# CHAPTER D

# ROAD USER COSTS AND TRAFFIC EXPERIMENTS

# 1 ORGANIZATION AND OBJECTIVES

Time and fuel savings are two important benefits which can result from road improvements. The Road User Costs and Traffic Experiments Group was established to investigate in detail the relationships between these two components of user costs and roadway characteristics. The main objective of the Group is to produce a model for predicting speeds and fuel consumption for Brazilian driving conditions, as a function of the road's geometry and surface quality.

To meet the objective, a model is being developed for estimating the speeds and fuel consumption of each vehicle class, as it traverses each section of roadway in a sequential manner. This approach requires relationships for predicting the speed and fuel consumption of each vehicle class, as a function of the individual geometric features of a roadway. To accommodate the variability of driver behavior and vehicle performance, empirical rather than theoretical relationships are being developed. Thus, a large experimental program was designed for collecting the data needed to develop regression equations for predicting the speed and fuel consumption of each vehicle class, as it traverses any roadway. The experiments were designed to include extremes of roughness and geometry, so that the relationships developed have the widest possible inference space.

A microscopic simulation model of the traffic-flow process is being developed to investigate how traffic volume and composition affect speed and fuel consumption of vehicles on homogeneous sections. In this model, vehicle-to-vehicle interactions are being realistically modeled to show the impact of various levels of traffic volume and composition on the speeds and fuel consumption of individual vehicles, as they traverse sections with specified characteristics. A staff of 39 was assembled to perform the experiments and develop the necessary models. As Figure 9 shows, this team consists of four engineers, a field supervisor, two clerks, a four-man survey crew, 15 observers, nine test drivers, an instrumentation technician, and three drivers. This team is divided into two field crews and a support staff. One engineer, six observers, and two drivers make up the radar crew which collects data on traffic speeds. The field supervisor, nine observers, and nine test drivers make up the fuel-consumption experiments crew. Nine vehicles representing seven classes, are used in the fuel-consumption tests.

Checking and organizing the data is an important task of the

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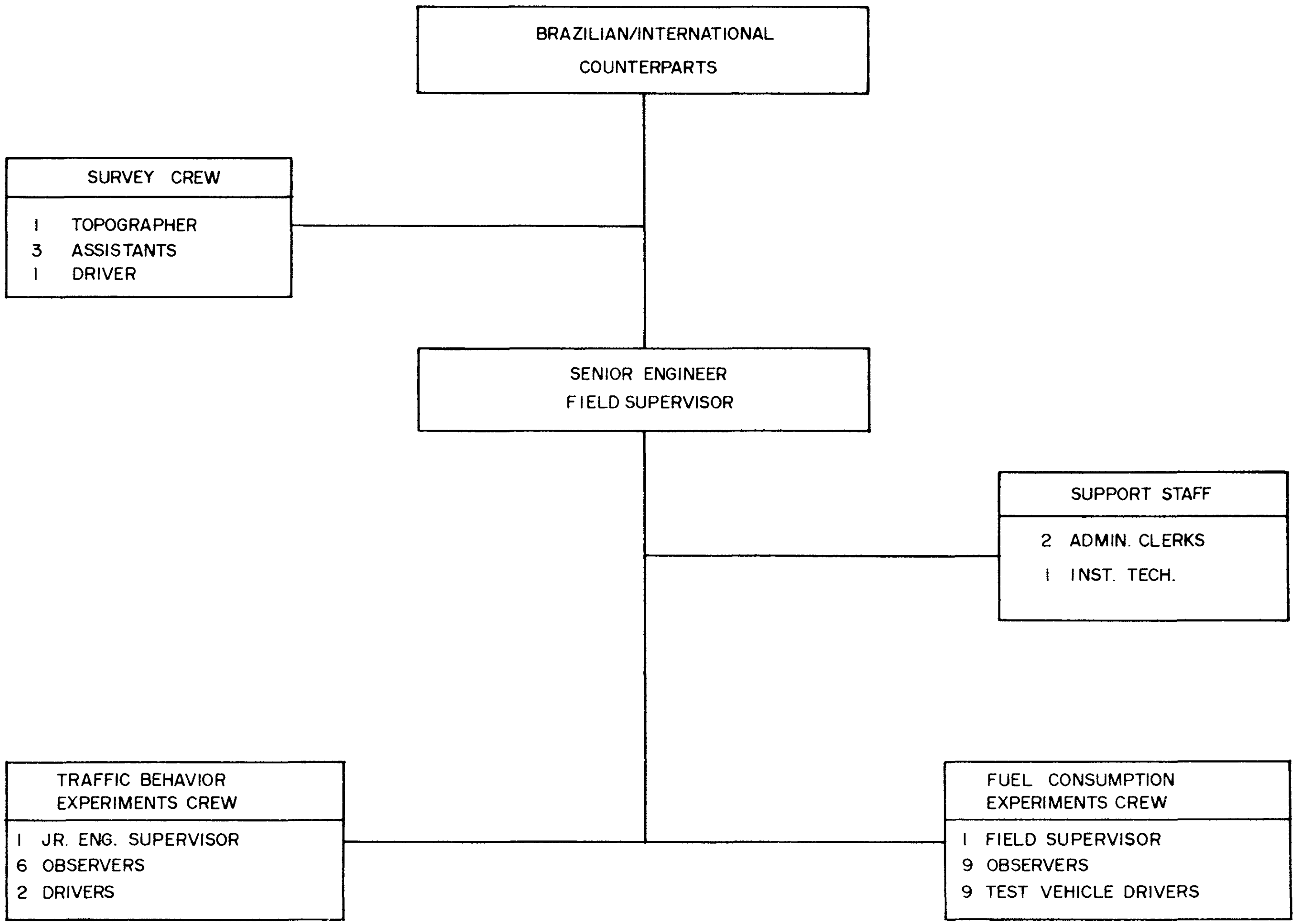


FIG. 9

ROAD USER COSTS AND TRAFFIC EXPERIMENTS PERSONNEL CHART support staff. To facilitate this task, all data are collected on forms which allow direct keypunching. After the data is collected, it is returned to the office for filing and manual editing as shwon in Figure 10. After key punching the data are edited for logic and limit errors and placed on permanent file.

The experimental program is being conducted primarily in the Federal District to minimize the cost of transporting the crews. However, when sections could not be found in the Federal District they were located in the States of Goiás and Minas Gerais, as shown in Figure 3, chapter A.

## 2 *MODELS*

The Road User Costs and Traffic Experiments Group is developing two models. A Time and Fuel Algorithm (TAFA) computes the physical quantities of time and fuel consumed by each vehicle class as it traverses any section of roadway. This algorithm will be an integral part of the Brazil Highway Investment Analysis Model. The second is a detailed traffic-flow simulation model called SOFOT. This model will be used primarily as a research tool within the project to study the impact of traffic volume and composition on speed and fuel consumption.

### a *Time and Fuel Algorithm* (TAFA)

The purpose of the Time and Fuel Algorithm is to predict the quantities of time and fuel used by each vehicle class as it traverses a road section. In TAFA, the individual geometric features of the roadway are analyzed consecutively. This approach is different from the one used in existing highway investment analysis models where the characteristics of the roadway being analyzed are represented by indices which describe the average characteristics of the roadway, such as the use of average rise and fall in the TRRL model. TAFA is an improvement over the index approach, in that the possibility of having two roadways with different characteristics but similar indices, is completely avoided.

The inputs to TAFA consist of parameters describing the traffic and roadway characteristics. The traffic parameters include hourly volumes by vehicle classification. The roadway characteristics are surface type, roughness, and details of vertical and horizontal alignment.

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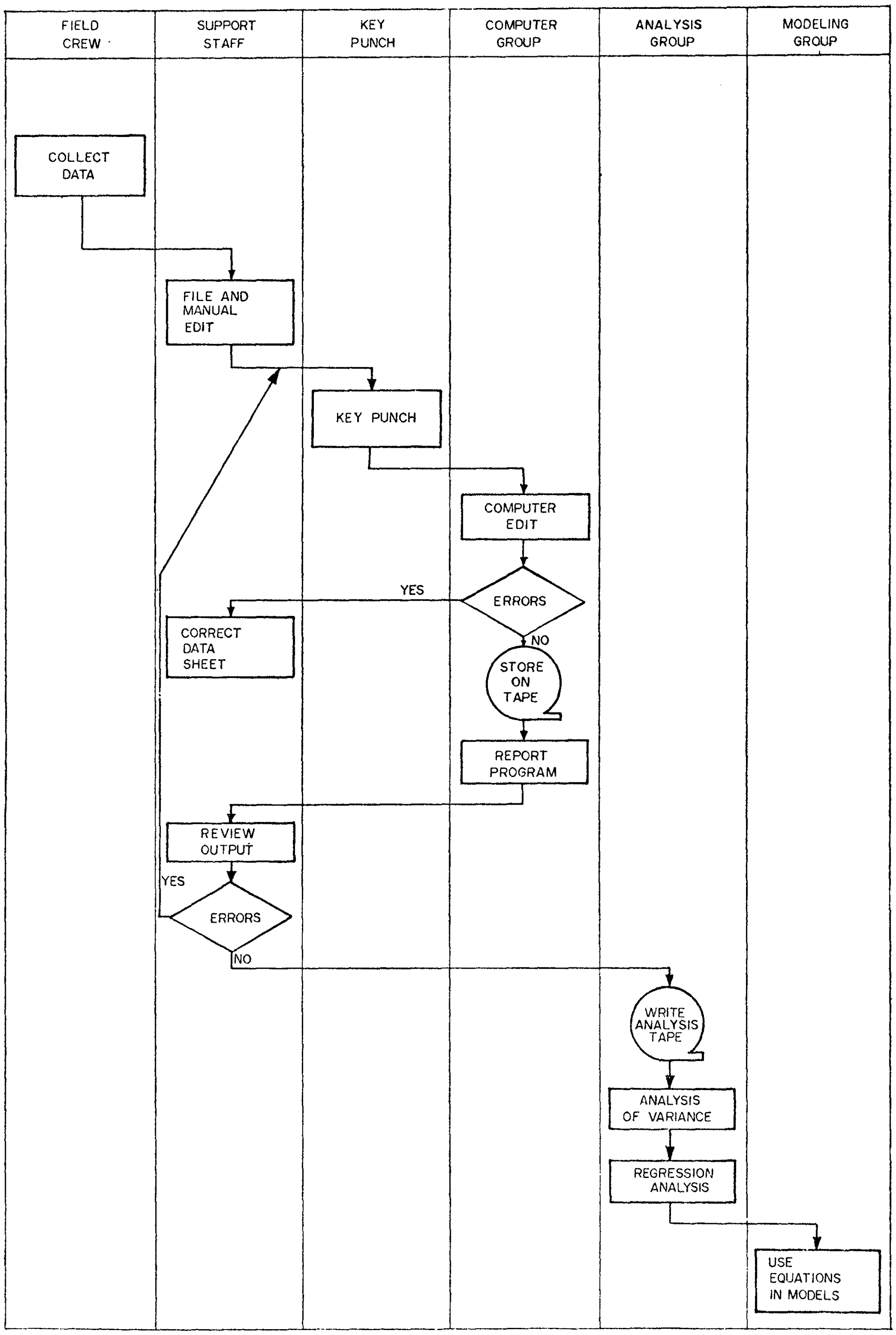


FIG. 10

DATA PROCESSING FLOW CHART

TAFA can be summarized in four steps which are repeated for each vehicle class. These steps are:

- Development of an initial speed profile, based on the vertical profile of the roadway and the performance characteristics of the vehicle class;
- Development of a free-speed profile by modifying the initial speed profile to account for the effect of horizontal alignment on speed;
- Modification of the free-speed profile for traffic volume and composition, thus producing an operating-speed profile;
- Calculation of time and fuel by each vehicle class, as a function of operating speeds.

The initial-speea profile for a vehicle class is computed by sequentially calculating the expected speeds of the vehicle class, as it traverses each constant grade section. The spot speeds of each vehicle class are calculated at points of transition between grades and/or modes of operation. The spot speeds calculated at this point in the model are independent of the effect of horizontal alignment and traffic.

