/h, or at about 71 km/h.

The equations obtained are represented graphically in Figure 3.1.

In the study of fuel consumption, the roughness effect was tested within the range of 90 QI to 110 QI, regardless of the type of surfacing. Within this range, the QI values for poorly maintained paved roads often match those for well maintained unpaved roads.

The influence of roughness was found significant for all vehicle classes. As QI values under 90 generally occur on paved roads, and those over 110 normally occur on unpaved roads this variable was used to represent the combined influence of surfacing type and roughness (Zaniewski, Morais e Moser, 1979).

Figure 3.2 illustrates the effect of roughness on the fuel consumption of a half-loaded utility vehicle running on a level section, by applying the equations of fuel consumption at steady-state speed (Table 8.3). One can see that the fuel consumption increases with the deterioration of the road surface; in other words, the rougher the road surface, the greater will be the fuel consumption per unit of time, independent of the vehicle speed.

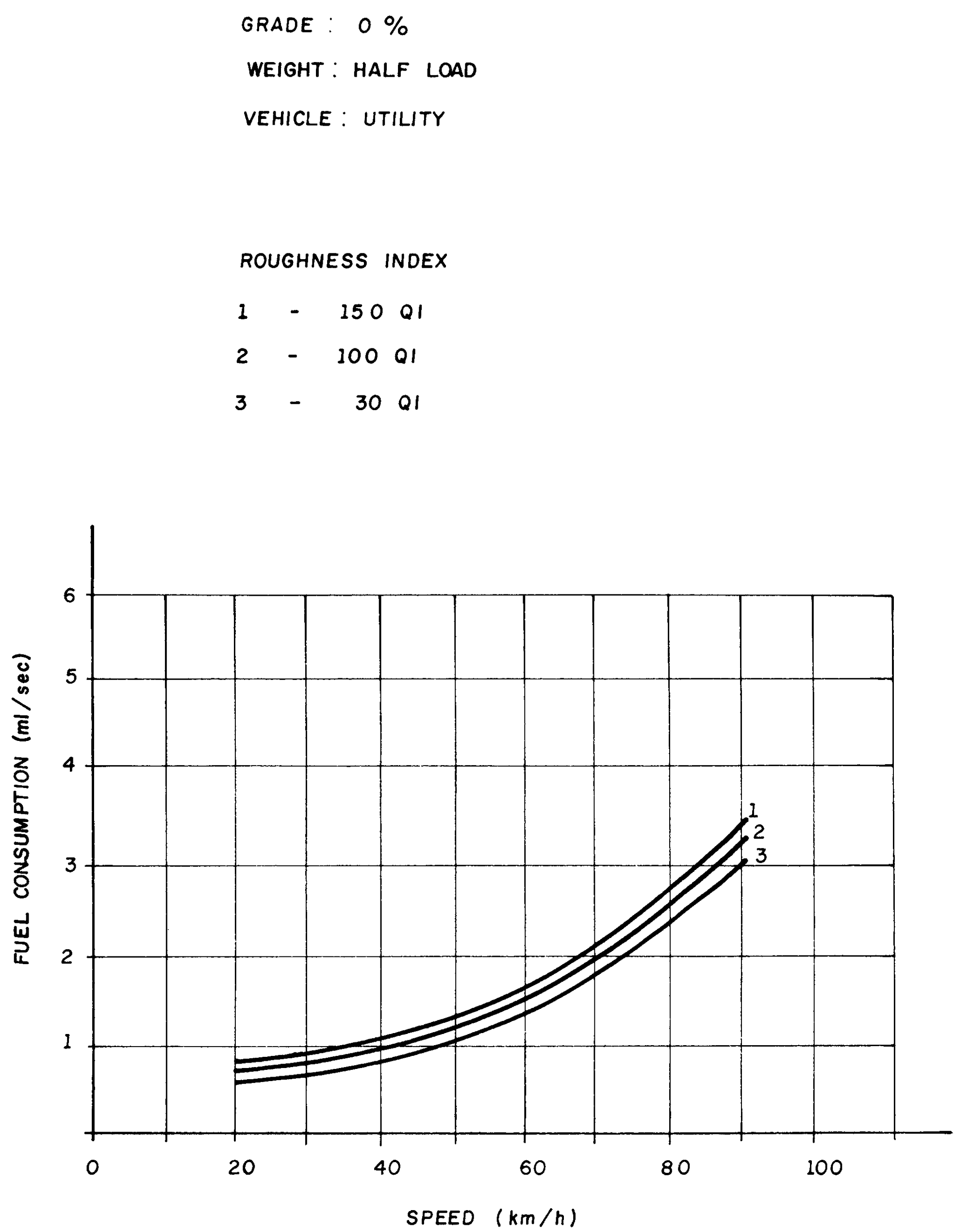


FIGURE 3.2- EFFECT OF ROUGHNESS ON FUEL CONSUMPTION.

CHAPTER 4
RESULTS OF FREE-FLOW SPEED SURVEYS

4.1 FREE-FLOW SPEEDS ON POSITIVE GRADES (TB-1) AND NEGATIVE GRADES (TB-2)

On highway segments of homogeneous characteristics it can be generally assumed that vehicles tend to run at a speed appropriate to their class and load, and limited by the type and state of maintenance of the surfacing. It can also be assumed that this speed always tends to keep constant and that the phases of acceleration and deceleration constitute transitory stages during which the vehicles seek to reach it.

To define this behaviour, road test sections were selected. They were straight with uniform grades, without any restrictions or obstacles that could interfere with the vehicles' speeds, allowing drivers to freely choose the most convenient speed for them with regard to road characteristics and to vehicle type and load.

Vehicle spot speeds were also measured by radar at predetermined points along these sections. The data were thus obtained to establish the equations which would translate vehicle behaviour as a function of the independent variables related to road type and maintenance state.

The analysis of the data set thus obtained determined the degree of influence of each of the variables (type of surface, roughness and grade) selected for study.

Equations were then developed: (1) to predict steady-state speed proper to each vehicle class on a given grade (Table 4.1), and (2) to simulate the variation in speed among the different vehicle classes as a function of the distance run from the beginning of the slope till the point where the vehicle stabilizes at the steady-state speed (Table 4.2) (Moser, 14/02/79, 19/02/79).

On unpaved roads the degree of a negative grade hardly influences the steady-state speed of vehicles, with the exception of buses and loaded trucks, which tend to have a higher steady-state speed as the declivity increases, even exceeding the speeds of light vehicles on negative grades around 6% (Figure 4.1a). On positive

TABLE 4.1 - STEADY-STATE SPEED ON UNIFORM GRADES (km/h)

Cars	$V = S1x(91.9-2.7xG_P-0.154xQI)+S2x(99.6-3.7xG_P+0.6xG_{N1}-0.214xQI)$
Buses	$V = S1x(84.3-0.5xG_N-10.8xG_{P1}-5.1xG_{P2}-0.154xQI)+S2x(67-6.8xG_{N1}-6.2xG_P-0.093xG_{P3}xQI)$
Empty utilities	$V = S1x(84.3-2.4xG_P-0.154xQI)+S2x(89.4-3.7xG_P+0.6xG_{N1}-0.177xQI)$
Loaded utilities	$V = S1x(84.3-3.7xG_P-0.154xQI)+S2x(83.9-3.7xG_P+0.6G_N-0.177xQI)$
Empty trucks	$V = S1x(74.6-3.0xG_N-3.7xG_P-0.154xQI)+S2x(80.9-3.7xG_P+0.6xG_{N1}-0.177xQI)$
Loaded trucks	$V = SLx(74.6-3.0xG_N-12.6xG_{P1}-3.5xG_{P2}-0.154xQI)+S2x(67-3.7xG_P-6.8xG_{N1}-0.177QI)$

$S1$ = 1 if paved; 0 if unpaved

$S2$ = 1 if unpaved; 0 if paved

G_N = G if $G < 0\%$; 0 otherwise

G_{N1} = G if $-3,6\% < G < 0\%$; $-3,6\%$ otherwise

G_P = G if $G > 0\%$; 0 otherwise

G_{P1} = G if $0\% < G \leq 3\%$; 3 if $G > 3\%$; 0 otherwise

G_{P2} = $(G-3)$ if $G > 3\%$; 0 otherwise

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

QI = Roughness Index

G = percent grade

TABLE 4.2 - SPEED VARIATION ON POSITIVE GRADES (km/h)

Cars	ΔV =	$D(-0.0001 \times G1 - 0.008 \times G2 - 0.0158 \times G3) \times S1 + DS_2 Ga$
Buses	ΔV =	$D(-0.0003 \times G1 - 0.0167 \times G2 - 0.0312 \times G3) \times S1 - 0.006 DS_2 G$
Empty utilities	ΔV =	$D(-0.0003 \times G1 - 0.008 \times G2 - 0.01 \times G3) \times S1 + DS_2 Ga$
Loaded utilities	ΔV =	$D(-0.0003 \times G1 - 0.008 \times G2 - 0.0152 \times G3) \times S1 + DS_2 Ga$
Empty trucks	ΔV =	$D(-0.0016 \times G1 - 0.008 \times G2 - 0.0125 \times G3) \times S1 + DS_2 Ga$
Loaded trucks	ΔV =	$D(-0.0037 \times G1 - 0.008 \times G2 - 0.0620 \times G3) \times S1 - 0.006 DS_2 G$

D = distance from beginning of acclivity up to the point where speed stabilizes

$$S1 = \begin{cases} 1 & \text{if paved} \\ 0 & \text{if unpaved} \end{cases}$$

$$S2 = \begin{cases} 1 & \text{if unpaved} \\ 0 & \text{if paved} \end{cases}$$

$$G1 = \begin{cases} G & \text{if } 0 < G < 3\% \\ 3 & \text{if } G \geq 3\% \end{cases}$$

$$G2 = \begin{cases} 0 & \text{if } G \leq 3\% \\ (G-3) & \text{if } 3\% < G < 5\% \\ 2\% & \text{if } G \geq 5\% \end{cases}$$

$$G3 = \begin{cases} 0 & \text{if } G \leq 5\% \\ (G-5) & \text{if } G > 5\% \end{cases}$$

$$a = \begin{cases} -0.000794 & \text{if } G \leq 3\% \\ -0.000794 - 0.001976 \left(\frac{G-3}{3}\right) & \text{if } 3\% < G < 6\% \\ -0.00277 & \text{if } G \geq 6\% \end{cases}$$

G = percent grade

slopes, Class 1, 3, 4 and 5 vehicles (see p. 56) are subject to a speed variation proportional to the inclination of the positive grade. Buses and loaded trucks (Class 2 and 6, respectively), whose steady-state speeds on positive grades are significantly reduced as the grade increases to 3%, show a substantial change in behaviour from this point on, with a smaller speed reduction on steeper inclines.

On unpaved roads, while Class 1, 3, 4 and 5 vehicles run at a steady-state speed almost independent of the steepness of the negative grade, buses and loaded trucks tend to run at higher steady-state speeds as the declivity grows steeper till approximately -3.5%. On unpaved positive grades, the decrease in steady-state speed due to the steepness is also substantial and very similar for all classes (Figure 4.1b). As for the deceleration mode, it was found that on positive grades, all classes of vehicles tended to lose speed in proportion to the acclivity's steepness, both on paved and unpaved roads, even though the decreases in speed caused by the steepness of the incline were substantially different on both types of surfacing. The equations in Table 4.2 define the behaviour of the five classes of vehicles studied, and quantify the speed loss of each class on positive grades as a function of the distance run from the beginning of the slope till the vehicles stabilize their speeds, the type of surfacing and the acclivity's steepness. Figure 4.2a graphically represents these equations for a grade of 5% on a paved road. On negative grades, it was found that only on paved roads would the vehicles accelerate proportionately to the declivity's steepness, according to the expression below (Moser, 14/02/79 and 19/02/79):

$$\Delta V = DG_N(0.00198+0.00120C_1-0.00166C_2-0.00134C_3-0.00157C_4) \qquad (4.1)$$

Where : D =distance for the vehicle to stabilize its speed

G_N =absolute value of grade

C_1 =1 if an automobile; 0 if another class

C_2 =1 if a bus; 0 if another class

C_3 =1 if an empty utility; 0 if another class

C_4 =1 if a loaded utility; 0 if another class

Figure 4.2b depicts this equation graphically, and exemplifies the behaviour of the different vehicle classes on a paved

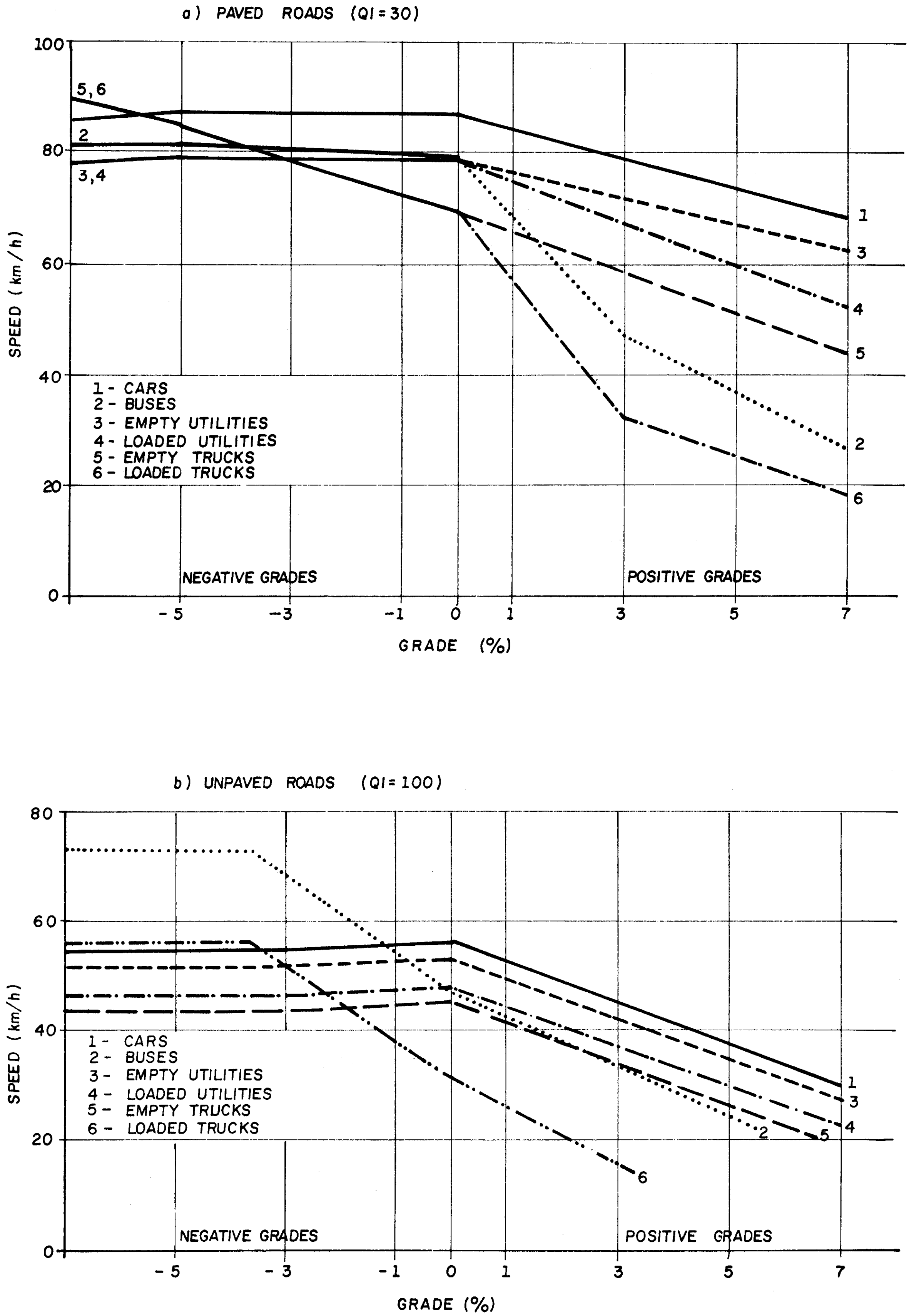


FIGURE 4.1 – VEHICLE PERFORMANCE ON UNIFORM GRADES (STEADY-STATE SPEED)

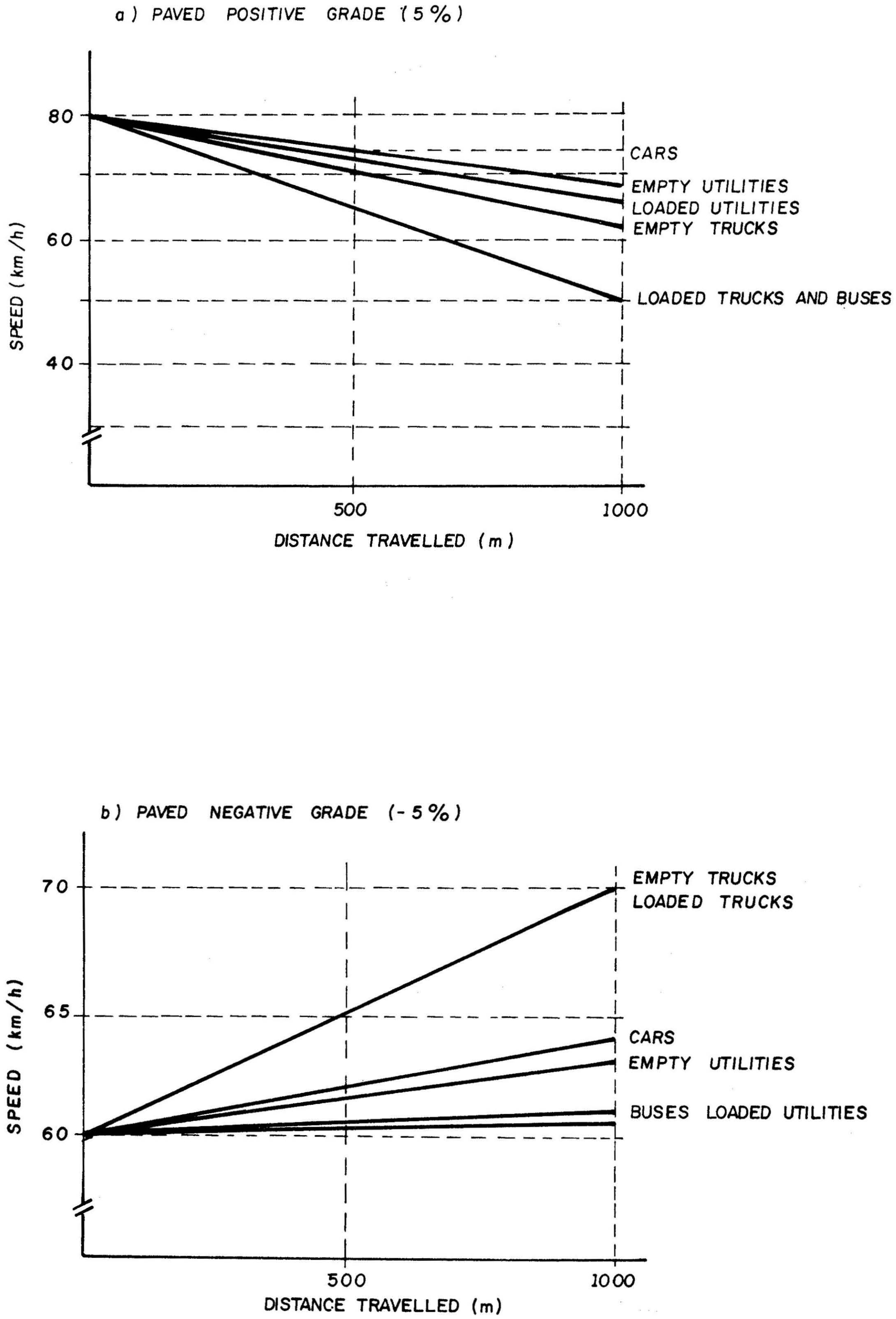


FIGURE 4.2 - VARIATION OF FREE-FLOW SPEED ON CONSTANT GRADES

declivity of 5%. It can be noted that buses and loaded utilities hardly change their speeds along the declivity. However, trucks, both empty and loaded, take advantage of the declivity and increase their speed by as much as 10 km/h for every 1000 meters, until they reach their steady-state speed for that declivity.

4.2 *FREE-FLOW SPEEDS ON CURVES (TB-4)*

The variables included in the study of vehicle behaviour on curves were: curve radius, type of surfacing, vertical geometry, state of surfacing, maintenance and superelevation.

Curves with radii from 20 m to more than 1000 m were included in the study, and as many as three curves for each profile and radius length were selected, depending on the position of the curve relative to the road profile (curve at the beginning of the slope, curve on the middle of the slope, and curve at the end of the slope). Thus over 150 curves were surveyed, about one hundred of which were found to have satisfactory conditions for statistical analysis.

In the analysis of variance of the data obtained, the type of surfacing, roughness, curve radius, superelevation, and vehicle class proved to significantly affect the variation in free-flow speeds on curves. Superelevation turned out to be significant for both types of surfacing, but on paved sections curve radius and superelevation are highly correlated; therefore, only radius was considered in the subsequent regression analysis.

The effects of curvature and roughness turned out to be non-linear. In the case of frequent variation in the radius of curvature, the speeds oscillated more on curves with short radii than on those of large radii. Similarly, the increase in roughness influenced speed more on well maintained roads (with a low level of initial roughness) than on poorly maintained roads (GEIPOT, 6/80).

Finally, it was found that curves with radii of less than 600 m significantly affect speed on paved curves, whereas on unpaved curves no significant effect was found on curves with a radius of more than 400 m. This can be attributed to the fact that vehicles tend to maintain lower speeds on unpaved roads.

Table 4.3 presents, for each vehicle class and for each surfacing type, the equations obtained from the statistical analysis of the data of Experiment TB-4. Table 4.4 presents a definition of those independent variables whose influence is significant. Figure 4.3 is the graphic representation of these equations for curves situated on level sections, both paved and unpaved, with roughness equal to 40 and 100 QI, respectively.

TABLE 4.3 - EXPRESSIONS FOR FREE FLOW SPEEDS ON CURVES

PAVED ROADS

Car

$$V = 17.756+0.428R_{100}+0.12R_{200}+0.035R_{400}+0.014R_{600}-0.71G-0.01QI_{1}-0.28QI_{2}$$

Bus

$$V = 17.756+0.29R_{100}+0.12R_{200}+0.035R_{400}+0.014R_{600}-0.71G-0.045QI_{1}-0.28QI_{2}$$

Empty utility

$$V = 17.756+0.39R_{100}+0.12R_{200}+0.035R_{400}+0.014R_{600}-0.71G-0.045QI_{1}-0.28QI_{2}$$

Loaded utility

$$V = 20.906+0.39R_{100}+0.12R_{200}+0.035R_{400}+0.014R_{600}-0.71G-0.14QI_{1}-0.28QI_{2}$$

Empty truck

$$V = 24.976+0.39R_{100}+0.12R_{200}+0.035R_{400}+0.014R_{600}-0.71G-0.14QI_{1}-0.28QI_{2}$$

Loaded truck

$$V = 17.756+0.39R_{100}+0.12R_{200}+0.35R_{400}+0.014R_{600}-0.71G-0.14QI_{1}-0.28QI_{2}$$

UNPAVED ROADS

Car

$$V = 20.87+0.35R_{100}+0.11R_{200}-0.21G-0.042QI_{3}-0.083QI_{4}+44.41SE$$

Bus

$$V = 20.87+0.19R_{100}+0.11R_{200}-0.85G-0.007QI_{3}-0.083QI_{4}+44.41SE$$

Empty utility

$$V = 30.71+0.19R_{100}+0.11R_{200}-0.21G-0.042QI_{3}-0.083QI_{4}+44.41SE$$

Loaded utility

$$V = 20.87+0.19R_{100}+0.11R_{200}-0.52G-0.083QI_{4}+44.41SE$$

Empty truck

$$V = 25.75+0.19R_{100}+0.11R_{200}-0.52G-0.042QI_{3}-0.083QI_{4}+44.41SE$$

Loaded truck

$$V = 20.87+0.19R_{100}+0.11R_{200}-0.52G-0.042QI_{3}-0.083QI_{4}+44.41SE$$

TABLE 4.4 - DEFINITIONS OF VARIABLES IN EXPRESSIONS OF FREE-FLOW SPEEDS ON CURVES

$$R_{100} = \begin{cases} R & \text{if } R < 100 \text{ m} \\ 100 & \text{if } R \geq 100 \text{ m} \end{cases}$$