After the initial-speed profile matrix has been established, the model then considers the effect of the horizontal alignment on the vehicle speeds. This is done by sequentially considering the properties of each individual curve. For each curve, the average speed of the vehicle class is calculated. This speed is then compared to the initial-speed profile at this point on the roadway. If the avegage speed for the curve is greater than or equal to the initial speed, then the curve has no effect on the speed profile and the next curve is selected from the horizontal alignment table. When a curve is found with a lower expected speed than the speed in the initial-speed profile, then the effect of the curve must be calculated and the speed profile modified.

The results of this process define the free-speed profile for the vehicle class. This profile is actually the average speeds of a typical vehicle in the vehicle class, if other traffic is not affecting the speed of the vehicles. Since the true or operating speed of vehicles will be affected by the volume and composition of traffic, parameters will be developed for estimating the operating speed of each vehicle class as a function of the free speed, the roadway geometry, and the traffic volume and composition. By applying these parameters to the free-speed profile for each section of roadway, an operating-speed profile can be developed. From the operating-speed profile, the time and fuel consumption of the vehicle class will be obtained for each combination of traffic volume and composition. The total time and fuel consumption for each vehicle class will then be obtained by summing the time and fuel consumption for each period of specified traffic volume and composition.

Flow charts have been developed for accomplishing the first step of the Time and Fuel Algorithm, i.e., the calculation of the initial-speed profile. Flow charts for accomplishing the second step, modifying the initial-speed profile to produce the free-speed profile, are presently being developed. Programming of the model has not been started.

### b *Simulation of Traffic Flow (SOFOT)*

The traffic-flow simulation model will provide the project with a research tool capable of generating data relating traffic volume and composition to time and fuel consumption for specific roadway characteristics. Initially, consideration was given to collecting the data experimentaly, but it was realized that traffic composition and directional split could not be controlled in conjunction with the other independent variables. Hence, these factors were to be used as covariates. This then indicated that unless the experiment was massive, variations in traffic composition and directional split would probably be small, and hence the relationships developed from such an experiment would have a limited inference space. Furthermore, fuel-consumption data could not be collected from this type of experiment. After examining other approaches for obtaining these data, development of a simulation model was selected as the most feasible alternative. It was reasoned that the simulation model, once calibrated, could be operated outside the inference space of the field observations, by using different traffic volumes, compositions, and directional splits, to produce the data necessary for developing models which could be used in TAFA for developing the operating-speed profile.

For the convenience of the user, the input to the model has been divided into two files. One file contains data about the free speed of vehicles as they traverse the roadway. The data in this file does not have to be altered when studying the effects of traffic volume and composition for a particular roadway. The second file consists primarily of traffic data, such as volume, percentage of vehicles in each class, and directional split, and parameters controlling the length of the run and the points of output.

Vehicle arrivals at the start of the section are randomly generated. Schuhl's distribution (Ref. 3) is used to determine the headway between vehicles at the start of the section. Vehicle Classifications are randomly assigned, but weighted according to the percentage of vehicles in each class. As each vehicle is generated, it is given a performance rating to reflect the variability of individual driving behavior. A normal distribution, truncated $\pm$ 2 standard deviations, is used to weight the distribution of performance ratings.

Once the arrival distribution of the vehicles has been determined, the program uses a periodic-scan technique to move the vehicles along the section. Processing of the vehicles along the roadway involves the simulation of vehicle-roadway and vehicle-vehicle interactions, The vehicle-roadway interactions are simulated by knowing the free-speed matrix for each vehicle class, plus the individual vehicle performance rating, which defines the maximum speed that a vehicle can have along the roadway. Vehicle-vehicle interactions are handled by looking for possible conficts at each time period. If a conflict can occur, then the vehicle is regulated to one of 11 modes of operation, and appropriate modifications are made to the speed of the vehicle.

SOFOT has been programmed and successful trial runs have been made using default values for the free-speed matrix. The model successfully simulated the queueing and subsequent passing of vehicles. The program must now be calibrated for Brazilian driving conditions, and a routine must be developed for generating the free-speed profile for each vehicle class. Completion of these steps will be subject to the progress being made on the experimental program.

## 3 *EXPERIMENTAL PROGRAM*

The preceding discussion of the models shows that a large experimental program is required for developing relationships to predict speed and fuel consumption for practically every phase of traffic behavior. As shown by Table D.1 several experiments have been designed for this purpose. The alpha-numerical designation of the experiments given in this table will be used when referring to an experiment.

Two levels of experiments have been defined. Main experi-

TABLE D.1 - ROAD USER COSTS AND TRAFFIC EXPERIMENTS

| CATEGORY | NUMBER | TITLE | PURPOSE |
|---|---|---|---|
| TRAFFIG BEHAVIOR MAIN EXPERIMENTS | TB-1 | Free Speed on Positive Grades | Determine the distribution of free speeds on positive grades for each vehicle class |
| | TB-2 | Free Speed on Negative Grades | Determine the distribution of free speeds on negative grades for each vehicle class |
| | TB-3 | Acceleration on Grades | Use test vehicles to determine acceleration rates on positive and negative grades |
| | TB-4 | Free Speed on Curves | Determine the distribution of free speeds on horizontal curves for each vehicle class |
| | TB-5 | Trip Purpose | Determine if free speeds are a function of trip purpose or length |
| | TB-6 | Free Speed Calibration | Independent data collection for verifying and calibrating models from experiments TB-1 through TB-5 |
| | TB-7 | Radar Effect | Determine if speed data is being affected by test procedures |
| | TB-8 | Speed/Capacity | Collect data for developing speed versus volume relationships for simulating operating speeds on rural roads |
| | TB-9 | Operating Speed Calibration | Independent data collection for verifying and calibrating models from experiment TB-8 |
| TRAFFIC BEHAVIOR SATELLITE STUDIES | TBS-1 | Wet/Dry | Define differences in driver behavior due to climatic conditions |
| | TBS-2 | Surface Types | Define differences in driver behavior due to different gravel surface types |
| | TBS-3 | Deceleration | Collect data on deceleration rates used when approaching a horizontal curve |
| | TBS-4 | Dust Effect | Collect data on the effect of dust on vehicle speeds and headways |

TABLE D.1 - ROAD USER COSTS AND TRAFFIC EXPERIMENTS (CONT'D)

| CATEGORY | NUMBER | TITLE | PURPOSE |
|---|---|---|---|
| FUEL CONSUMPTION MAIN EXPERIMENTS | FC-1 | Steady-State Fuel Consumption | Collect data for vehicles operating at steady-state speed over tangent test sections on a variety of grades |
| | FC-2 | Momentum | Determine the effect of momentum on fuel consumption. Important at the base of positive grades preceded by negative grades |
| | FC-3 | Curvature | Test the effect of horizontal curvature on fuel consumption |
| | FC-4 | Fuel Consumption Calibration | Collect independent data over long sections to verify and calibrate models developed from FC-1 to FC-3 |
| FUEL CONSUMPTION SATELLITE STUDIES | FCS-1 | Tuned vs.Untuned | Test the variability of fuel consumption due to engine condition |
| | FCS-2 | Curvature | Similar to FC-3 but more complete coverage of curvature |
| | FCS-3 | Sag Curves | Determine fuel consumption when sag curves are traversed |
| | FCS-4 | Acceleration | Determine the effect of acceleration on fuel consumption when approaching a sag curve |
| | FCS-5 | Big Cars | Determine the fuel consumption of an Opala and Dodge car at steady-state speed |

ments are necessary for accomplishing the objective of the research. Satellite studies would benefit the project by increasing the inference space of the experiments, or by reducing the assumptions needed in developing the models. Satellite studies can generally be delayed until the end of the project, and will be performed only if time and money permit, unless there are valid reasons for performing these studies earlier.

The geometric features of test sections are surveyed prior to testing and the location of each station is marked. Rut depth of the sections is measured using the device designed at the AASHO Road Test (Ref. 4). Roughness is measured with Mays-Ride-Meters which are calibrated against a surface dynamics Profilometer. On gravel sections, roughness is measured before and after testing. The looseness and corrugations of gravel sections are measured periodically using the procedures developed at the Kenya Road Study by TRRL (Ref. 5). Wind, rainfall, and temperature are measured periodically throughout the days when tests are being performed.

### a *Traffic-Behavior Experiments*

The traffic-behavior experiments will provide the data required for modeling vehicle speeds as a function of roadway characteristics. Nine main experiments have been designed, six for measuring the free speed of vehicles, two for measuring operating speed, and one for measuring acceleration using the project test vehicles.

Radar speed meters are used for measuring the spot speeds of vehicles at specific points on the test sections. Vehicles are classified according to Figure 11 as they are observed. In addition, each class except for cars, is categorized as empty, half full, full, or undefined.

#### (1) *Free Speeds on Positive Grades (TB-1)*

The purpose of this experiment is to define the speed pattern of vehicles on positive grades. The sampling frame, Table D.2, shows that a minimum of 12 test sections are required, but due to the variability of traffic speeds, repeat sections will be sought for at least half of the cells. Thus a total of 18 sections will be used.

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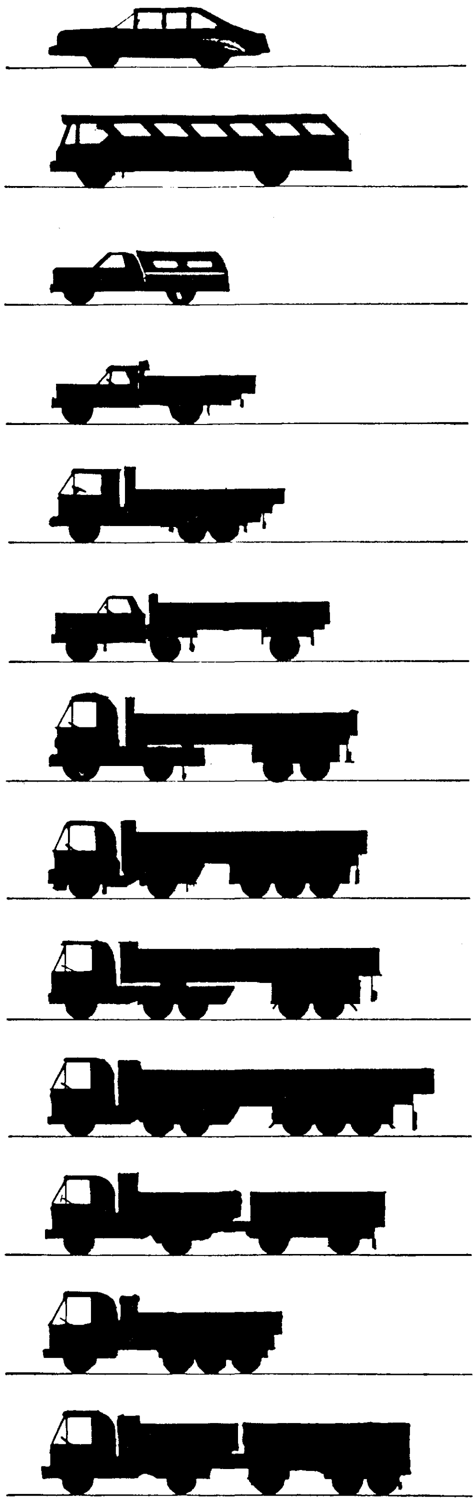
VEHICLE TYPES



| | |
|---|---|
| 1 | CARS |
| 2 | BUS |
| 3 | UTILITIES |
| 4 | TRUCK |
| 5 | TRUCK |
| 6 | SEMI TRAILER |
| 7 | SEMI TRAILER |
| 8 | SEMI TRAILER |
| 9 | SEMI TRAILER |
| 10 | SEMI TRAILER |
| 11 | TRUCK WITH TRAILER |
| 12 | TRUCK |
| 13 | TRUCK WITH TRAILER |

FIG. 11

VEHICLE CLASSES

TABLE D.2 - SAMPLING FRAME FOR TRAFFIC ON POSITIVE GRADES, EXPERIMENT TB-1

| HORIZ. ALIGN. | VERT. PROFILE | SURFACE TYPE: PAVED | | SURFACE TYPE: UNPAVED | |
|---|---|---|---|---|---|
| | ROUGHNESS | 1 | 2 | 3 | 4 |
| TANGENT | 0-2 | | | | |
| | 3-4 | | | | |
| | 5-9 | | | | |

The data are collected using three radar units and nine mirror boxes set up as shown by Figure 12. Thus a total of nine spot speeds are measured at intervals of 167 meters. This methodology is used because the speed pattern of the vehicles is more accurately defined than if space-mean speeds were measured.