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

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

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

$$QI_1 = \begin{cases} QI & \text{if paved road with } QI \leq 75 \\ 75 & \text{if paved road with } QI > 75 \end{cases}$$

$$QI_2 = \begin{cases} 0 & \text{if paved road with } QI \leq 75 \\ (QI - 75) & \text{if paved road with } QI > 75 \end{cases}$$

$$QI_3 = \begin{cases} QI & \text{if unpaved road with } QI \leq 140 \\ 140 & \text{if unpaved road with } QI > 140 \end{cases}$$

$$QI_4 = \begin{cases} 0 & \text{if unpaved road with } QI < 140 \\ (QI - 140) & \text{if unpaved road with } QI \geq 140 \end{cases}$$

G : percent grade

SE : superelevation, in decimals

R : curve radius, in meters

QI : roughness of riding surface

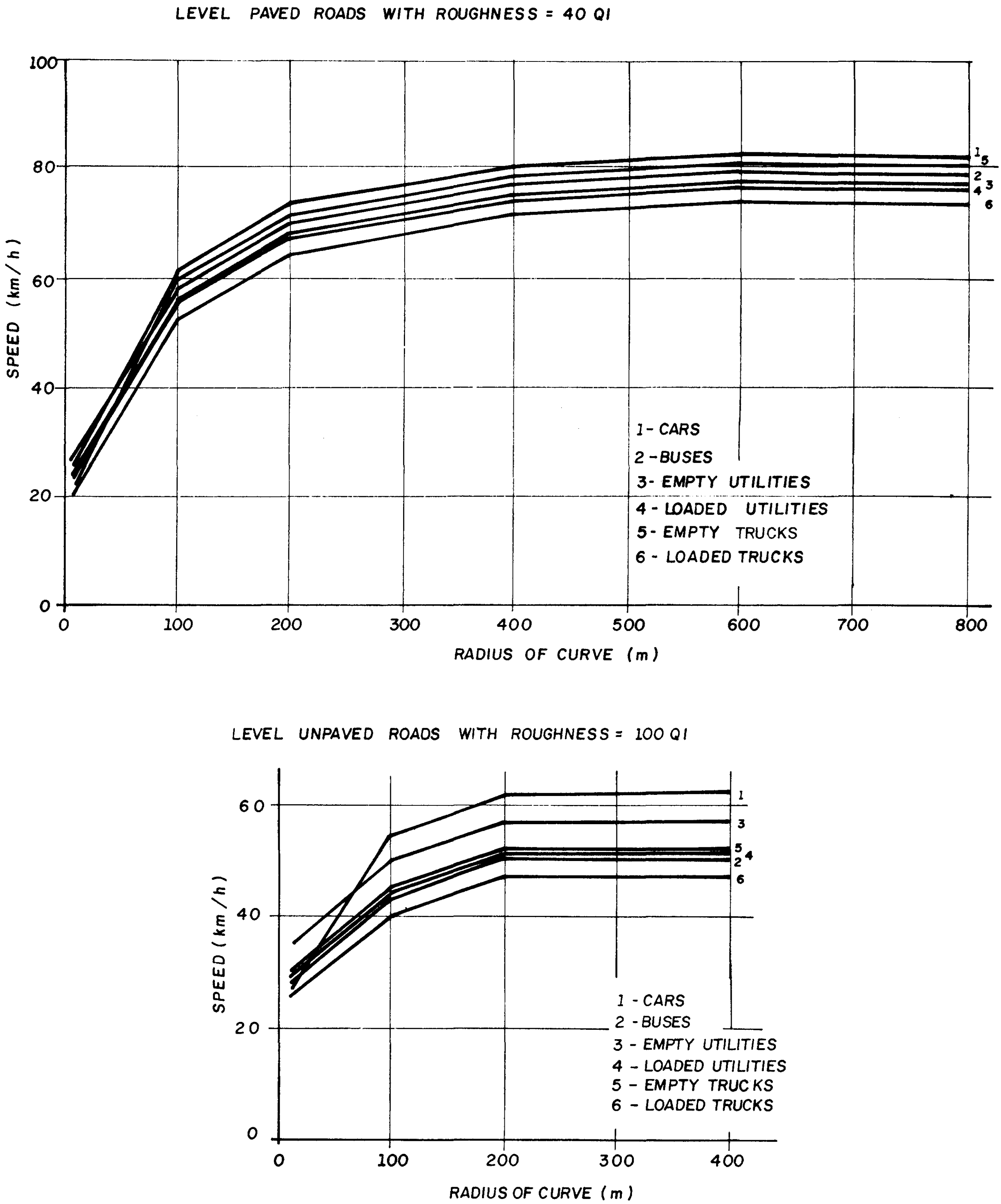


FIGURE 4.3 - SPEED ON CURVES

CHAPTER 5

RESULTS OF SPEED-MODE SURVEY AS VEHICLES APPROACH OBSTACLES OR SMALL-RADIUS CURVES (TBS-3)

To determine how vehicles decelerate when approaching controlled-speed locations or short-radius curves, a pilot survey was carried out on test sections with grades ranging from 2.0 to -3.5% (Table 5.1). Measured on these sections were: (1) the speed of different vehicle types at three given moments: the beginning of deceleration, the moment the driver stepped on the brake, and the moment the vehicle reached the beginning of the speed-controlled location), and (2) the instant when each event occurred.

In the data analysis, it was assumed that vehicles ran, within each interval, at a uniformly varied rectilinear movement, and based on this hypothesis deceleration at three intervals was determined: from the beginning of deceleration (Point A) to the moment when the vehicle was braked (Point B), and from this point to the end of the section studied (Point C), and later on the whole road segment, from (A) to (C) (Table 5.1).

The results obtained clearly show the influence of vehicle type and load. Table 5.2 presents, for each class of vehicle, the average deceleration before and after braking, and the weighted average deceleration of these two averages. The weighted average reflects the change in speed on approaches to curves or highway intersections.

As to the time periods in which vehicles were decelerating, it was found, on a nearly level highway intersection, that in the case of trucks and cars the first deceleration phase lasted for a period varying from ten to fifteen seconds. The second (after the use of brakes) lasted approximately five seconds for cars, and from six to twelve seconds for trucks. These results, however, should only be used as a first approximation of the solution to the problems of predicting decelerations, since they are based on the hypothesis of uniformly varied rectilinear movement, which does not actually occur, as deceleration varies along the road segment.

At the moment, the PICR is working on a new experiment to measure the distance run by the vehicles and the time they will take on it, at intervals short enough to permit the development of a model to describe deceleration and acceleration as a function of time (or distance), which will better reproduce the speed modes of vehicles

TABLE 5.1

MEAN VEHICLE DECELERATION WHEN APPROACHING CURVES OR INTERSECTIONS

TEST SECTION	GR. %	RADIUS m	INTERVALS	CARS	BUSES	UTILITIES		TRUCKS	
						EMPTY	LOADED	EMPTY	LOADED
765	0.7	40	A → B	0,39	0,57(2)	0,36	0,30	0,23	0,22
			B → C	1,49	1,68	1,15	1,11	1,11	1,01
			A → C	0,70	0,63	0,58	0,59	0,49	0,43
766	0,8	95	A → B						
			B → C	0,72	0,39	0,68	0,68	1,00(1)	0,55
			A → C	0,45		0,55	0,39		
647	2,0	80	A → B	0,36				0,11	
			B → C	0,41		1,38		0,80	
			A → C	0,38		0,57	1,39(1)	0,45	0,26
603	1,0	175	A → B	1,50(3)			0,34		
			B → C	0,25			0,59		
			A → C	0,49	0,75	0,34	0,42	0,19	0,10
846	-2,0	20	A → B	0,56	0,44	0,91(2)			0,34
			B → C	1,17	0,79	1,10	0,42(1)	0,31(1)	0,69
			A → C	0,98		0,97(3)	0,49	0,43	0,47
967	-3,5	20	A → B	0,84	1,20(1)	0,77	0,09(1)		0,10
			B → C	1,40	0,66	1,37		1,54	0,83
			A → C	0,99	0,56	0,56		0,76	0,52
ALL SECTIONS ABOVE			A → B	0,54	0,69	0,46	0,21	0,26	0,22
			B → C	1,40	0,92	1,11	0,65	0,89	0,68
			A → C	0,70	0,64	0,51	0,43	0,45	0,35
				AVERAGE ALL VEHICLES					
			A → B	Deceleration previous to braking = 0,41					
			B → C	Deceleration during braking = 1,14					
			A → C	Deceleration before and after braking = 0,53					

NOTE: The numbers in brackets indicate the number of observations available for calculation of the mean acceleration.

TABLE 5.2

MEAN DECELERATION IN m/sec^2

CLASSES OF VEHICLES	DECELERATION		
	BEFORE USE OF BRAKE	AFTER USE OF BRAKE	DURING THE ENTIRE SECTION
Cars	-0.54	-1.40	-0.60
Buses	-0.69	-0.92	-0.64
Empty utilities	-0.46	-1.11	-0.55
Loaded utilities	-0.21	-0.65	-0.63
Empty trucks	-0.26	-0.89	-0.46
Loaded trucks	-0.22	-0.68	-0.35

passing a section or obstacle which restricts their normal speed (see Volume 9 of this Report).

CHAPTER 6
RESULTS OF THE EXPERIMENT ON VEHICLES-ACCELERATION MEASUREMENT ON POSITIVE AND NEGATIVE GRADES (TB-3)

The purpose of experiment TB-3 is to study the way vehicle speed varies on positive and negative grades during the acceleration phase to regain the steady-state speed.

For this experiment two hypotheses were initially considered. The first consisted of stopping a certain number of vehicles of different classes at the beginning of a previously selected positive grade, and observing them by means of radar while they accelerated to return to their normal traffic speed. The second consisted of simulating this situation with the PICR test fleet, and measuring acceleration by means of instruments installed in the vehicles.

The first hypothesis, although more realistic, presented a number of logistical problems which made it impracticable; so it was decided to carry out the experiment with the test fleet.

The use of the second hypothesis made it possible to observe, simultaneously with acceleration, fuel consumption during the acceleration phase (see experiment FCS-4).

In order to eliminate the influence of driver behaviour and make the results obtained comparable, the drivers were instructed to use maximum acceleration to reach the steady-state speeds proper to their vehicles on that specific positive grade. Although necessary for making the results comparable, this procedure constituted a restriction on the experiment in the case of cars, because the results may reflect a somewhat exaggerated acceleration as compared to normal driving. In the case of trucks, the influence of maximum acceleration seems insignificant, since truck drivers tend to adopt this behaviour due to the low acceleration power of freight vehicles.

The analysis of variance shows that the significant factors in the determination of speed increments are the distance run by the vehicle, the type of vehicle, the load, the grade, and the roughness of the riding surface (Swait, 5/9/79 and 5/23/79).

Tables 6.1 and 6.2 present, for each class of vehicle and type of surfacing, the equations of speed change as a function of the distance run by the vehicle during the acceleration phase, as well as of the interaction of this factor with all other significant factors

TABLE 6.1 - EQUATIONS OF SPEED INCREMENTS (PAVED SURFACE)

Car	ΔV = {0.04444+0.00016x(PW-46.1)-0.00238xG-0.000038xQI}xD
Bus	ΔV = {0.03903+0.00037x(PW-17.1)-0.00109xG-0.000038xQI}xD
Utility	ΔV = {0.04894+0.00037x(PW-38.1)-0.00109xG-0.000038xQI}xD
Light Gasoline Truck	ΔV = {0.04538+0.00037x(PW-46.5)-0.00109xG-0.000038xQI}xD
Light Diesel Truck	ΔV = {0.03903+0.00022x(PW-28.2)-0.00109xG-0.000038xQI}xD
Heavy Truck	ΔV = {0.03737+0.00037x(PW-11.1)-0.00109xG-0.000038xQI}xD
Semi-Trailer	ΔV = {0.03903+0.00037x(PW-9.6)-0.00109xG-0.000038xQI}xD

TABLE 6.2 - EQUATIONS OF SPEED INCREMENTS (UNPAVED SURFACE)

Car	ΔV = {0.05639+0.00021x(PW-46-1)-0.00169xG-0.000046xQI}xD
Bus	ΔV = {0.03811+0.00021x(PW-17.1)-0.00131xG}xD
Utility	ΔV = {0.04735+0.00021x(PW-38.1)-0.00245xG-0.000025xQI}xD
Light Gasoline Truck	ΔV = {0.04152+0.00021x(PW-46.5)-0.00131xG}xD
Light Diesel Truck	ΔV = {0.03325+0.00021x(PW-28.2)-0.00131xG}xD
Heavy Truck	ΔV = {0.03951+0.00021x(PW-11.1)-0.00131xG}xD
Semi-Trailer	ΔV = {0.03325+0.00021x(PW-9.6)-0.00131xG}xD

Mean Square Error = 1.998 $(m/s)^2$

Coefficient of Determination = 0.895

Number of Observations = 3445

ΔV = speed increment (m/s)

D = distance run during acceleration (m)

G = grade (%)

QI = roughness index

PW = power/weight ratio (HP/t)

mentioned in the previous paragraph.

Figure 6.1 shows the change in speed as a function of the distance run. The vehicle observed was a heavy truck (power/weight ratio of 14.9 hp/t and 7.3 hp/t, corresponding to the vehicle empty and loaded, respectively), on a paved road (30 QI roughness) on a level section, and on a slope with a grade of 6%, running in both traffic directions.

The determination of steady-state speed on positive and negative grades was worked out with the equations obtained from the Experiments TB-1 and TB-2, respectively, whose results are shown in Figure 6.1 to illustrate vehicle speed behaviour on the different grades.

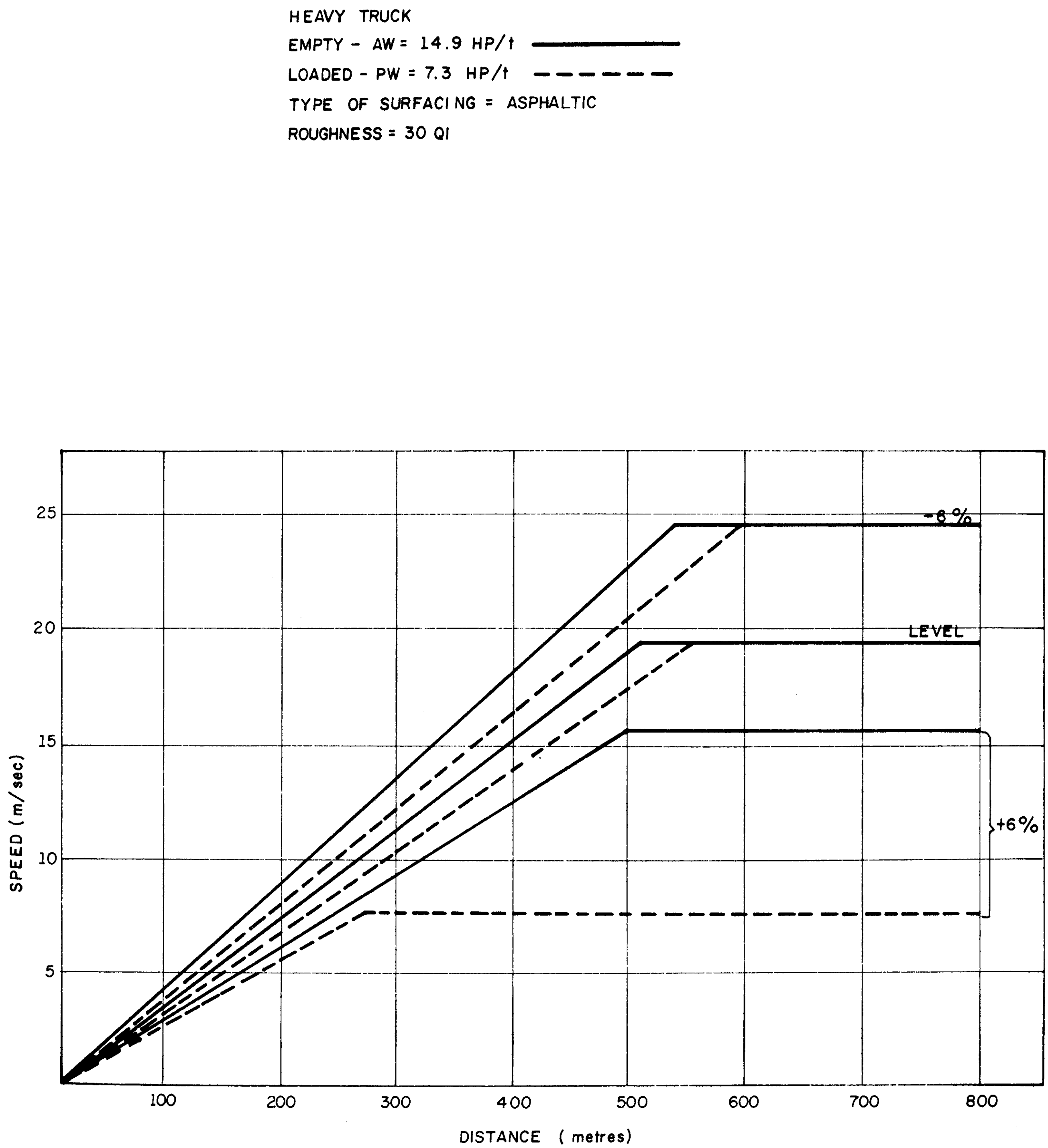


FIGURE 6.1 - CHANGE IN SPEED AS A FUNCTION OF DISTANCE RUN BY VEHICLE

CHAPTER 7
INFLUENCE OF ADDING ALCOHOL TO GASOLINE

Since August 1978, it has been the official policy of the Government to add alcohol to gasoline, to reduce the consumption of imported fuel. To evaluate the effect of this mixture on fuel consumption, experiment FC-1 was partially repeated with the VW-1300, Kombi and F-400 gasoline truck, this time using as fuel a mixture of 20% alcohol and 80% gasoline. The factors and levels considered in this experiment are presented in Table 7.1.

TABLE 7.1 - FACTORS AND LEVELS OF EXPERIMENT FCS-6

FACTORS	LEVELS
Cargo	Empty, Loaded
Grade	0, 4, 6%
Direction of Grade	Positive, Negative
Type of Surfacing	Paved, Unpaved
Type of Fuel	Pure Gasoline, Alcohol/Gasoline Mixture

The analysis of variance of the data generated by this experiment showed an insignificantly small difference in consumption between the two types of fuel. The volume of fuel consumed under the same conditions was slightly higher for the mixture of alcohol and gasoline.

Figures 7.1, 7.2 and 7.3 show the dispersion of the consumption data for the three vehicles studied (car, utility and light gasoline truck) around the straight line of equality. The results of the analysis of variance show insignificant differences in the consumption of both types of fuel by the three vehicles tested. This indicates that any adjustment in the equations is unnecessary since it would not perceptibly increase their present level of precision.

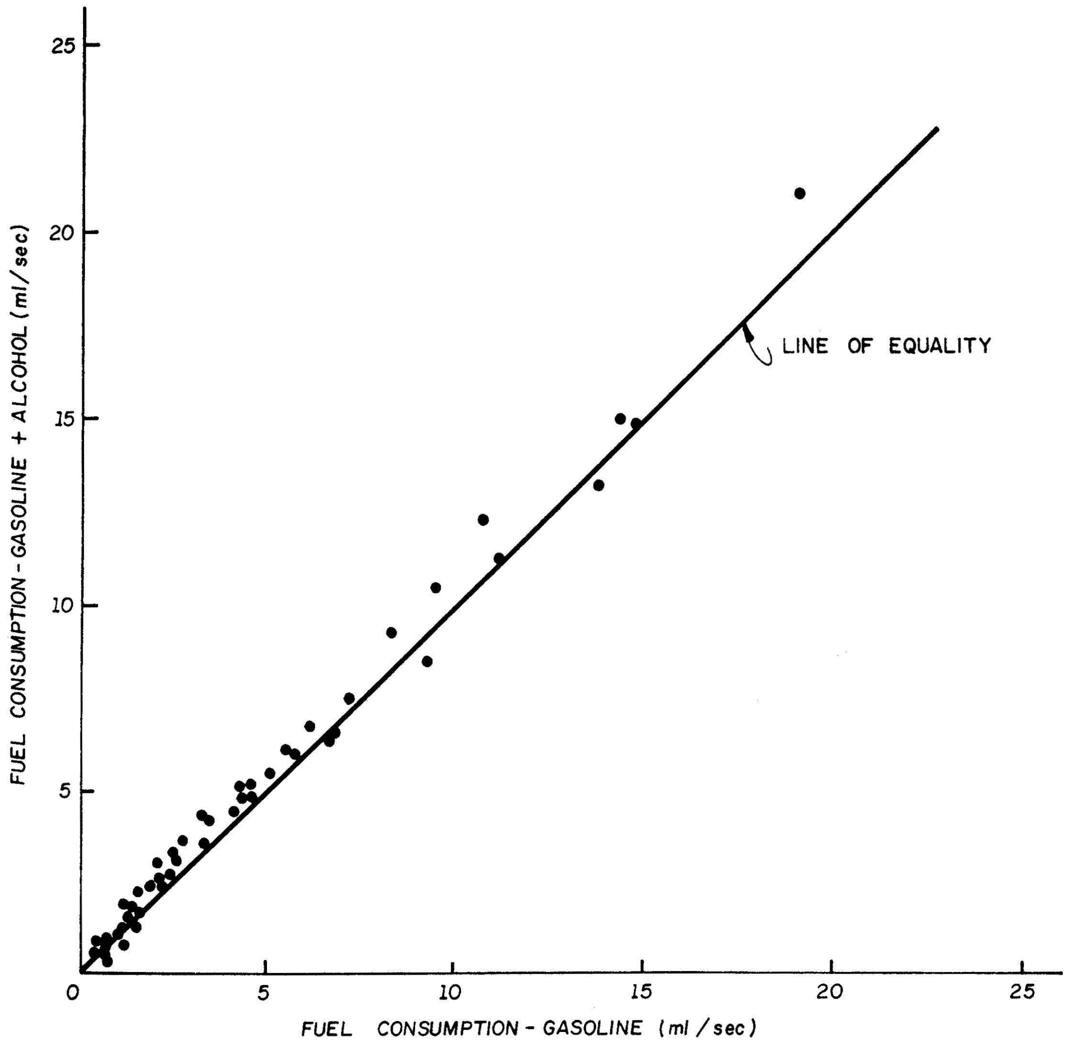


FIGURE 7.1 - GRAPH COMPARING THE CONSUMPTION OF PURE GASOLINE WITH THAT OF GASOLINE + ALCOHOL (LIGHT GASOLINE TRUCK).

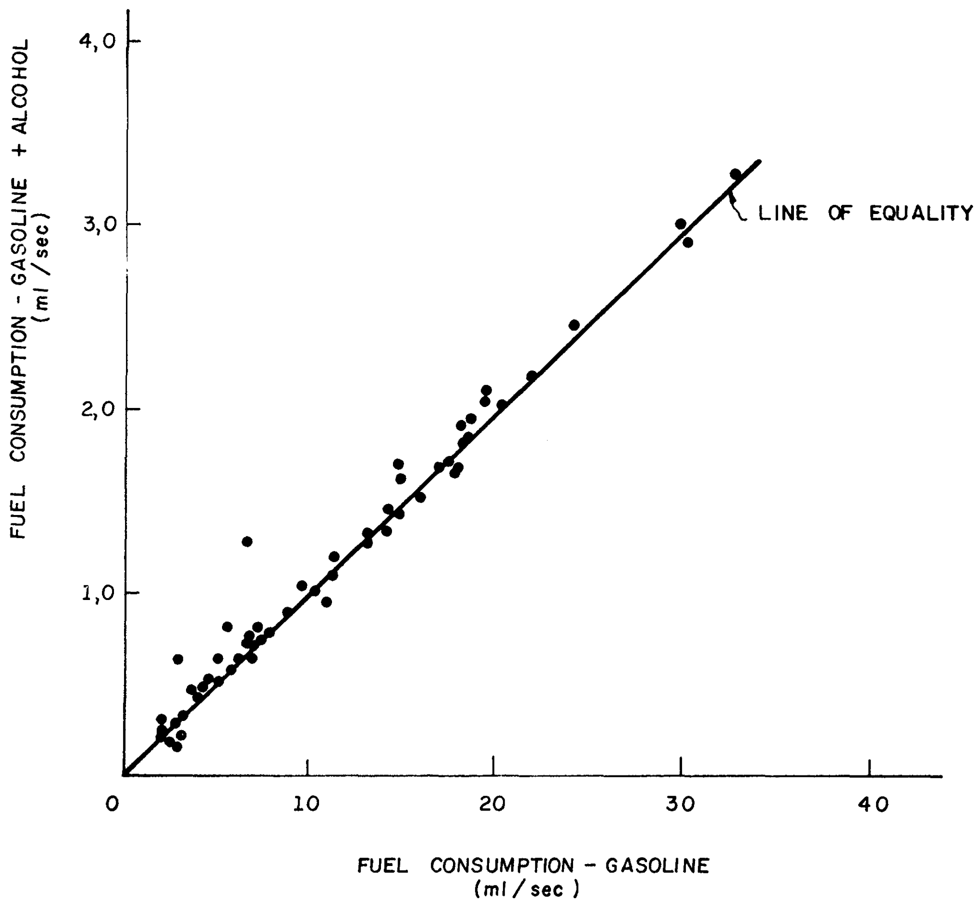


FIGURE 7.2 - GRAPH COMPARING THE CONSUMPTION OF PURE GASOLINE WITH THAT OF GASOLINE + ALCOHOL (VW - 1300 CAR)