Data have been collected on nine test sections covering six cells in the factorial. However, after the experiment had been in progress for about six months, the Brazilian government instituted a program of strict speed-limit enforcement. Therefore, a study has to be performed to indicate how this new policy affected the speeds measured prior to the start of the enforcement program.

(2) *Free Speeds on Negative Grades* (TB-2)

The purpose of experiment TB-2 is to determine the speed pattern of vehicles on negative grades. The sampling frame and test section requirements are the same as for experiment TB-1. Whenever possible, the same test sections are used for both experiments. The radar units are set up at intervals of 500 meters and measure speeds at five points.

Data have been collected on 11 test sections covering six cells or one half of the factorial. These data have also been affected by the change in the government policy on speed-limit enforcement. To determine if the speed-limit enforcement policy affected the speeds being observed, data were collected on four sections before and after the change in enforcement policy. The analysis of these data presented later indicates that the speeds measured after the speed-limit enforcement program were significantly lower than before the law. This effect was much more pronounced on the steeper grades where speeds are generally higher.

(3) *Acceleration on Grades* (TB-3)

The purpose of this experiment is to determine the acceleration rates vehicles can use on grades. Two methods of performing this experiment were considered:

- Stop a sample of vehicle in all classes at the start of the test section and measure spot speeds of vehicle as they

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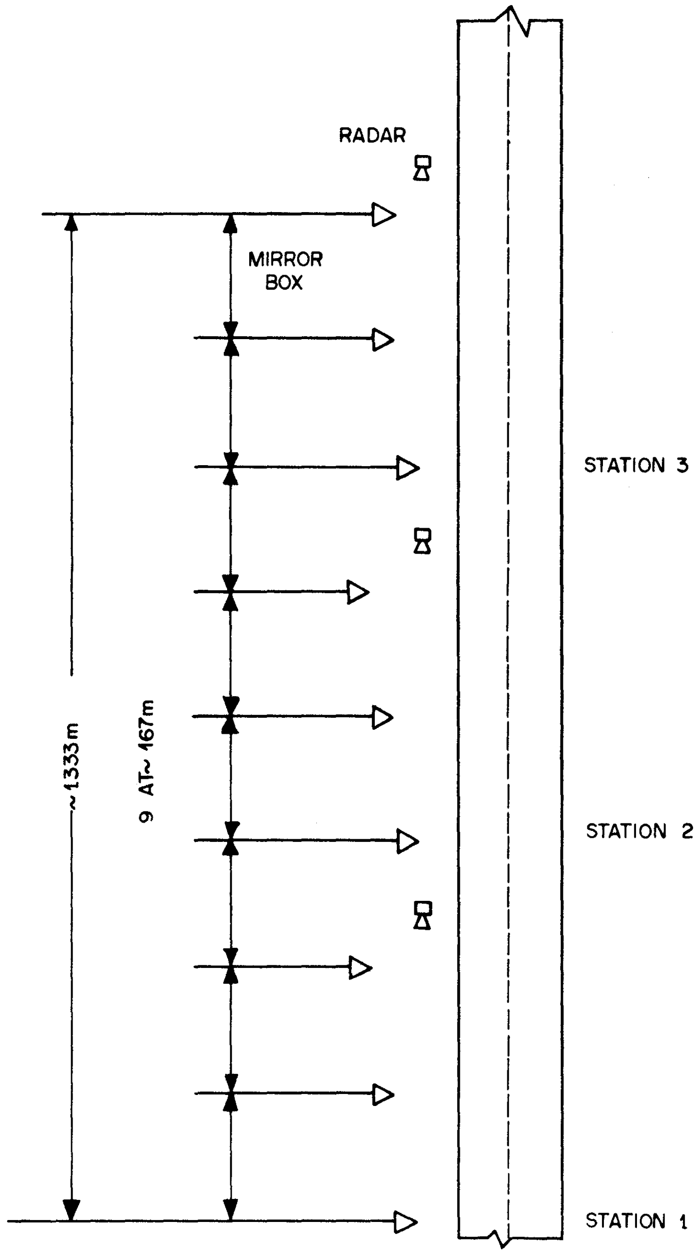


FIG. 12

LAYOUT OF EQUIPMENT FOR EXPERIMENT TB-1 AND TB-2 accelerate;

- Measure the acceleration of the project vehicles.

Due to logistic problems associated with the first method and the possibility of having a bias sample, use of the project test vehicles was selected.

The sampling frame of this experiment is the same as for experiments TB-1 and TB-2. However, because a fleet of controlled test vehicles is being used, it is not necessary to have repeat sections, so only 12 test sections will be used for this experiment.

Three camera boxes consisting of a movie camera, a distance measuring instrument (DMI), a crystal stopwatch, and an information screen have been constructed for performing this experiment. The crystal stopwatch has been modified so that every second, the DMI and stopwatch freeze and the camera is tripped. After the camera shutter has closed, the DMI and stopwatch catch up to display the actual time and distance until it is time for the next shot. After the film has been shot and developed, it is returned to the office where the data are transcribed to data forms.

The methodology for performing the experiment is to start the test vehicles at the beginning of the section, from a dead start, and then have the vehicles accelerate to maximum speed while the camera box is operating. Currently, to maintain repeatability, the drivers are instructed to use maximum acceleration. It is believed that this is fairly realistic for the trucks and bus, since they have low-acceleration rates. It may not be realistic for the lighter vehicles to use maximum acceleration. Therefore, further tests will be performed using less than maximum acceleration with the Volkswagen and Kombis.

Acceleration rates of all vehicles have been measured on the rough paved test sections which represent one fourth of the factorial. These data are currently being transcribed in the office and are not yet available for analysis.

### (4) *Free Speeds on Curves (TB-4)*

The purpose of this experiment is to determine the speeds drivers use on curves. In this experiment, speeds are measured on individual curves which are classified according to their radius, surface type, and roughness. Speeds on individual curves are being studied as this allows the extremes of curvature to be investigated since and it is possible to locate sharp curves on smooth paved roads in semi-urban areas. Superelevation of the curves will be used as a covariate in the analysis. The sampling frame for experiment TB-4 is shown in Table D.3.

Radar speed meters placed tangentially to the center of the curve are used to measure the spot-speed of the vehicles. The radar crew is hidden from the view of the drivers for this experiment.

The speeds of vehicles on curves have been measured for all of the smooth paved test sections, a few of the required rough paved test sections, and some rough and smooth gravel sections. In all, the experiment is about 50% completed.

## (5) *Trip Purpose (TB-5)*

It has been hypothesized that speeds will vary as a function of trip length or purpose, and that in general these parameters are related to geographical location. The purpose of this experiment is to determine if there is a significant relationship between speeds and geographic location. If there is such a relationship, then adjustments will have to be made to the prediction of expected speeds on level tangent sections which will in turn affect the whole speed profile predicted for a roadway.

The sampling frame is shown on Table D.4. Spot speeds will be measured at the midpoint of level tangent sections which are at least 1500-m long. Only smooth paved test sections will be studied.

## (6) *Free-Speed Calibration (TB-6)*

The above experiments will provide the relationships required to develop the free-speed part of TAFA. The purpose of experiment TB-6 is to provide independent data for checking and calibrating this part of the algorithm. No work has actually been performed on this experiment, but two methods for collecting the data have been proposed.

First, free-speed observations will be made on two fairly short sections (4 to 5 km) of road in rolling terrain. Observers stationed

TABLE D.3 - SAMPLING FRAME FOR EXPERIMENT TB-4

| HORIZ. ALIGN. | VERT. PROFILE | SURFACE TYPE / ROUGHNESS: PAVED 1 | PAVED 2 | UNPAVED 1 | UNPAVED 2 |
|---|---|---|---|---|---|
| <100 m | 0-2 | | | | |
| | 5-9 | | | | |
| 100 - 200 m | 0-2 | | | | |
| | 5-9 | | | | |
| 200 - 400 m | 0-2 | | | | |
| | 5-9 | | | | |
| >600 m | 0-2 | | | | |
| | 5-9 | | | | |

TABLE D.4 - SAMPLING FRAME FOR TRIP PURPOSE, EXPERIMENT TB-5

| GEOG. AREA | 1 | | | 2 | | | 3 | | | 4 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| LOCATIONS / VEH. CLASS | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
| 1 | | | | | | | | | | | | |
| 2 | | | | | | | | | | | | |
| ●<br>●<br>● | | | | | | | | | | | | |
| 12 | | | | | | | | | | | | |

along the sections will record intermediate times and ensure that the vehicles observed are actually travelling at free speed. The average space-mean speed of each vehicle class throughout the section can then be computed and compared to estimates made by TAFA. Homogeneous subsections, where the estimates are not in agreement with the observed data, will have to be retested so that the predictive equations can be more accurately developed.

The second method of calibration is to obtain speed profiles from user vehicles operating on fixed routes approximately 50 km in length. The field crews will not be involved in the collection of these data. The speed profiles will then be compared to output generated by TAFA. Some speed profiles of buses on fixed routes have already been collected by the Survey Group.

## (7) *Radar Effect (TB-7)*

In experiments TB-1 and TB-2, the radar equipment and mirror boxes are set up on the side of the road in plain view of the drivers. Since the police in Brazil use radar for speed-limit enforcement, the experimental setup may be affecting the behavior of the drivers. Therefore, the purpose of experiment TB-7 is to collect data with the radar crews completely hidden to determine if the equipment set up is affecting driver behavior.

Hidden radar data have been collected on four sections. It is necessary to collect data on at least three more sections in order to develop parameters for correcting the data already collected in experiments TB-1 and TB-2. In the future, the radar will be hidden whenever possible to avoid the need for correction factors.

## (8) *Speed/Capacity (TB-8)*

The purpose of experiment TB-8 is to provide data for the development of the traffic-flow simulation model. The following information will be collected during this experiment:

- Headway;
- Space-mean speed;
- Vehicle classification;
- Estimate of each vehicle load;

- Traffic flow per time for each direction;
- Number of passing maneuvers.

The data will be collected on six sections representing three levels of grade and two levels of passing-sight distance. On each section, the data will be collected on free-flow, medium, and heavy traffic.

The methodology originally proposed for performing this experiment requires the use of a Super-8 movie camera set up to simultaneously photograph the traffic and a stopwatch. The camera would be able to shoot a single frame, each time the shutter was released by a vehicle passing over a road tube placed across the roadway. This methodology has been field tested, and it was found that the repeatability of reading the stopwatch was very low. Therefore, methods for improving the methodology are being sought. Alternatives being investigated include the use of a stopwatch which is easier to read,and use of induction loop detectors to automatically record vehicle headways on magnetic tapes which can be mechanically reduced.

(9) *Operating-Speed Calibration* (TB-9)

The purpose of this experiment is to provide independent data for calibrating and verifying the SOFOT model. The methodology for this experiment wil be identical to TB-8.

(10) *Wet/Dry* (TBS-1)

The purpose of this satellite study is to determine the effect of rainfall on free speed. The methodology for this experiment will be identical to experiments TB-1 and TB-2. Data for this experiment will be collected when the crews are set up for either TB-1 or TB-2, and it is raining.

(11) *Surface Types* (TBS-2)

The main experiments are restricted to one gravel type, laterite, because this is the predominant gravel type in the main study area. It is possible that other gravel types, with the same roughness as laterite will have a different effect on free speeds. Therefore, the purpose of this satellite study is to determine the effect of gravel type on free speeds.

(12) *Deceleration (TBS-3)*

The purpose of this satellite study is to investigate the deceleration rates drivers use when approaching a curve or a slower vehicle. Because this is a satellite study, no work has been performed toward developing a methodology.

(13) *Dust Effect (TBS-4)*

It has been hypothesized that the amount of dust a vehicle stirs up when traveling a gravel road can have a direct effect on the speed of vehicles on the road. Thus, if there is sufficient time, a small experiment will be performed to quantify how dust affects vehicle speeds.

b *Fuel-Consumption Experiments*

The fuel-consumption experiments will provide the data required for modeling fuel consumption as a function of the roadway characteristics. Four main fuel-consumption experiments have been defined. One of these experiments has been completed, two are currently in progress, and the fourth has not yet been started.

Unlike the speed-measurement experiments, where the general vehicle population can be sampled for the development of relationships, fuel-consumption data must be taken from measurements made with a fleet of test vehicles. Thus the project purchased nine vehicles covering seven classes representing the types of vehicle produced in Brazil. As shown by Table D.5, the vehicles used for fuel-consumption measurements are a Volkswagen 1300, two Volkswagen Kombis, a Ford F400 (gasoline), a Ford F4000 (diesel), two Mercedes Benz L-1113/42, a Mercedes Benz O-362 bus, and a Scania 110/38.

Each of these vehicles has been fitted with a reservoir type fuel meter, a distance measuring instrument, and a split-second hand

TABLE D.5 - TEST VEHICLE DESCRIPTION

| VEHICLE | FUEL | BRAKE HORSE-POWER | TARE WGT. (KG) | GROSS WGT. (KG) | LOAD* | | |
|---|---|---|---|---|---|---|---|
| | | | | | EMPTY | HALF FULL | FULL |
| Volkswagen 1300 | Gasoline | 48 | 780 | 1,160 | 0 | 130 | 280 |
| Volkswagen Kombi | Gasoline | 60 | 1,195 | 2,155 | 0 | 280 | 550 |
| Ford F-400 | Gasoline | 169 | 2,277 | 6,000 | 150 | 1,730 | 3,510 |
| Ford F-4000 | Diesel | 102 | 2,444 | 6,000 | 0 | 1,540 | 3,325 |
| Mercedes Benz L-1113/42 | Diesel | 147 | 6,395 | 18,500 | 1730 | 5,985 | 11,970 |
| Scania 110/38 Articulated | Diesel | 285 | 13,420 | 40,000 | 0 | 13,300 | 26,600 |
| Mercedes Benz 0-362 Monobloco | Diesel | 147 | 7,500 | 11,500 | 0 | 1,010 | 2,250 |

* The loads given do not include the weight of the driver and observer, which is approximately 140 kg.

stopwatch. The basic design of the fuel meters was developed at the Kenya Road Study [Ref. 5], but the design has been greatly modified to better suit the conditions encountered on this project.

(1) *Steady-State Fuel Consumption (FC-1)*

The purpose of experiment FC-1 is to collect fuel-consumption data for vehicles traveling on grades at constant speed. This is the largest of the fuel-consumption experiments. The sampling frame is the same as for experiments TB-1 and TB-2. Fuel-consumption measurements are made in both the positive and negative directions.

Test sections 1-km long with a 500-m transition on each end are sought, but there are cases where it was not possible to find sections with the desired characteristics of sufficient length. Thus, some sections only 700-m long have been used.

The testing procedures is for the driver to enter the transition section at the proper speed and gear for the run and maintain constant speed for the entire length of the section. As the vehicle passes the marker indicating the start of the transition section, the observer switches on the DMI. When the DMI reads 500 m, the observer switches on the fuel meter and starts the stopwatch. When the DMI reads 500 m plus one half the length of the section, the observer stops one hand of the stopwatch. When the DMI reads 500 m plus the length of the section, the observer stops the stopwatch and the fuel meter. The vehicle is stopped and the observer records the data and primes the fuel meter for the next run.

Using this procedure, it is possible to compute the space-mean speed for each half and the entire run. Thus, checks can be made to ensure that the vehicle was driven at a constant speed. The drivers have been carefully trained and it is unusual for a run to be more than 2 km/h off the desired speed.

Data have been collected in this experiment for more than a year now, and only four rough gravel sections are required for completing this experiment. This report contains regression equations developed from the data for smooth paved and unpaved sections. The work on the rough paved sections was not completed in time to be reported.

### (2) *Momentum* (FC-2)

A readily observable driving pattern is for a driver to accelerate on a negative grade to build up momentum for climbing a positive grade. Work performed by Sawhill (Ref. 6) shows that fuel consumption is up to 50% lower when momentum is used to climb a hill rather than using constant speed. Thus a pilot study will be performed on three sections where conditions are favorable for using momentum for climbing a positive grade.

Data will be collected using the camera boxes and the fuel meter. The driver will enter the section at a speed higher than the steady-state speed, and try to maintain speed. The vehicle will decelerate due to gravity. As the vehicle enters the section, the observer switches on the camera box and the fuel meter; when the drivers signals the observer that steady-state speed has been reached, the observer switches off the fuel meter and camera box. The fuel reading is recorded on the information screen form and some photos are taken to make a permanent record of the fuel consumption on the film.

From these data it will be possible to determine the deceleration rate of the vehicle and the fuel consumption. Runs will be made with a range of entry speeds from the maximum entry speed down to 10 km/h above the steady-state speed. Thus it will be possible to determine the effect of entry speed on fuel consumption and the deceleration rate.

Data are currently being collected on one 7% and one 6% section. A suitable 4% section is being sought to complete the experiment.

### (3) *Curvature Experiment* (FC-3)

Sawhill (Ref. 6) has shown that for very small radius curves, fuel-consumption can be significantly affected. The purpose of this experiment is to determine if this also accurs on Brazilian highways. Therefore, fuel-consumption tests were made on one section of extreme curvilinear alignment on a gravel road. The methodology for this experiment is the same as for experiment FC-1.

As discussed later, an analysis of the data from this experiment showed that the effect of horizontal curvature on fuel consump tion is minimal. Therefore, this factor will not be investigated further.

(4) *Fuel-Consumption Calibration* (FC-4)

This experiment will be conducted in a manner similar to the free-speed calibration experiment. In addition to tachographs, the vehicle will be fitted with positive-displacement fuel meters. These meters can continuously measure the fuel consumed over long routes. The vehicles will be run over routes of known characteristics and the data from these runs will be compared to the output from TAFA. By taking fuel readings at intermediate points, it will be possible to test the calibration of the model.

In order to test out the methodology for this experiment, tachographs have been installed in two of the vehicles and the positive-displacement fuel meters have been installed in one vehicle. Thus, the capability to perform the experiment was demonstrated. However, no actual data have been collected.

(5) *Tuned VS. Untuned* (FCS-1)

During the main fuel-consumption experiments, the test fleet will be kept tuned at all times. Prof. Rebelo of the Centro Técnico Aeroespacial, sampled 320 diesel trucks in 1972 and determined that over 60% were out of tune. This could significantly affect fuel consumption. Thus, the purpose of this satellite study, is to determine the fuel consumption of untuned vehicles. If this study is perfomed, the sampling frame and methodology of experiment FC-1 can be used.

(6) *Curvature Study* (FCS-2)

This study was to be performed if the results of experiment FC-3 showed that curvature had a significant effect on fuel consumption. The results of experiment FC-3 show that it is not necessary to perform this experiment.

(7) *Sag Curves* (FCS-3)

Currently it is proposed to ignore the effect of sag curves in the model by assuming that the tangent portions of the grades can be extended to the point of intersection. However, if the calibration experiment shows that this is causing unaceptable errors, then it may be necessary to measure the fuel consumption of vehicles traversing sag curves. If this study is performed, a methodology similar to experiment FC-2 will be used.

(8) *Acceleration* (FCS-4)

The purpose of this experiment is to measure the fuel-comsup tion rate of vehicles while accelerating. Currently the fuel consumption of the vehicles is being measured as they perform experiment TB-3. This will provide some data about the fuel-consumption rate of vehicles while accelerating, but it does not provide any data for an intermediate speed change such as would be used in a passing maneuver. Therefore, if this study is performed, measurements will be made for specific speed changes which are representative of passing maneuvers.

(9) *Large Cars* (FCS-5)

In order to increase the inference space of the fuel-consump tion test for passenger vehicles, GEIPOT lent the project two of its executive type of passenger cars. The cars were a 198 HP Dodge weighing 1495 kg and a 138 HP Opala weighing 1046 kg. The tests were run empty and with a 350-kg load. Using the methodology developed for experiment FC-1, fuel consumption was measured on five smooth paved sect ions and one smooth gravel section, in both the positive and negative direction. This work has been completed, but the data were not availa ble in time for the analysis to be included in this report.

## 4 PRELIMINARY ANALYSES

Even though only one of the experiments has been completed at this time, it is possible to report partial results for several experiments. These analyses represent only a portion of the total amount of data currently available. Analyses have been performed for experiments TB-2, FC-1, and FC-3. In addition, analysis of the impact of the speed-limit enforcement law has been performed.

### a *Preliminary Analysis on TB-2*

The purpose of this analysis was to develop a preliminary regression equation which would predict the free speeds on negative grades. The analysis was performed in November 1976 with a modification and update done in March 1977. The data were collected before the enforcement of the 80-km/h speed-limit law, and the radar meters were in view of the drivers. Because of the possible effects of the exposed radar on these data and the effect of the speed-limit enforcement program on future observations, the analysis presented here will have to be modified. The analysis and results are described simply to explain the types of relationships that will be developed in the future. They are not to be accepted as final since the speed-limit and exposed-radar effects are not explained in these equations.

#### (1) *Background*

The sampling frame used for this study is given in Table D.6. A total of six smooth paved sections were used in the experiment. On each section spot speeds of vehicles were collected at five stations 500-m apart. Eleven separate vehicle classes were used for classification of the observed vehicles as well as four load classifications. A total of more than 17,000 vehicles were recorded.

#### (2) *Analysis*

It was impossible to observe many of the vehicle classes under various load conditions on all of the sections and at all of the stations. Of particular difficulty were the truck classes. In order to ensure that data were available for all classes, all sections, and at all stations, new vehicle classes were defined by grouping the original load and vehicle class combinations. The decision on how to define these new classes was based on available sample sizes and vehicle type and weight similarities. The new classes are defined as follows:

TABLE D.6 - SAMPLING FRAME FOR FREE-SPEEDS-ON-NEGATIVE-GRADES PILOT STUDY

| | | GRADE | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | | | | | 2 | | | | | 3 | | | | |
| REPLICATES | 1 | STATION | | | | | STATION | | | | | STATION | | | | |
| | | 1 | 2 | 3 | 4 | 5 | 1 | 2 | 3 | 4 | 5 | 1 | 2 | 3 | 4 | 5 |
| | | | | | | | | | | | | | | | | |
| | 2 | STATION | | | | | STATION | | | | | STATION | | | | |
| | | 1 | 2 | 3 | 4 | 5 | 1 | 2 | 3 | 4 | 5 | 1 | 2 | 3 | 4 | 5 |
| | | | | | | | | | | | | | | | | |

1 = Cars
2 = Buses, All Loads
3 = Utilities, Empty
4 = Utilities, Half and Full Load
5 = Trucks, Empty
6 = Trucks, Half and Full Load

As a preliminary analysis procedure, the mean spot speeds were analyzed "as if" they were all estimated from equal sample sizes. The exact methodology for this procedure is described in Scheffé (Ref. 7), and Anderson and McLean (Ref. 8). This unweighted analysis was valuable in a number of ways (Refer to Table D.7):

- The repeat error mean square was very large in comparison to the mean square for grades indicating that there are fixed environmental factors contributing to the size of the repeat mean square. Therefore, the repeat effects should be considered fixed unquantifiable factors, not as error terms. The error term used for testing higher factor interactions should be the within pooled error of the variances of the means in each cell, $\varepsilon$ ;
- In addition to the size of the repeat mean square, less than 1% of its total was contributed by the difference between the repeats in the lowest level of grade. A great deal of this nonhomogeneity can be caused by the unquantifiability of the environmental effects, such as driver behavior, trip length, trip purpose, etc. Part of this nonhomogeneity could be caused by the unequal sample sizes in the cells;
- Examination of the variances of the original spot speeds showed great homogeneity in cells where the sample sizes were large enough to give good estimates of the variances. This implies that the "relative reliability" of the estimates of the means in each cell is dependent on the sample sizes. Therefore, under the assumption that the variances of the spot speeds in each cell are equal, the regression analysis applied to the mean spot speeds should be weighted in relation to the square root of the sample sizes;
- The analysis-of-variance table showed that the significant effects to be used in the regression analysis were vehicle class, station, grade and possibly the interactions grade x class or grade x station. The means of each of these

TABLE D.7 - ANALYSIS-OF-VARIANCE TABLE FOR THE UNWEIGHTED MEAN SPOT SPEEDS ON NEGATIVE GRADES BEFORE SPEED-LIMIT ENFORCEMENT PROGRAM

| SOURCE | df | MEAN SQUARE | |
|---|---|---|---|
| G | 2 | 1081.1* | |
| R(G) | 3 | 692.2 | |
| C | 5 | 801.6* | |
| G x C | 10 | 68.7* | |
| R(G) x C | 15 | 51.1 | |
| L | 4 | 329.5* | |
| G x L | 8 | 121.3* | |
| R(G) x L | 12 | 49.5 | |
| C x L | 20 | 23.9 | |
| G x C x L | 40 | 8.7 | 9.2 pooled within error |
| R(G) x C x L | 60 | 10.1 | |
| Within Error (ε) | 48 | 8.5 | |

Where G = Grade in Percent

R = Repeat Sections within Grades

C = New Vehicle Class

L = Station

ε = Within Error

* Possible significant effects that can be used to develop a regression function.

significant factors were plotted. The plots indicated a number of different functions that could be used in developing the equations;

- Newman-Keuls test was run on the means of the factor stations and grade x station to determine which of the individual means were significantly different. This procedure further defined possible relationships between the mean spot speeds and the position of the vehicles on the negative grades.