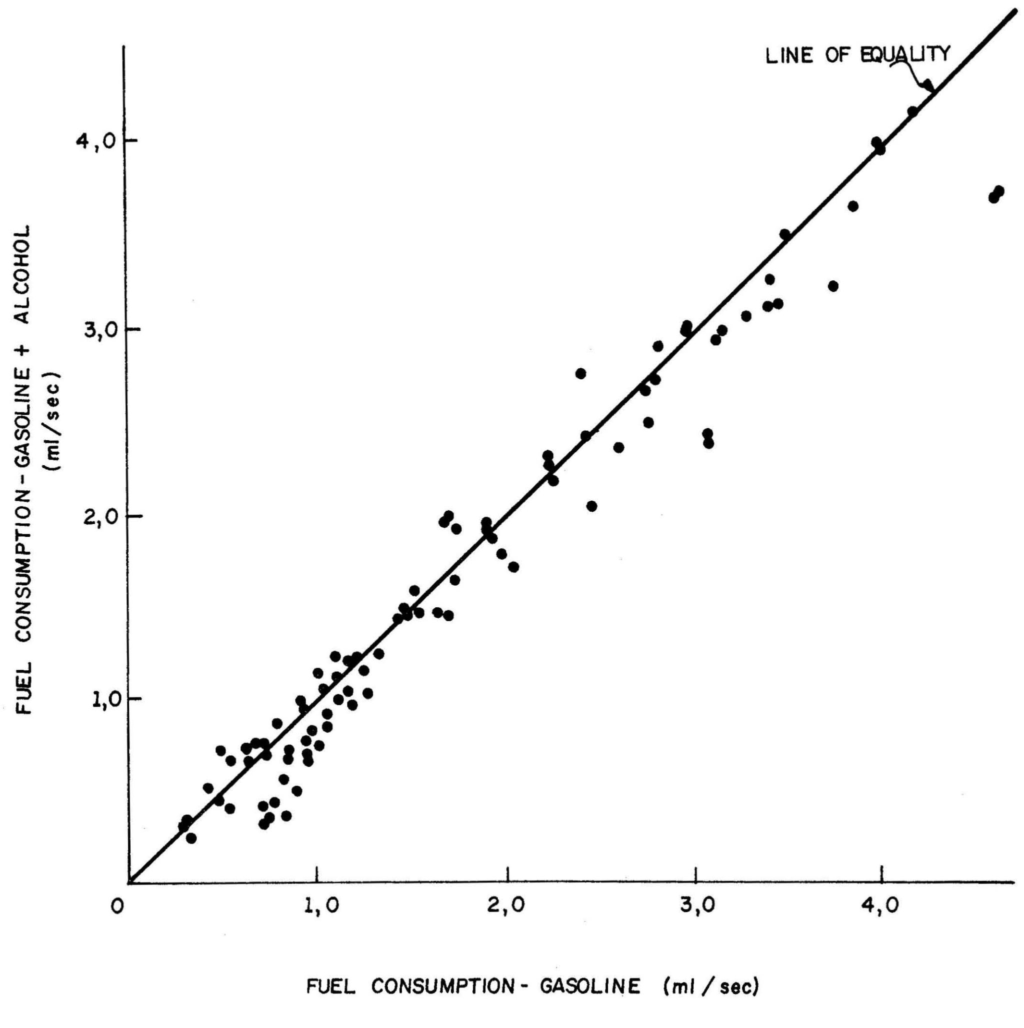


FIGURE 7.3 - GRAPH COMPARINC THE CONSUMPTION OF PURE GASOLINE WITH THAT OF GASOLINE + ALCOHOL (UTILITIES).

CHAPTER 8
RESULTS OF THE EXPERIMENTS ON FUEL-CONSUMPTION MEASUREMENT AT STEADY-STATE SPEED

8.1 FUEL CONSUMPTION ON TANGENTS (FC-1)

The experiment of fuel consumption measurement at steady-state speed was the largest experiment carried out with the PICR test fleet. It consisted of approximately 30.000 measurements on twenty-five test sections with different characteristics. The nine vehicles specified in Table 8.1 were used in this experiment; they were run on the test sections at a constant speed, from a minimum of 10 km/h to a maximum of 120 km/h (car on negative grades), in different combinations of speed and gear.

For the analysis of variance the factors and levels shown in Table 8.2 were considered, where the load was determined according to the maximum loads recommended for each type of vehicle (Zaniewski, Plautz e Morais), and the roughness varied from 23 QI to 118 QI, on paved roads, and from 48 QI to 225 QI on unpaved roads. The dependent variable was the average fuel consumption (in mililiters/second), obtained from the three measurements carried out for each combination of the different levels of factors shown in Table 8.2. Analysis of variance was employed to evaluate the influence of each of the main factors and their interactions, and for identification of those which had a significant effect on fuel consumption. This identification served as the basis for formulating equations capable of explaining the variation in fuel consumption as a function of the independent variables associated with the significant factors.

After the more significant independent variables were identified, a non-linear regression procedure was used to estimate their coefficients. Thus the equations for the prediction of fuel consumption were developed for the seven classes of vehicles studied (Zaniewski, Morais e Moser, 1979).

Table 8.3 presents the equations obtained, as well as the determination coefficients and the mean square errors for each equation. Figures 8.1 to 8.5 illustrate the form of the equations and the magnitude of each of the main effects evidenced by the analysis of field data. Figure 8.1 shows the fuel consumption of each type of vehicle as a function of operating speed when the vehicles were running half loaded on a paved, level, well maintained surface (roughness

TABLE 8.1 - MAIN SPECIFICATIONS OF TEST-FLEET VEHICLES

TYPE	CAR	UTILITY	BUS	LIGHT TRUCK		HEAVY TRUCK		SEMI TRAILER	
MAKE	VOLKSWAGEN	VOLKSWAGEN	MERCEDES BENZ	FORD		MERCEDES BENZ		SCANIA TRACTOR	TRAILER
DIMENSION	1300	KOMBI	0-362	F-400	F-4.000	L-1113	L-1113-C MUNK	L-110-38S	
DIMENSION (m)									
Ground clearance	0.152	0.200	0.273	0.200	0.200	0.279	0.279	0.300	
Total height	1.500	1.912	2.945	1.890	1.890	2.454	2.454	2.013	
Width	1.540	1.746	2.500	2.030	2.030	2.350	2.350	2.403	
Distance between axles	2.400	2.400	5.500	4.030	4.030	4.200	4.200	3.800	8.750
Front overhang	0.760	1.130	2.310	0.750	0.750	1.100	1.100	1.480	0.900
Rear overhang	0.910	0.867	2.800	2.200	2.200	3.850	4.600	...	2.600
Total length	4.070	4.397	10.860	8.980	6.980	9.150	9.900	16.630	12.250
MOTOR									
Fuel	Gasoline	Gasoline	Diesel	Gasoline	Diesel	Diesel	Diesel	Diesel	
Type	Horiz.Opp.		In line	V	In line	In line	In line	In line	
Number of cilinders	4	4	6	8	4	6	6	6	
Bore (mm)	77	83	97	92	105	97	97	127	
Stroke (mm)	69	79	128	84	120	128	128	145	
Displacement (cc)	1.285	1.493	5.675	4.457	4.163	5.675	5.675	11.000	
Compression Ratio	6.6	6.6	17	73	17,8	17	17	16	
Torque/RPM (m.kgf)	9.1/2.600	10.3/2.600	37/2.600	33.5/2.200	29.2/1.600	37.0/2.000	37/2.000	79/1.200	
Horse Power	48/4.600	60/4.600	147/2.800	169/4.400	102/3.000	147/2.800	147/2.800	285/2.200	
TRANSMISSION RATIO									
1st gear	3.8	3.8	8.02	6.40	5.30	8.02	8.02	13.51	
2nd gear	2.06	2.06	4.77	3.09	2.85	4.77	4.77	10.07	
3rd gear	1.32	1.32	2.75	1.69	1.56	2.75	2.75	7.55	
4th gear	0.87	0.89	1.66	1.00	1.00	1.66	1.65	5.66	
5th gear	-	-	1.00	-	-	1.00	1.00	4.24	
6th gear	-	-	-	-	-	-	-	3.19	
7th gear	-	-	-	-	-	-	-	2.38	
8th gear	-	-	-	-	-	-	-	1.78	
9th gear	-	-	-	-	-	-	-	1.34	
10th gear	-	-	-	-	-	-	-	1.00	
Differential	4.375	4.375	4.875	5.140	4.630	4.875	4.875	4.710	

SOURCE: Vehicle owner's manuals.

TABLE 8.2 - FACTORS AND LEVELS CONSIDERED IN THE ANALYSIS OF THE FC-1

FACTORS	LEVELS	
Type of Vehicle	1, 2, ..., 7 (models in the fleet)	
Vehicles Repeated Within the Classes	1, 2 (Kombi, Heavy Truck)	
Gross Weight	Own weight, own weight + load	
Type of Surfacing	Paved, unpaved	
Roughness	Paved section	Low (< 40 QI) High (> 90 QI)
	Unpaved section	Low (<100 QI) High (>140 QI)
Vertical Geometry	0-2% 3 to 5% 6 to 8% > 8% *	
Direction of Grade	Positive, negative	
Speed Gear	10, 20, ... V (km/h) 1ª, 2ª, ... MARC	

*Test section 555 with primary surfacing and 13% grade.

TABLE 8.3

CONSUMPTION EQUATIONS FOR STEADY-STATE SPEED

VEHICLE	S^2_c	R^2	
Car	0.037	0.91	$COMB = 0.142e^{(0.2287V+0.000855(V)GR+0.03782P(GR+3)+0.2695(5-MARC)+0.0001024(QI)(GR+14))}$
Utility	0.060	0.93	$COMB = 0.197e^{(0.02579V+0.001062(V)GR+0.02932P(GR+3)+0.2485(5-MARC)+0.0000785(QI)(GR+14))}$
Light Gasoline Truck	0.410	0.94	$COMB = 0.906e^{(0.0127+0.00063P+0.00699(5-MARC)+0.0000215(QI)V+0.01234GR(P)MARC)}$
Light Diesel Truck	0.140	0.90	$COMB = 1826e^{(0.0325V+0.00208(GR)V+0.0254P(GR+1)+0.2333(5-MARC)+0.001405QI)}$
Medium Truck	0.190	0.93	$COMB = 0.583e^{(0.02356+0.000491(P).(GR+1))V+(0.00594P+0.01224GR).(6-MARC)+(0.00057QI)}$
Heavy Truck	0.410	0.96	$COMB = (2.54/\sqrt{1+G})e^{(0.00505+0.00029.P(GR+1)+0.00035QI)V}$
Bus	0.170	0.92	$COMB = 0.195e^{(0.0359S+0.0044(GR)V+0.0075(P).(GR+1)+0.2781(6-MARC)+0.0002088(P)QI)}$

COMB = fuel consumption (ml/sec)

V = speed (km/h)

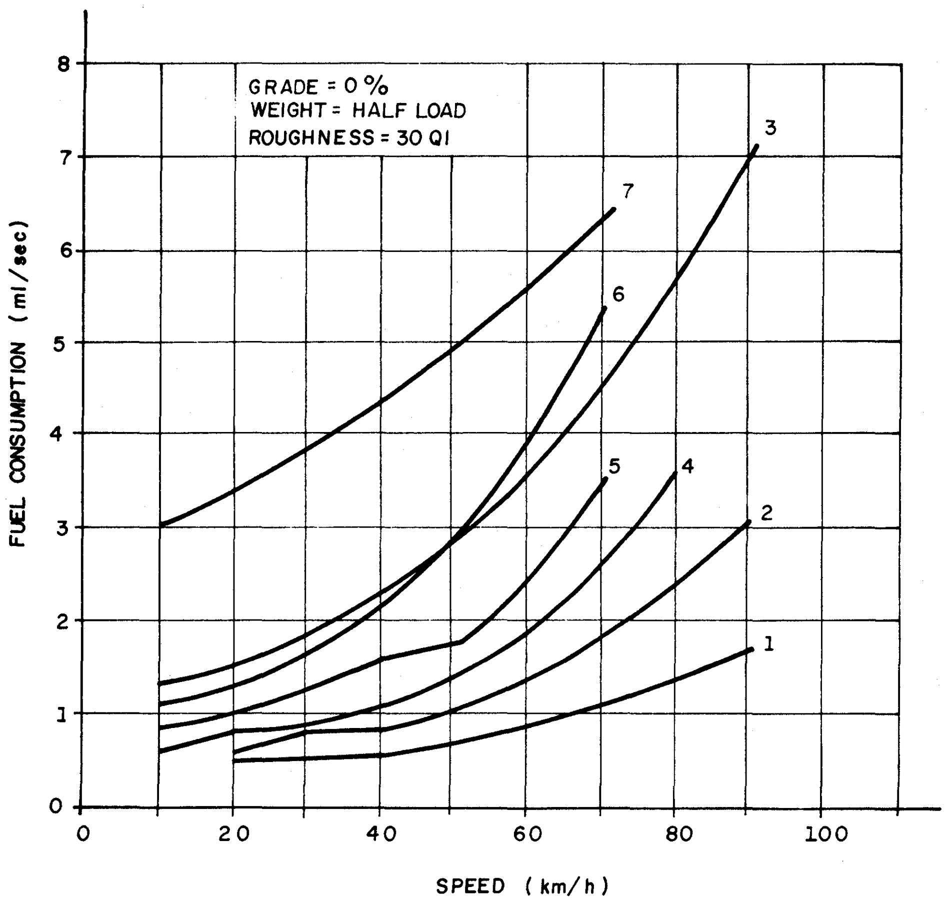
GR = grade (%)

G = |GR| for negative grades
0 otherwise

P = gross weight (t)

QI = roughness index

MARC = vehicle gear



1 - CAR

2 - UTILITY

3 - LIGHT GASOLINE TRUCK

4 - LIGHT DIESEL TRUCK

5 - BUS

6 - HEAVY TRUCK

7 - SEMI - TRAILER

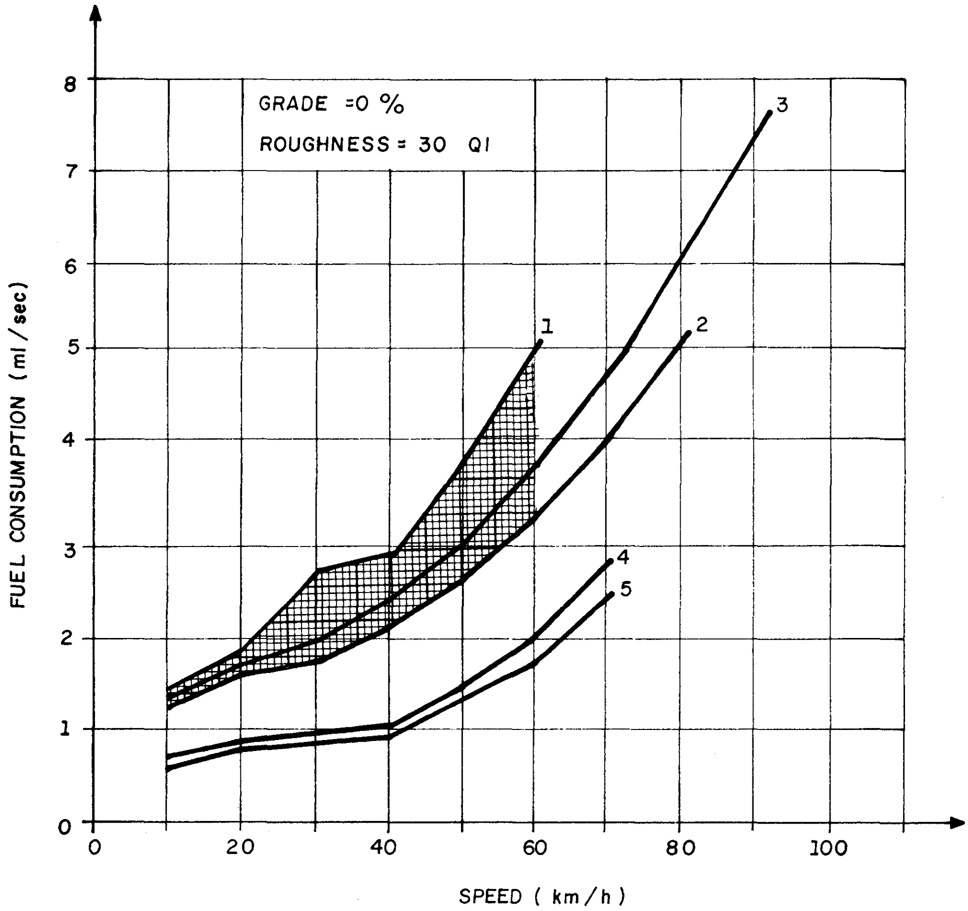
FIGURE 8.1 - EFFECT OF SPEED ON FUEL CONSUMPTION

of 30 QI). For each speed, the highest gear which the vehicle could use was employed on the test section. Therefore, each curve in Figure 8.1 represents the curve of lowest fuel consumption for each vehicle. The positions of the curves in the figure indicate a general tendency for fuel consumption to increase with increasing vehicle weight, except for the light gasoline truck, whose fuel consumption surpasses that of the medium truck when travelling at low speeds. However, for speeds in excess of 50 km/h the tendency mentioned above holds.

Figure 8.2 shows fuel consumption as a function of speed. For this purpose the equations used were those for light gasoline trucks and diesel trucks when travelling on level roads with roughness of 30 QI. Besides this, Figure 8.2 shows the effects, on fuel consumption, of the variation of load and of the use of different gears for the same speed. Curves 1 and 2 show the effect of gears on fuel consumption in an empty light gasoline truck. It can be noted that at speeds of less than 20 km/h this effect is not so great as at speeds between 20 km/h and 60 km/h. Curves 2 and 3, like curves 4 and 5, illustrate the effect of load on fuel consumption; these curves indicate that the effect of load variation on fuel consumption is greater for light gasoline trucks than for light diesel trucks, particularly at speeds over 40 km/h. Curves 2 and 5, like curves 3 and 4, show the difference in consumption between both types of fuel and indicate a clear advantage for light diesel trucks over light gasoline trucks. In the same conditions, the volume of diesel fuel consumed is as much as 50% less than the volume of gasoline consumed.

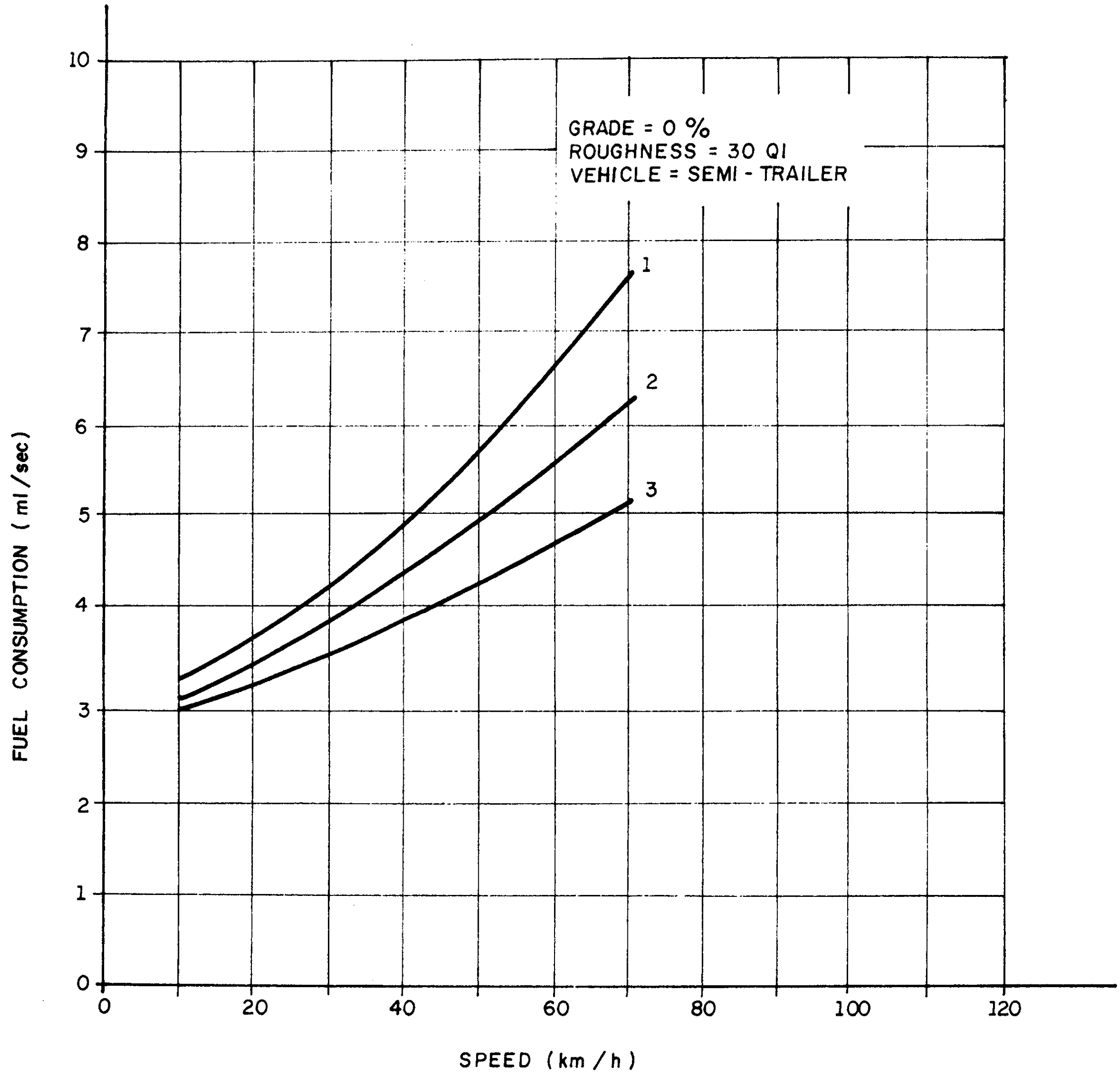
Figure 8.3 shows the effect of load/speed interaction on fuel consumption for a semi-trailer travelling on level roads with roughness of 30 QI. At low speeds the variation of weight due to the vehicle load produces little difference in the fuel consumption of trucks, whereas at higher speeds this difference is very high, reaching almost 3 ml/sec at a speed of 70 km/h, which corresponds to an increase of about 50% in fuel consumption.