Weighted regression analysis was performed on the functions and the following equation represents the best fit of the functions tried.

$$S=59.3+7.3\,\{18.6-(G-3.8)^2\}^{.5} - 3.25C+.56L+.240\,L^{G/2.6}$$

where S = mean spot speed

L = station (1, 2, 3, 4, 5)

1 = is equivalent to 2000 meters up a negative grade

2 = is equivalent to 1500 meters up a negative grade

3 = is equivalent to 1000 meters up a negative grade

4 = is equivalent to 500 meters up a negative grade

5 = is equivalent to the bottom of a negative grade

C = new vehicle class (1, 2, 3, 4, 5, 6)

G = grade in percent

The equation is graphically presented in Figures 13 through 15.

## b *Effect of the Speed-Limit Enforcement Program*

Free-speed data from four negative grade sections have been collected with the radar units in view before and after the speed-limit law. The four sections have grades of 1.3%, 3.6%, 6.0%, and 6.1%. As a preliminary examination, it is possible to compare the effects of the speed-limit law on the speed patterns of the four sections.

### (1) *Analysis*

The Analysis-of-Variance layout used for this experiment is given in Table D.8. The grades of 6 and 6.1% are used as repeat sections and the various error terms in the analysis are calculated from dif-

## MT-GEIPOT

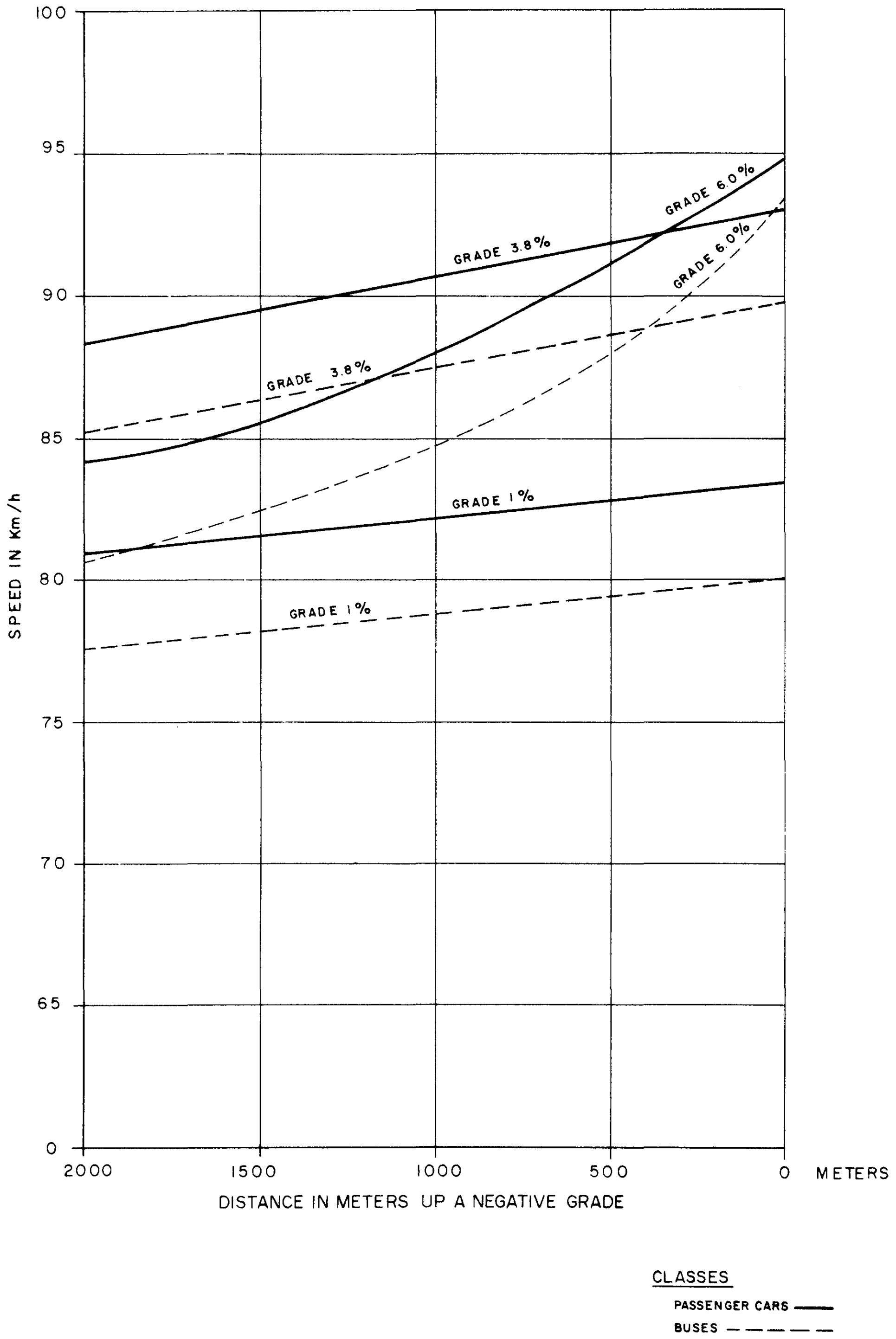


FIG. 13

## FREE SPEED RELATED TO DISTANCE

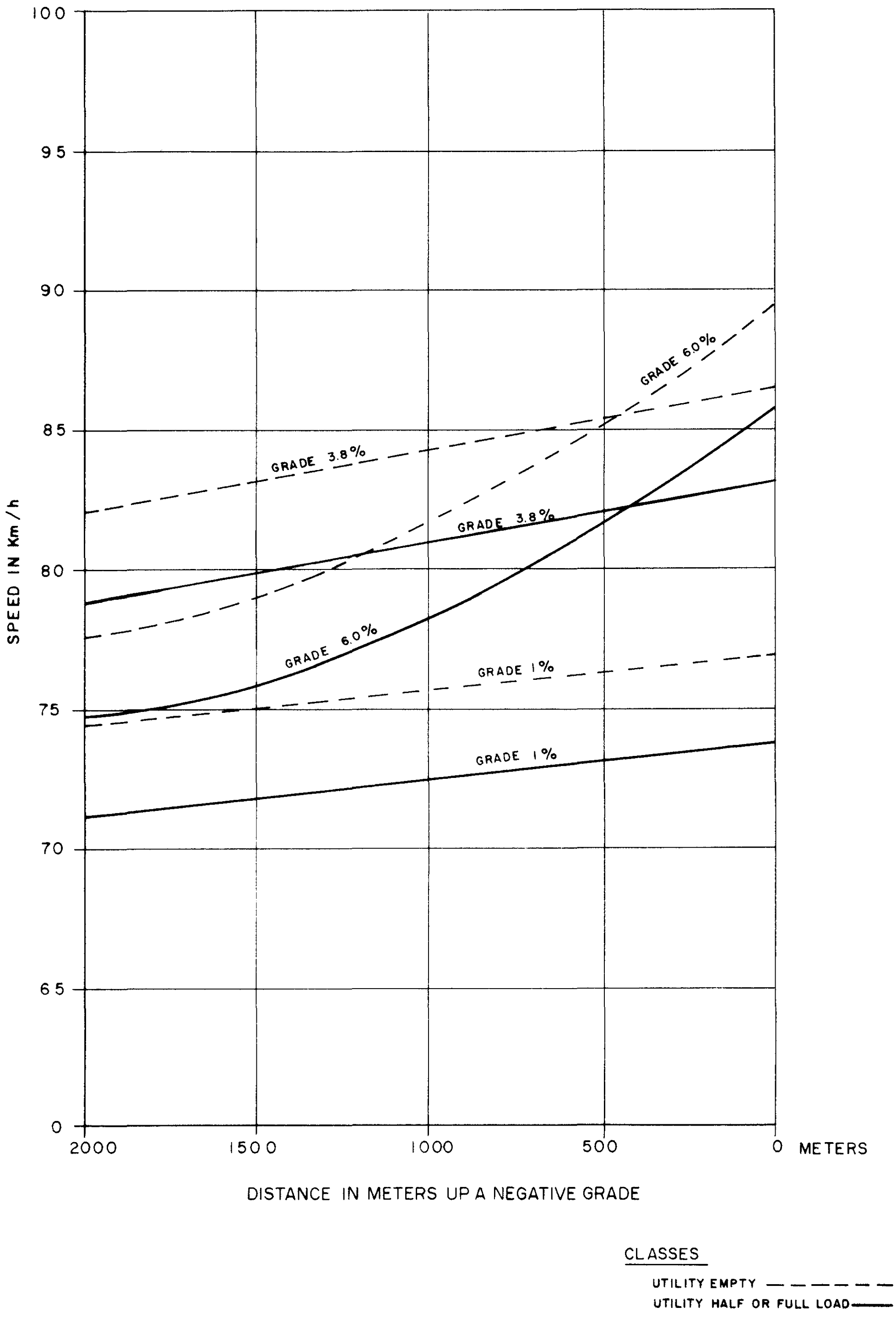


FIG. 14

## FREE SPEED RELATED TO DISTANCE

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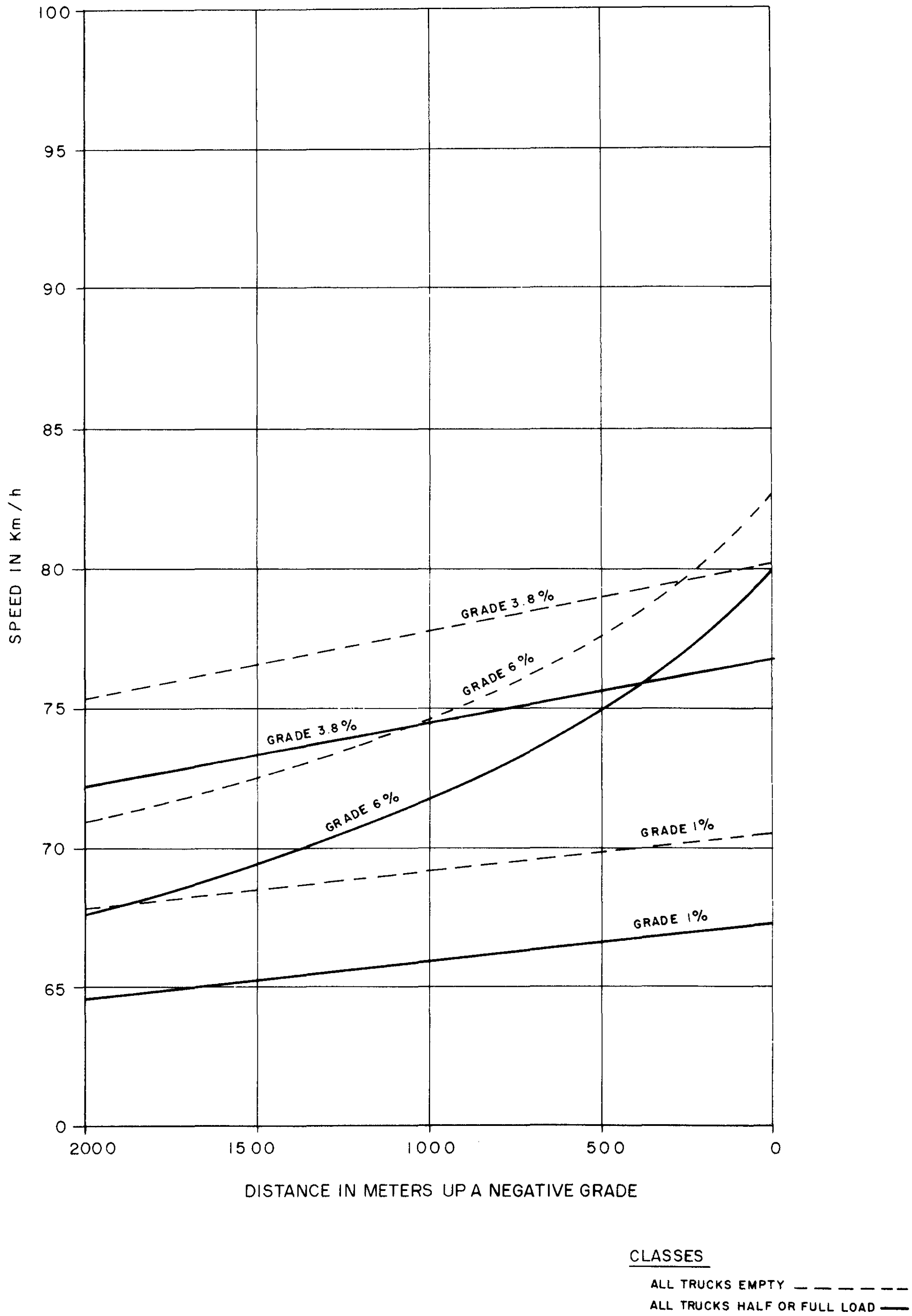