Figure 8.4 shows the effect of vertical geometry (grade) on fuel consumption for a heavy truck travelling half loaded (gross weight of 14 tons) on a paved section with roughness of 30 QI. For each speed the highest possible gear was used. Besides the effect of the grade itself, the influence of the interaction between grade and speed



1. Light gasoline truck, empty and using the lowest gear
2. Light gasoline truck, empty and using the highest gear
3. Light gasoline truck, loaded and using the highest gear
4. Light diesel truck, loaded and using the highest gear
5. Light diesel truck, empty and using the highest gear

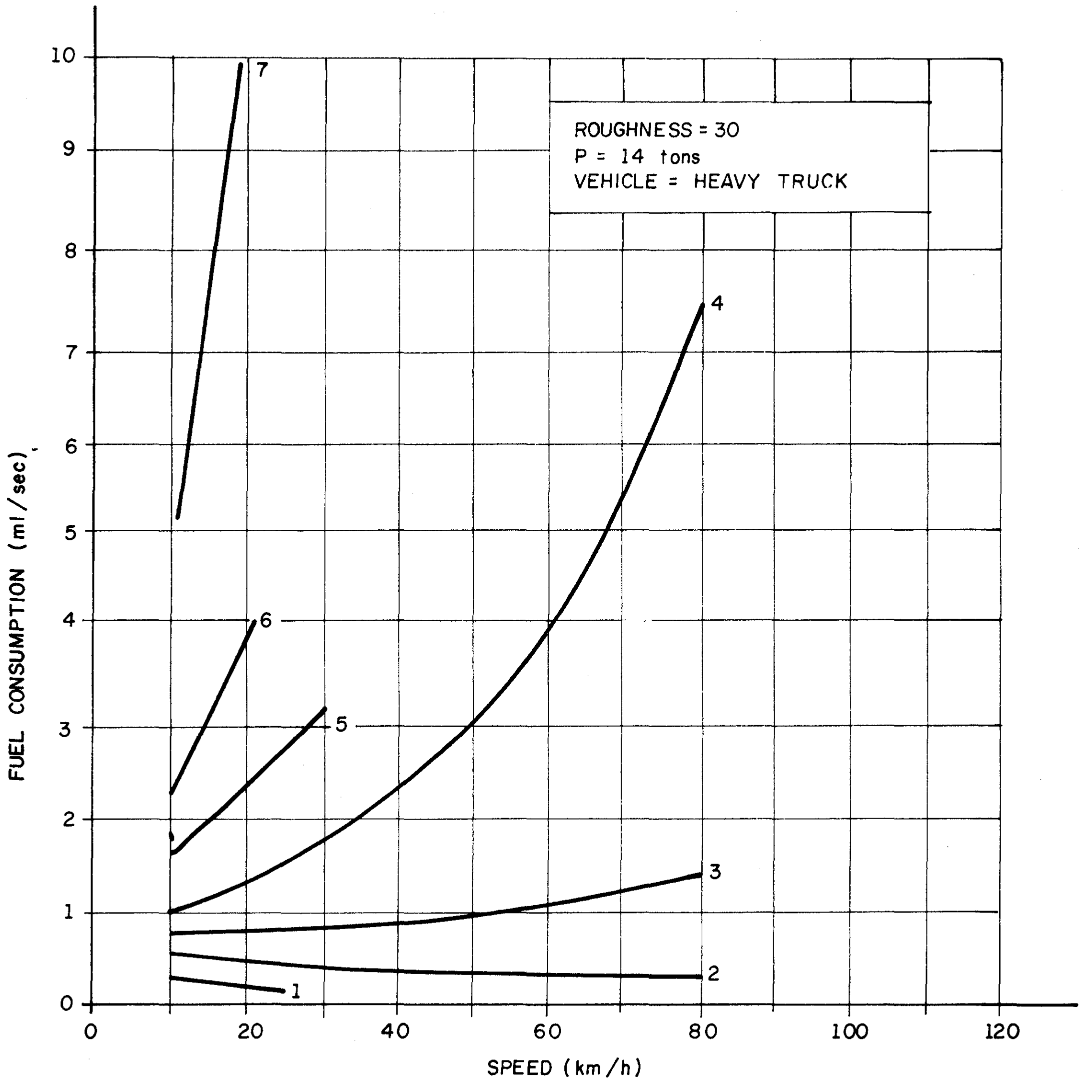
FIGURE 8.2 - EFFECT OF GEARS, LOAD AND TYPE OF FUEL ON CONSUMPTION.



GROSS WEIGHT:

1 - 40.74 tons
2 - 27.44 tons
3 - 14.14 tons

FIGURE 8.3 - EFFECT OF LOAD - SPEED INTERACTION ON FUEL CONSUMPTION



GRADE

1 - -13%
2 - -6 %
3 - -3 %
4 - 0 %
5 - +3%
6 - +6 %
7 - +13 %

FIGURE 8.4 - EFFECT OF GRADE - SPEED INTERACTION ON FUEL CONSUMPTION.

on fuel consumption can be noted. That is, at low speeds, the influence of the grade is much smaller than at high speeds.

It is interesting to observe that curves 1 and 2 show that fuel consumption decreases as speed increases. This is attributed to the fact that for heavy trucks the engine is used as a brake to maintain low speeds on very steep negative grades, thus consuming more fuel than at higher speeds, when the engine is not used to brake the vehicle.

8.2 FUEL CONSUMPTION ON CURVES (FC-3)

The objective of this experiment was to examine the effects of short-radius curves on fuel consumption.

The data for analysis were obtained from an experiment carried out with vehicles of the PICR fleet (with the exception of the light diesel truck) on two test sections with an 8% positive grade and a riding surface of laterite gravel, one of them on a straight section and the other with two short-radius curves. The factors and levels included in the experiment are presented in Table 8.4.

TABLE 8.4 - FACTORS AND LEVELS OF THE EXPERIMENT

FACTORS	LEVELS	Nº
Loads	Empty and loaded	2
Horizontal Geometry	Curved and rectilinear sections	2
Speeds	10 to 50 km/h	5
Grades	+8% to -8%	2

In the analysis of variance of the data generated by experiment FC-3, no significant influence of horizontal curves on fuel consumption was found within the inference space of the experiment. That is, the differences observed in the fuel consumption of a given vehicle that travels at the same steady-state speed on sections which are differenciated only by their radii of curvature are not significant.

However, it is relevant to emphasize that the radius of curvature influences vehicles speeds (as shown in experiment TB-4) and, consequently, fuel consumption. But, at a given steady-state speed, consumption will be the same both on curves and straight sections.

8.3 FUEL CONSUMPTION FOR LARGE CARS (FCS-5)

Although not included in the original plans of the ICR Research, the Brazilian Transportation Planning Agency (GEIPOT) decided to undertake several experiments for measuring fuel consumption at steady-state speeds with large cars. For this purpose, two cars were used: a 6-cylinder 146-HP Opala, and an 8-cylinder 198-HP Dodge Dart (See Volume 2 of this report, Chapter 4, Table 4.4).

With these vehicles, experiments were carried out to measure fuel consumption at steady-state speeds on paved test sections with roughness below 40 QI and grades of 0 to 6%, as well as on a level test section with laterite gravel surfacing, with roughness below 100 QI, both with the vehicles empty and with a load of 350kg. After the necessary screening, the data collected were incorporated into the Project file, but at the end of 1981 they had not yet been statistically analyzed, due to time restrictions.

Table 8.5 presents a synthesis of mean fuel consumption (in ml/sec) on level sections and on positive grades of 4 to 6%, at different speeds and gears. On the positive grade of 6%, both vehicles showed a tendency to consume more fuel when empty than when loaded. However, this tendency could not be confirmed, since it was discovered only after the PICR was no longer in possession of the vehicles. Thus it is recommended that these measurements be repeated with vehicles of the same type before a definite analysis is made.

In Figure 8.5 the fuel consumption of these vehicles can be compared with that of the VW 1300 belonging to the PICR fleet. At low speeds of about 30 km/h, the differences are much lower than at high speeds.

Figure 8.6 shows the variation in fuel consumption as a function of slope steepness for the same vehicles at speeds of 40 km/h and

TABLE 8.5 - FUEL CONSUMPTION OF LARGE CARS (mℓ/sec)

			OPALA				DODGE			
			NEGATIVE GRADE		POSITIVE GRADE		NEGATIVE GRADE		POSITIVE GRADE	
GRADE	SPEED (kph)	GEAR	EMPTY	LOADED	EMPTY	LOADED	EMPTY	LOADED	EMPTY	LOADED
	30	1	1.67	1.41	2.99	2.79		1.38	2.67	2.41
	30	2	0.75	0.37	2.06	2.12	0,85		1.91	1.75
	30	3	0.37	0.37						
	40	1	2.46	2.17	4.15	4.15	2.00	1.88	3.88	3.36
	40	2	2.07	0.78	2.76	2.71	1.29	0.99	2.66	2.44
	40	3	0.38	0.33	2.16	2.12	0.66	0.33	2.11	2.11
	50	1	3.19	2.97	5.69	5.67	2.78	2.50	5.42	4.38
6%	50	2	1.43	1.11	3.41	3.40	1.53	1.25	3.47	3.19
	50	3	0.55	0.41	2.78	2.71	0.69	0.41	2.77	2.63
	60	2	1.83	1.50	4.52	4.32	1.66	1.49	4.02	4.10
	60	3	0.66	0.58	3.34	3.33	0.99	0.49	3.49	3.33
	70	2	2.50	1.85	5.43	5.25	2.14	1.94	5.26	5.06
	70	3	0.97	0.77	4.18	4.19	1.36	0.58	4.28	4.09
	80	2	2.55	2.32	6.53	6.16	2.66	2.22	6.43	6.22
	80	3	1.22	1.21	5.00	4.83	1.32	0.88	4.88	4.88
	90	3	1.49	1.26	5.74	5.52	1.48	1.24	5.46	5.99
	100	3	1.74	1.69	6.19	6.51	2.19	1.66	6.62	6.65
	30	1	1.91	1.75	2.74	2.68	1.66	1.50	2.25	2.16
	30	2	0.81	0.75	1.71	1.83	0.91	0.80	1.49	1.58
	30	3	0.50	0.33	1.34	1.37				
	40	1	2.66	2.50	4.08	3.88	2.33	2.11	3.22	3.32
	40	2	1.27	1.11	2.38	2.44	1.33	1.11	2.11	2.22
	40	3	0.72	0.50	1.72	1.88	0.88	0.66	1.66	1.77
	50	1	3.66	3.62	5.24	5.34	3.05	2.92	4.16	4.58
	50	2	1.62	1.46	2.98	3.12	1.80	1.53	2.78	2.92
4%	50	3	0.90	0.76	2.15	2.29	1.11	0.97	2.22	2.36
	60	2	2.01	2.00	3.75	3.90	2.17	2.00	3.51	3.68
	60	3	1.08	0.91	2.58	2.83	1.50	1.16	2.67	2.94
	70	2	2.46	2.33	4.42	4.95	2.72	2.53	4.47	4.61
	70	3	1.26	1.26	3.21	3.49	1.75	1.49	3.31	3.43
	80	2	3.00	2.87	5.33	5.70	3.32	3.11	5.56	5.56
	80	3	1.66	1.66	3.77	4.55	2.00	1.77	3.76	4.01
	90	3	2.13	2.13	4.38	5.21	2.25	1.99	4.25	4.75
	100	3	2.50	2.36	5.68	5.97	2.77	2.22	4.99	5.57
	30	1	2.25	2.04	2.33	2.21	1.91	1.75	1.91	1.83
	30	2	1.25	1.25	1.37	1.33	1.25	1.16	1.33	1.08
	30	3	0.75	0.75	0.87	0.83				
	40	1	3.11	2.94	3.22	3.05	2.62	2.55	2.99	2.66
	40	2	1.77	1.66	1.77	1.89	1.66	1.66	1.89	1.69
	40	3	1.16	1.27	1.33	1.33	1.22	0.99	1.22	1.11
	50	1	4.65	4.31	4.72	4.58	3.61	3.61	3.89	3.75
	50	2	2.36	2.22	2.50	2.36	2.21	2.23	2.50	2.21
0%	50	3	1.52	1.46	1.73	1.59	1.52	1.39	1.66	1.52
	60	2	2.75	2.83	3.00	2.92	2.67	2.83	2.77	2.67
	60	3	1.91	1.91	2.08	2.08	2.00	1.83	1.99	1.88
	70	2	3.60	3.40	3.60	3.41	3.30	3.56	3.44	3.31
	70	3	2.33	2.33	2.53	2.52	2.33	2.34	2.33	2.33
	80	2	4.66	4.11	4.88	4.44	4.01	4.23	3.99	4.00
	80	3	2.77	2.77	3.00	2.99	2.73	2.87	2.88	2.88
	90	3	3.13	3.37	3.25	3.76	3.24	3.26	3.25	3.33
	100	3	3.75	4.17	3.88	4.28	3.61	3.87	3.87	3.87