FIG.15

**FREE SPEED RELATED TO DISTANCE**

TABLE D.8 - ANALYSIS-OF-VARIANCE LAYOUT TO TEST EFFECT OF SPEED-LIMIT ENFORCEMENT

| | | |
|---|---|---|
| Grade G | 2 | |
| Repeat Grades R(G) | 1 | |
| Limit L | 1 | where |
| GL | 2 | G = effect of the three levels of grade |
| LR(G) | 1 | |
| Station S | 2 | |
| GS | 4 | R = repeat grade effect |
| SR(G) | 2 | |
| LS | 2 | L = effect of the speed limit law |
| GLS | 4 | |
| SLR(G) | 2 | |
| C | 5 | S = effect of the distance from the base of the grade; three stations are analyzed here; each is 500 meters apart |
| GC | 10 | |
| CR(G) | 5 | |
| LC | 5 | |
| GLC | 10 | |
| LCR(G) | 5 | |
| SC | 10 | C = effect of the different vehicle classes |
| GSC | 20 | |
| SCR(G) | 10 | |
| GSC | 10 | |
| GLSC | 20 | |
| LSCR(G) | 10 | |
| | 143 | |

ferences in their speed patterns. Although the other two smaller grades do not have repeat sections, previous analysis indicates that the repeat errors are larger for steeper grades. Therefore, tests made with the error term from a 6% grade are conservative in the sense that the true errors should be less than or equal to the errors used here.

Analysis of the results indicates that the speeds measured after the speed-limit law are significantly lower than those measured before the law. The effect of the law is much more pronounced on the steeper grades where speeds are in general higher. For this reason the GL interaction is significant. The interactions LS and LC are not significant since the mean speeds decrease evenly at all stations and for all classes.

(2) *Conclusions*

The preliminary analysis of these data indicates that the speed-limit law has reduced speeds significantly on negative grades when the radar units are visible. A large mass of free-speed data was collected within three months after initiation of the speed-limit law with the radar visible. Recommendations are being considered now for further work, so that adjustments can be made on these reduced speeds.

c *Steady-State Fuel Consumption (FC-1)*

The analysis of the steady-state fuel consumption experiment is presented primarily to demonstrate the types of relationships which are being developed. The relationships presented are only temporary since more data will be collected and more work is required to refine the analysis.

In performing this analysis, some of the data available have not been used. Data for the Ford F4000 have been rejected because fuel meter irregularities resulted in unreliable data for two test sections. The runs on these sections are being repeated and will be used in future analysis. Due to time restrictions and computer limitations, it was not possible to develop relationships for the Mercedes Benz bus operating on negative grades.

Fuel consumption is analyzed and discussed in units of mililiters per second. This form of the dependent variable will be used in the Time and Fuel Algorithm. In many cases, runs were made in more than one gear for a given situation. When this occurred the mean fuel consumption for all gears was analyzed.

The factors and levels analyzed are described in Table D.9. Not all combinations are possible, so the analysis does not involve predictions for every situation.

(1) *Analysis Approach*

It would be a difficult if not impossible task to develop one general equation for such a wide variety of conditions and for so many vehicles. Different equations were therefore developed for positive and negative grades and paved and unpaved roads. Four equations were developed for each vehicle, with the exceptions that the VW-1300 and the Kombis were analyzed together and the MB 0-362 bus was not analyzed for negative grades. Thus, 18 separate regression equations were developed.

Two major benefits arise from using such a large number of equations. First, since the number of observations in each combination is reduced to between 50 and 250, a much closer first examination can be made of the influence of the various factors and interactions. Second, since the number of observations is small, nonlinear regression programs can be utilized which enables a much wider range of equation forms to be examined.

The first problem was to determine which main factors and intercations were significant for each equation. In order to test the effects correctly, certain intricacies of the design and data collection had to be recognized. Since data from a maximum of three vehicles are used to develop each equation, various error components must be separated within the analysis. These various error components affect the predictive power of the equation by causing the within error terms in regression to be underestimated. The inferences are therefore limited since the value of the prediction has been overrated by the small error value.

The repeat vehicle error and the interaction error components were separated and used to test the main effects and interactions of the factors speed, grade, and load. Two repeat vehicle types were

TABLE D.9 - FACTORS AND LEVELS OF FUEL-CONSUMPTION ANALYSIS

| Factors | Levels |
|---|---|
| Vehicles | VW-1300, 2 Kombi 15, Ford-400, 2 MB-1113, MB-0362 Bus, Scania |
| Surface Type | Paved, Unpaved |
| Grades | 0, 2, 4, 6, 7, 8% |
| Sign of Grade | +, - |
| Speeds | 10, 20, 30, ......, 120 km/h |
| Load | Empty, Full |

tested, a Kombi and a MB-1113. The assumption was made that VW.Kombi and Ford-400 repeat errors are homogeneous and that MB-1113.MB 0-362 bus, and Scania repeat errors are homogeneous. The Kombi error was used to test effects for the gasoline vehicles and the MB-1113 was used to test effects for the diesel vehicles. Limited inferences have to be placed on the error terms since they reflect differences between only two vehicles in each case. However, without the repeat vehicles no error terms could be estimated.

### (2) *Analysis-of-Variance Results*

Four sets of analysis-of-variance were run on the data to test for significant effects. The sets used were Volkswagen and Kombis on positive grades, trucks and bus on positive grades, Volkswagen and Kombis on negative grades and trucks and bus on negative grades. The main effects and interactions were tested using the error term described above. Gravel and paved sections were analyzed separately.

For the Volkswagen and Kombis on positive grades, the main effects speed, load, grade, and class all proved to be significant. In addition, many of the interactions showed strong influences. The load x speed, grade x speed, and class x speed interactions were all significant. The fuel consumption differences between the levels of the load, grade, and class factors increased with increasing speed. The interaction load x grade was also significant. Fuel consumptions in the laden state were not significantly different from the fuel consumption in the empty state, when the vehicles operated on zero percent grades. However, the differences between the fuel consumption empty and laden, increased with increasing grade. The fuel consumption differences between the Volkswagen and Kombi also increased as grade increased, causing the class x grade term to be significant.

The nonlinear model that produced the lowest residual error and had the simplest form was:

$$\text{Fuel/sec} = A_0 + (A_1 + A_2C + A_3I)^{A_4S} \qquad (1)$$

where $A_0 - A_4$ = coefficients

C = dummy-vehicle class value: 1 = Volkswagen, 2 = Kombi

I = interaction term which consists of a load factor, a class factor and a grade term.

S = true speed of the vehicle.

Inspection of the function shows that the influences of the main effects as well as the interaction effects are explained by the model. The actual equations for the paved and unpaved situations are presented in Table D.10 with the other equations.

The same procedures were used for the analysis of the bus and trucks on positive grades. Each of these vehicles were analyzed separately using the error terms described previously. Similar main effects and interactions were significant for all the vehicles in this category for both the paved and unpaved fuel data. The same influences that affected the fuel consumption of the Volkswagen and Kombis were also significant for the trucks and bus. The main effects speed, load, and grade, were all significant in each case. The interactions load x speed, grade x speed, load x grade were also significant for these vehicles. It was also found that although the fuel-consumption relationships for the Ford and Mercedes were similar; the relationship for the Scania was different, since it appeared more linear. For this reason two functions were tested. The nonlinear model (2) is applied to the Ford-400, the Mercedes Benz 1113, and the Mercedes Benz 0.362 bus. The linear model (3) is used for the Scania. The two functions are presented below:

$$\text{Fuel/sec} = (A_0 + A_1 L + \exp(A_2 \text{Grade}(1 + A_3 L)))^{A_4 S} \qquad (2)$$

where $A_0$-$A_4$ = coefficients

$L$ = dummy load value (0=EMPTY, 1 = FULL)

$G$ = percent of the grade

$S$ = true mean speed

$$\text{Fuel/sec} = A_0 + A_1 L + A_2 I \qquad (3)$$

where $A_0$-$A_2$ = coefficients

$L$ = dummy load value (0=EMPTY, 1 = FULL)

$I$ = interaction of load, speed, and grade factors

The equations for the paved and unpaved test sections are given in Table D.10.

The fuel-consumption regression equations for positive gra-

TABLE D.10 - FUEL CONSUMPTION REGRESSION EQUATIONS FOR POSITIVE GRADES

Volkswagen and Kombi Unpaved

$$F = -.53 + (1.1 + .189\ C + .0153(C + .4)(L + 1.7)\ G)^{.035}\ V$$

$$S = .05$$

Volkswagen and Kombi Paved

$$F = -.62 + (1.14 + .17\ C + .009(C + .4)\ (L + 2.5)\ G)^{.036}\ V$$

$$S = .05$$

Ford-400 Unpaved

$$F = .84 + (.554 + e^{(.066\ G(1+1.15\ L))})^{.05}\ V$$

$$S = 1.01$$

Ford-400 Paved

$$F = .8 + (.65 + .24\ L + e^{(.11\ G(1+1.27\ L))})^{.0344}\ V$$

$$S = .82$$

MB-1113 Unpaved

$$F = (.95 + .45\ L + e^{(.21\ G(1+1.96\ L))})^{.0343}\ V$$

$$S = .09$$

MB-1113 Paved

$$F = (1.52 + .627\ L + e^{(.32\ G(1+1.32\ L))})^{.0236}\ V$$

$$S = .16$$

MB-Bus Unpaved

$$F = (1.36 + .167\ L + e^{(.3\ G(1+.44\ L))})^{.0245}\ V$$

$$S = .32$$

MB-Bus Paved

$$F = (2.3 + .24\ L + e^{(.5\ G(1+.31\ L))})^{.015}\ V$$

$$S = .30$$

Scania Unpaved

$$F = 1.02 - .3\ L + .072(L+1)\ V + .03(L+1)^{1.45}\ G\ V$$

$$S = .30$$

Scania Paved

$$F = 1.35 - .403\ L + .054(L+1)^{1.32}\ V + .026(L+1)^{1.32}\ G\ V$$

$$S = .54$$

where C = Class, 1=Volkswagen, 2=Kombi
G = Grade in Percent
V = Velocity in Km per hour
L = Load factor, 0=Empty 1=Full
F = Fuel in ml per second
S = Standard error of the equation

des are presented in Figures 16 through 27

For the Volkswagen and Kombies, the same main effects and interactions that were significant for the positive paved sections were also significant for the negative paved sections. The influences, however, are different in some cases. The most obvious difference is related to the effect of the load. For negative grades less than 2%, the empty vehicle consumes less than the laden vehicle assuming all other effects are held constant. However, for both the Volkswagen and the Kombis, the influence of the load changes as the negative grade increases from 2 to 4%. For negative grades of more than 4% the ladened vehicle consumes less than the empty vehicle.

For negative unpaved sections, all load effects proved to be non-significant. For this reason different models were used for the paved and unpaved equations for the Volkswagen and Kombis. The function for the paved case is much more complicated since it has to account for the load effects. Since there are many unique functions for the negative grades, the general forms are not presented for each case. Table D.11 presents all equations in their final forms.