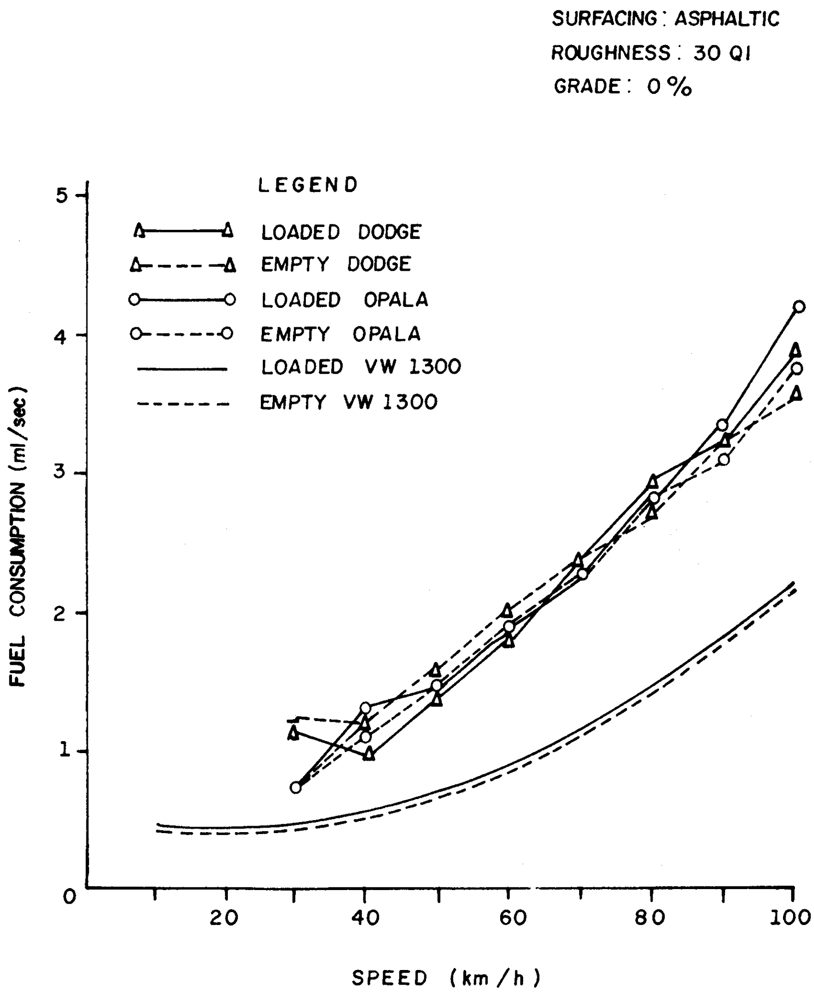


FIGURE 8.5 - FUEL CONSUMPTION OF THE VW 1300, DODGE AND OPALA AS A FUNCTION OF SPEED.

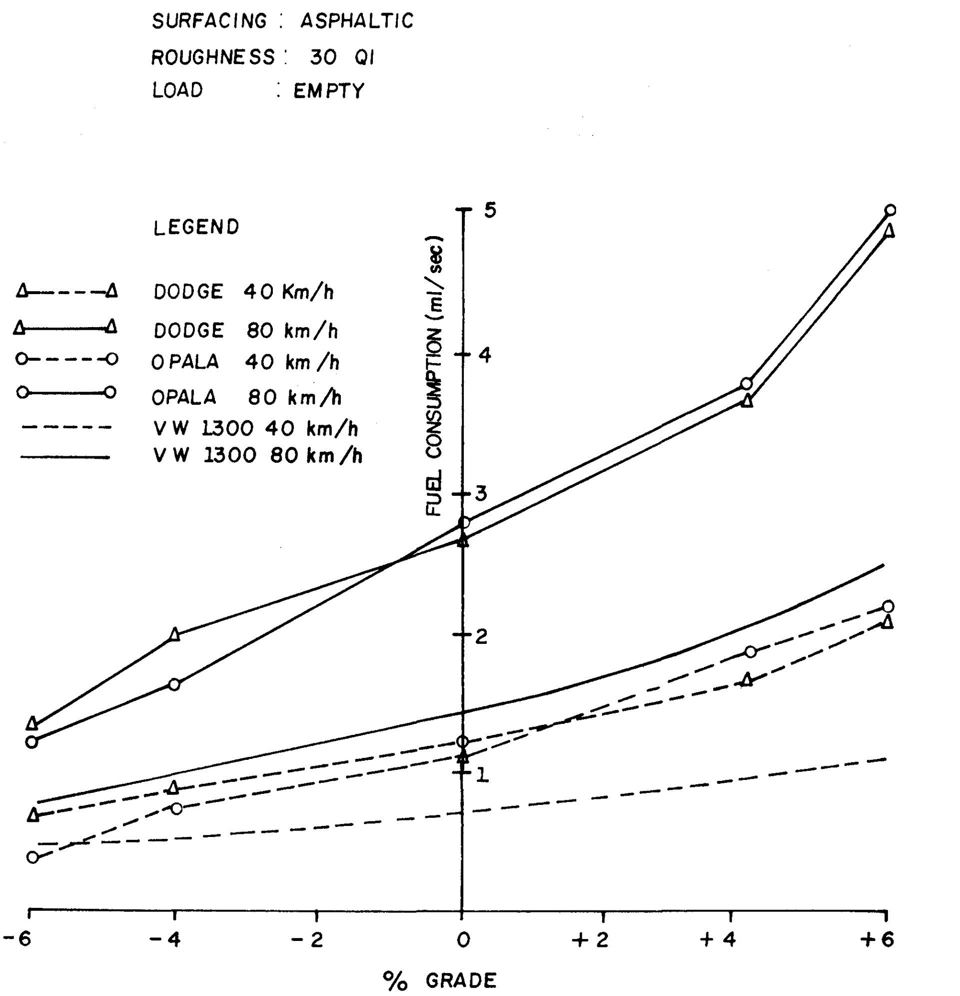


FIGURE 8.6 - FUEL CONSUMPTION OF THE VW 1300, DODGE AND OPALA AS A FUNCTION OF GRADE

80 km/h. It can be noted that the heavier vehicles, although possessing more powerful engines than the VW 1300, show a fuel consumption more sensitive to the variation in slope steepness, particularly on positive grades.

CHAPTER 9

INFLUENCE OF MOMENTUM ACQUIRED BY VEHICLES ON NEGATIVE GRADES (FC-2)

In situations where a road has steep negative grades followed by positive ones, the vehicles tend to acquire a momentum on the declivities that helps them climb the subsequent acclivities, with higher initial speeds and less use of low gears. It is expected that this behaviour influences significantly the fuel consumption of vehicles, especially trucks, which normally increase acceleration on a declivity (see experiment TB-2), thus gaining additional kinetic energy for climbing the subsequent acclivity more easily.

In this study, the vehicles were subjected to different accelerations on negative grades in order that different initial speeds (speeds at the beginning of a positive grade) could be obtained. The data thus obtained were used for analyzing the influence of initial speed and the effect on fuel consumption of its interactions with acclivities, grades and vehicle gross weights.

After the data generated by this experiment were screened, it was found that at speeds above 80 km/h the odometer was quite inconsistent. This constituted a difficulty for measuring with the required accuracy the total length of the fuel consumption test section (from the beginning of the acclivity up to the point where the vehicle slowed down to its steady-state speed). Due to this, all measurement results obtained at speeds above 80 km/h were rejected.

This affected the statistical analysis, since the remaining data were not sufficient to determine the influence of any of the variables studied. Therefore, fuel-consumption estimates were determined by averaging data considered reliable, that is, data obtained at speeds under 80 km/h. Thus the influence higher speeds could have on fuel consumption was deleted.

Table 9.1 presents the estimates, for each vehicle type, of the mean and standard deviation of fuel consumption, as well as the number of observations considered and the maximum and minimum consumptions measured.

TABLE 9.1 - FUEL CONSUMPTION DURING GRAVITY-EFFECTED DECELERATION (FC-2)

VEHICLE	Nº OF OBSERVATIONS	FUEL CONSUMPTION (ml/sec) MEAN	STANDARD DEVIATION	MINIMUM	MAXIMUM
Car	6	2.45	0.164	2.20	2.70
Bus	17	6.10	0.698	4.70	7.30
Utility	11	3.83	0.380	3.10	4.50
Light Truck (G)	12	10.86	1.072	10.60	14.40
Light Truck (D)	5	4.50	0.339	3.90	4.70
Heavy Truck	31	6.77	1.148	5.30	10.10
Semi-Trailer	15	12.12	1.012	10.60	14.40

With the experience gained from this experiment, a new experiment was designed in which small changes were introduced to allow for more information on speed modes and fuel consumption (see Volume 2, Chapter 4 of this report). The installation of the signal-generating system of the electronic odometer was also modified to make it less sensitive to the test-vehicle speeds.

Fuel consumption on positive grades was recorded at intervals of five seconds in this new experiment. Additional data were thus generated to determine the variation in fuel consumption due to both gear changes and the variation of pressure on the accelerator, in an attempt to maintain stable speed throughout the route. This new procedure represented a considerable advantage over the previous process, which only measured the total volume of fuel consumed from the beginning of the acclivity up to the point of speed stabilization.

This procedure allowed for a better data set to be obtained, as well as more copious information on the influence that the momentum acquired on negative grades can have on the performance of the vehicle on the following positive grade.

After the survey is concluded and the data analyzed, the PICR expects to establish equations which include fuel consumption and independent variables (initial speeds, grades, and gross weights) for each type of vehicle studied.

CHAPTER 10
RESULTS OF THE EXPERIMENT ON FUEL-CONSUMPTION MEASUREMENT IN DECELERATION MODE (TBS-6)

The factors and levels considered in the analysis of variance of the data produced by experiment TBS-6 are presented in Table 10.1.

In this experiment the vehicles started from the beginning of a level section at a given speed and, from a given point, the driver maintained the vehicle in gear, stepped on the brake and stopped the vehicle in the shortest possible space, using the clutch at the last moment. Thus, the smaller the space run between the point where braking began and that where the vehicle stopped, the less the time spent on this space and the less the volume of fuel consumed. It is possible, therefore, that the ratio between the volume of fuel consumed and the time spent remain unchanged for the different level combinations of the factors considered.

TABLE 10.1 - FACTORS AND LEVELS CONSIDERED IN THE TBS-6 ANALYSIS

FACTORS	LEVELS	
Vehicles Repeated Within the Classes	1, 2 (Kombi, MB 1113 Truck)	
Roughness	(Paved Surface)	Low (< 40 QI) High(> 90 QI)
	(Unpaved Surface)	Low (<100 QI) High(>140 QI)
Initial Speed	1, 2, ... V	
Types of Surfacing	Paved, Unpaved	

The results of the analysis support this hypothesis since the influence of these factors on fuel consumption were not found significant.

Table 10.2 presents the estimated mean and standard deviation of fuel consumption for each type of vehicle, as well as the number of observations and maximum and minimum consumptions measured.

TABLE 10.2 - FUEL CONSUMPTION DURING DECELERATION (TBS-6)

VEHICLE	Nº OF OBSERVATIONS	FUEL CONSUMPTION (ml/sec)			
		MEAN	STANDARD DEVIATION	MINIMUM	MAXIMUM
Car	16	0.50	0.19	0.28	0.97
Bus	6	1.57	0.61	1.17	2.68
Utility	26	0.66	0.18	0.31	1.03
Light Truck (G)	14	4.81	1.74	1.50	6.75
Light Truck (D)	14	2.53	0.93	1.21	4.38
Heavy Truck	20	2.04	0.63	0.80	3.25
Semi-Trailer	6	2.41	0.18	2.21	2.71

CHAPTER 11

RESULTS OF THE EXPERIMENT ON FUEL-CONSUMPTION MEASUREMENT IN ACCELERATION MODE (FCS-4)

The analysis of variance of the data generated by experiment FCS-4 showed that none of the factors considered in the experiment had any significant influence on fuel consumption during acceleration. Considering that the vehicles were stopped at the beginning of the positive grade and then were accelerated to the maximum until the speed stabilized (steady-state speed), one could tell that the fuel consumption per unit of time would not be significantly different for each vehicle class and factor combination. This was confirmed in the field-data analysis which evidenced that the *volume of fuel per unit of time* ratio remained the same for each class of vehicle, for the different level combinations of the factors considered.

Table 11.1 presents, for each class of vehicle, the estimated mean and standard deviation of fuel consumption, as well as the number of observations and minimum and maximum consumption observed.

TABLE 11.1 - FUEL CONSUMPTION DURING ACCELERATION (FCS-4)

		FUEL CONSUMPTION (ml/sec)			
VEHICLE	Nº OF OBSERVATIONS	MEAN	STANDARD DEVIATION	MINIMUM	MAXIMUM
Car	69	2.72	0.11	2.50	2.90
Bus	65	5.85	0.46	4.00	7.60
Utility	143	3.60	0.49	2.10	4.40
Light Truck (G)	66	10.03	0.95	8.40	12.50
Light Truck (D)	69	3.78	0.35	2.80	4.60
Heavy Truck	149	5.80	1.01	2.60	8.80
Semi-Trailer	92	10.08	1.14	7.00	12.80

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