The load effect for the truck on negative grades was similar to that for the lighter vehicles. For flat sections, the laden vehicle consumed more than the empty vehicle. As the grade becomes steeper the load effect reverses.

A major difference in the effect of speed occurred for the Scania data. In general all of the equations reflect an increase in fuel consumption per second with increasing speed. The speed influence reverses itself for the Scania operating on negative grades.

On the negative unpaved sections the influence of speed reverses for grades of four percent. At the four-percent level, the empty vehicle consumes more than the laden vehicle and increasing speed causes decreasing fuel consumption. On the negative paved sections, the influence of speed reverses for grades of two percent. At the two-percent level, increasing speed causes decreasing fuel consumption, and the empty vehicle consumes more than the laden vehicle. Table D.11 contains the equations for the trucks for negative grades. Each of the functions is a non-linear form with the exception that the Scania equation is intrinsically linear. Figures 28 through 36 present the equations for fuel consumption on negative grades in graphical form.

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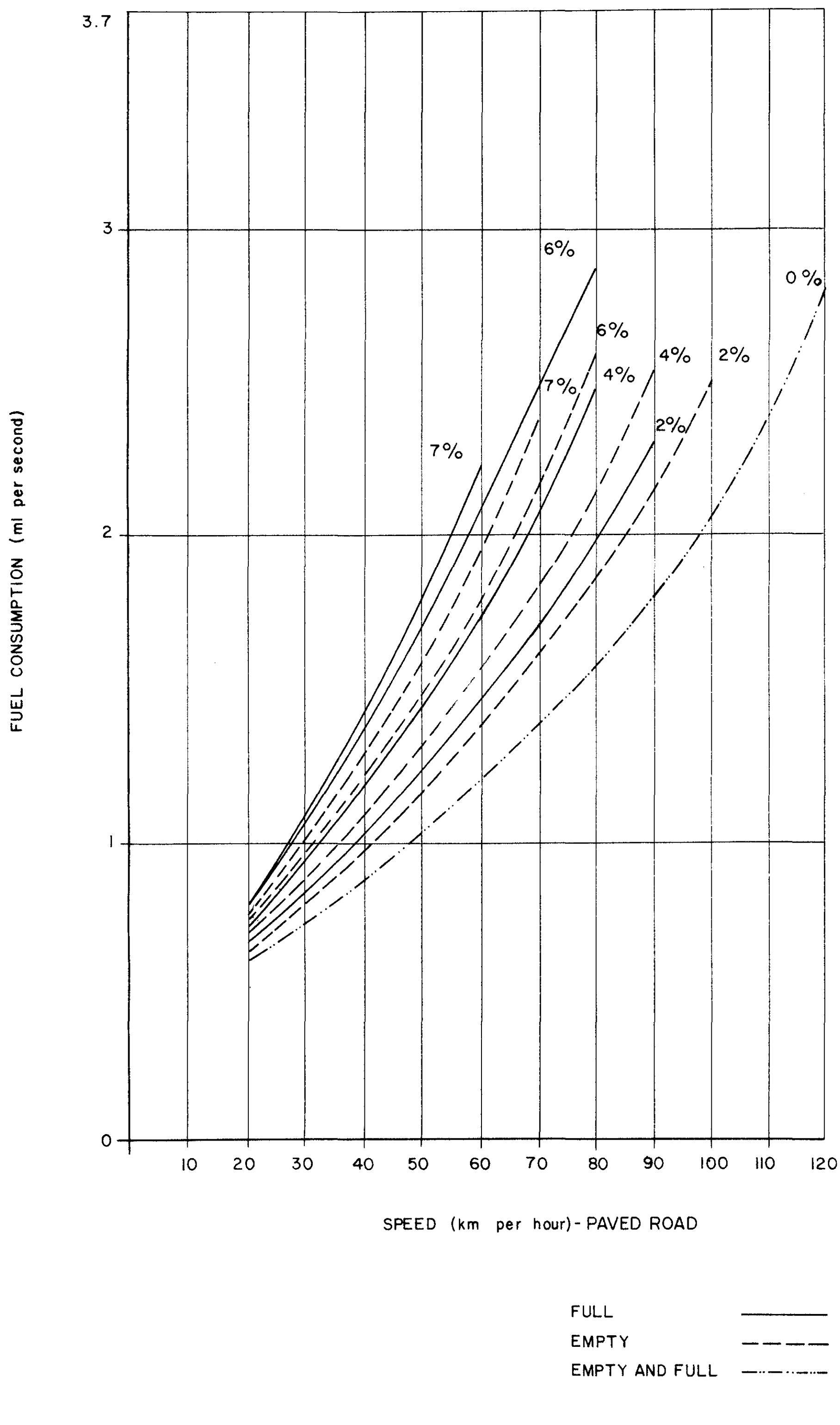


FIG. 16

FUEL CONSUMPTION - VOLKSWAGEN 1300 - POSITIVE GRADE

MT-GEIPOT

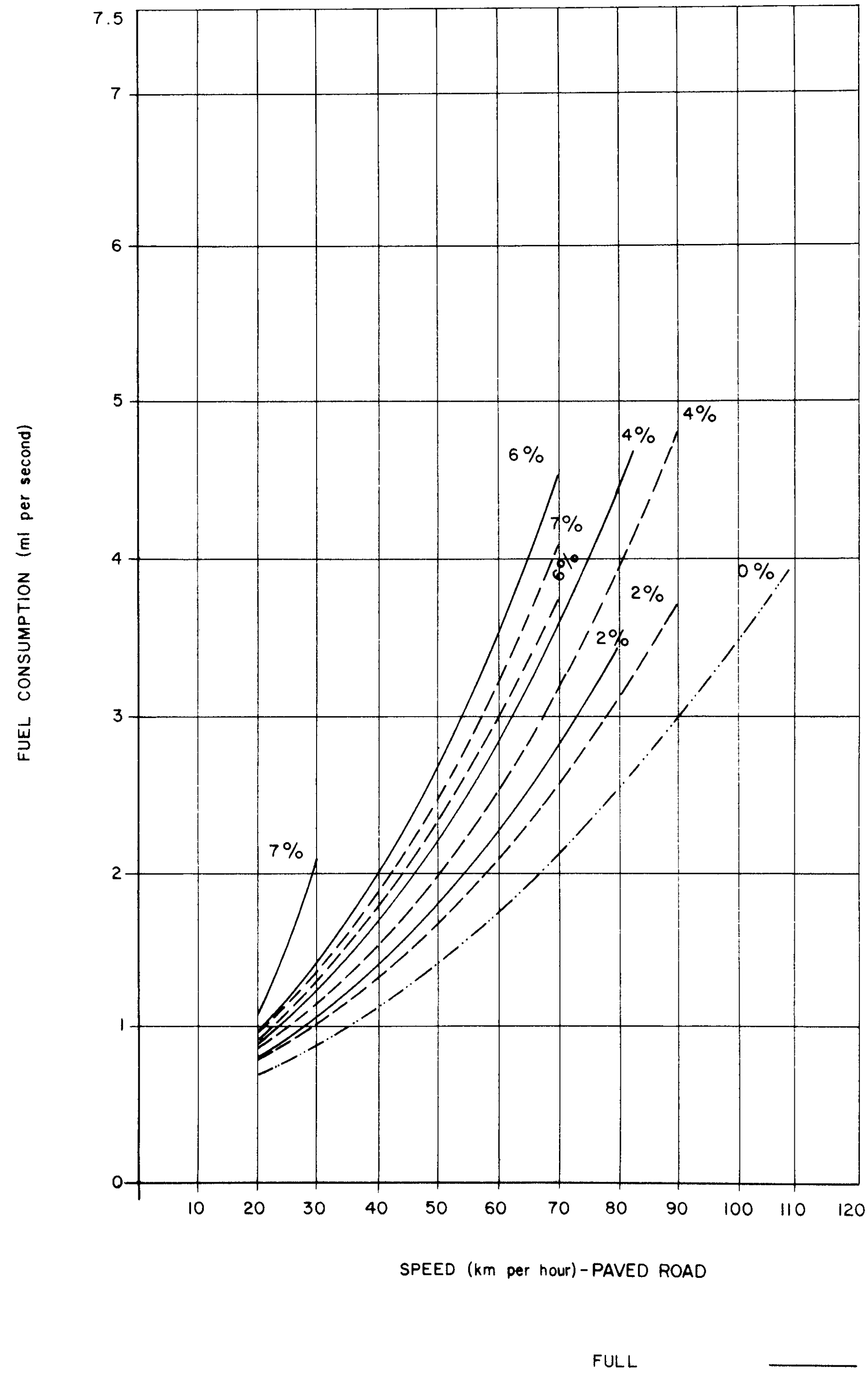


FIG. 17

FUEL CONSUMPTION - KOMBI - POSITIVE GRADE

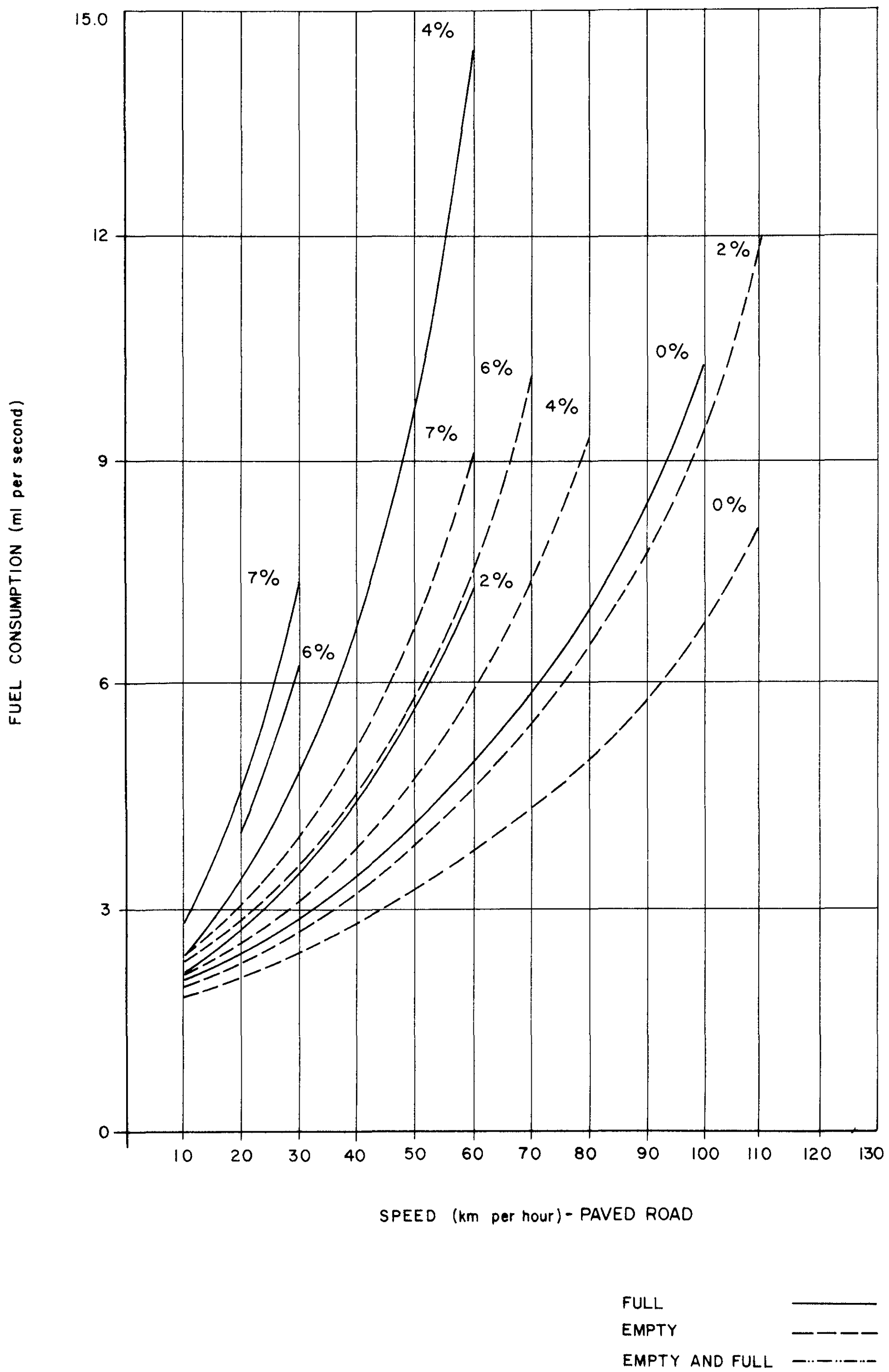


FIG.18

# FUEL CONSUMPTION - FORD 400 - POSITIVE GRADE

MT-GEIPOT

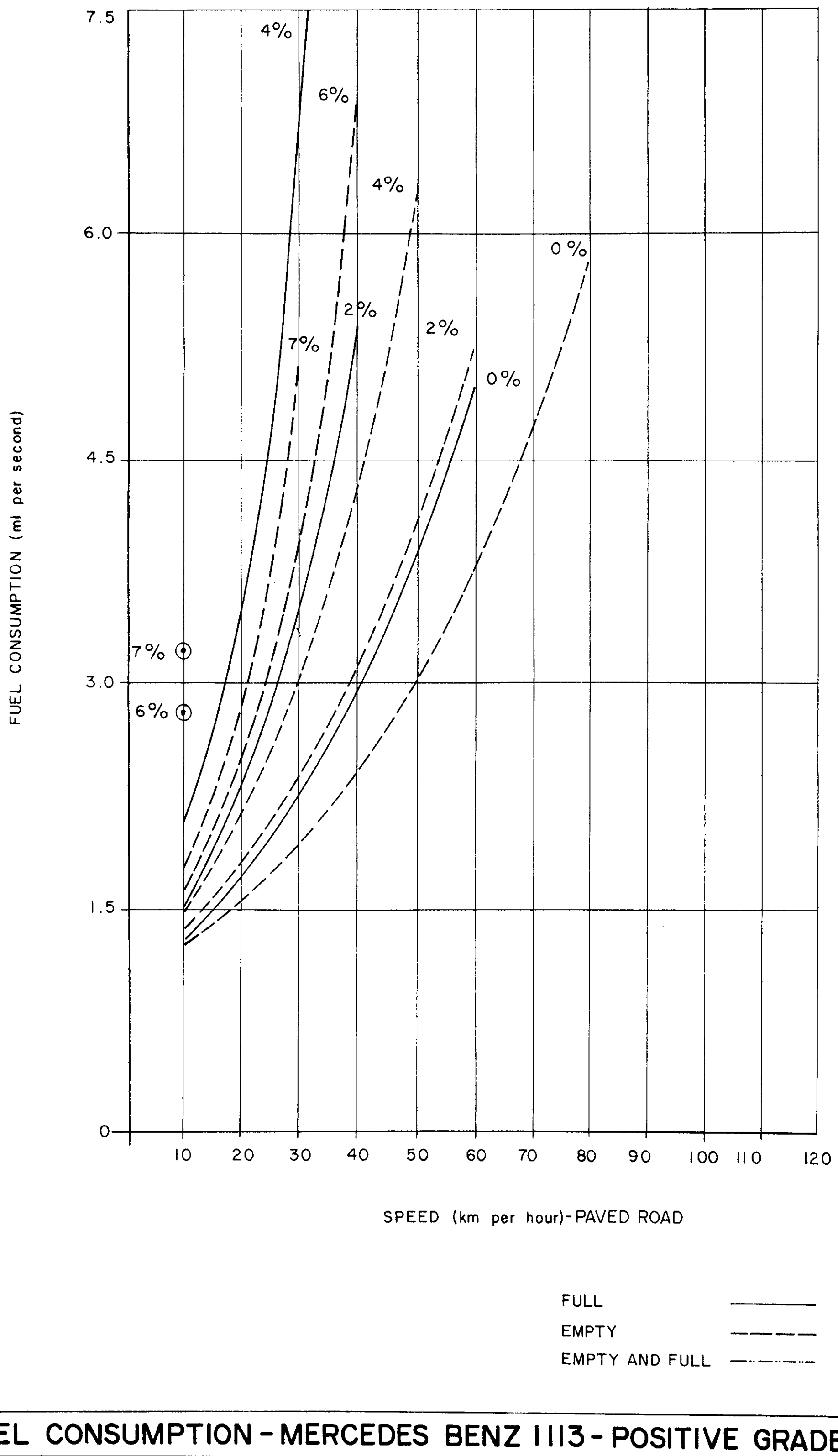


FIG. 19

FUEL CONSUMPTION - MERCEDES BENZ 1113 - POSITIVE GRADE

MT-GEIPOT

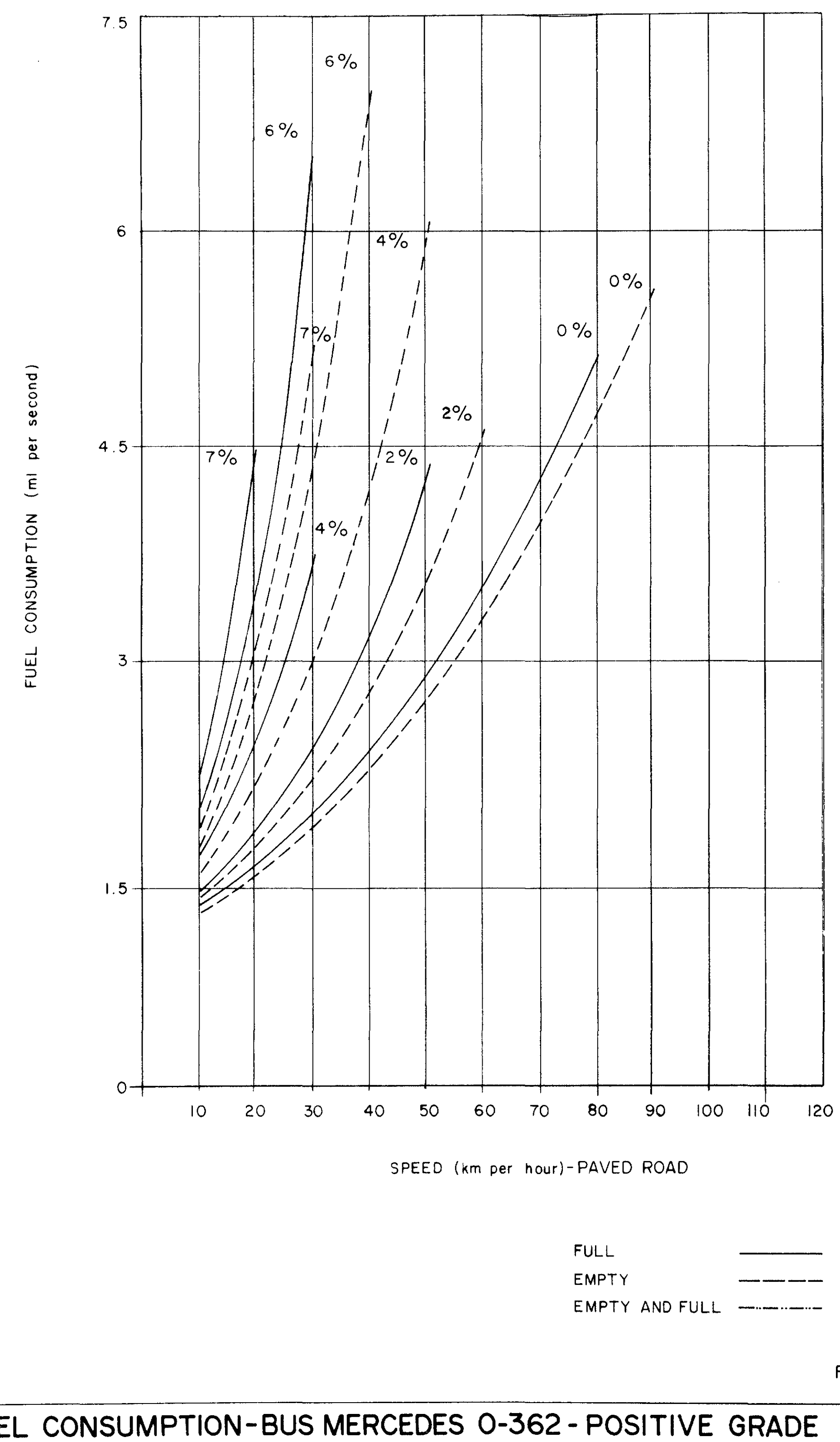


FIG.20

FUEL CONSUMPTION-BUS MERCEDES O-362-POSITIVE GRADE

MT-GEIPOT

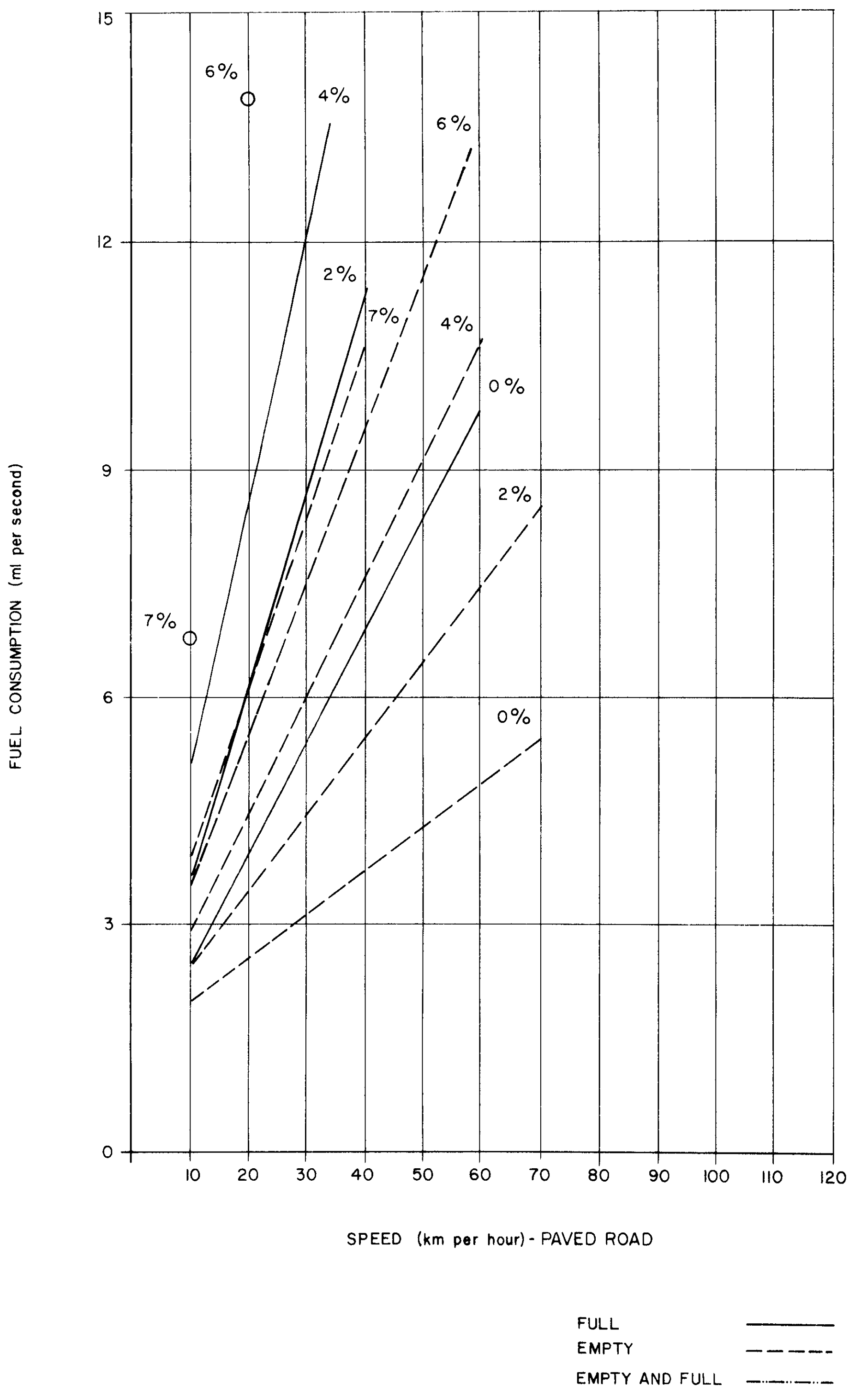


FIG. 21

FUEL CONSUMPTION - SCANIA - POSITIVE GRADE

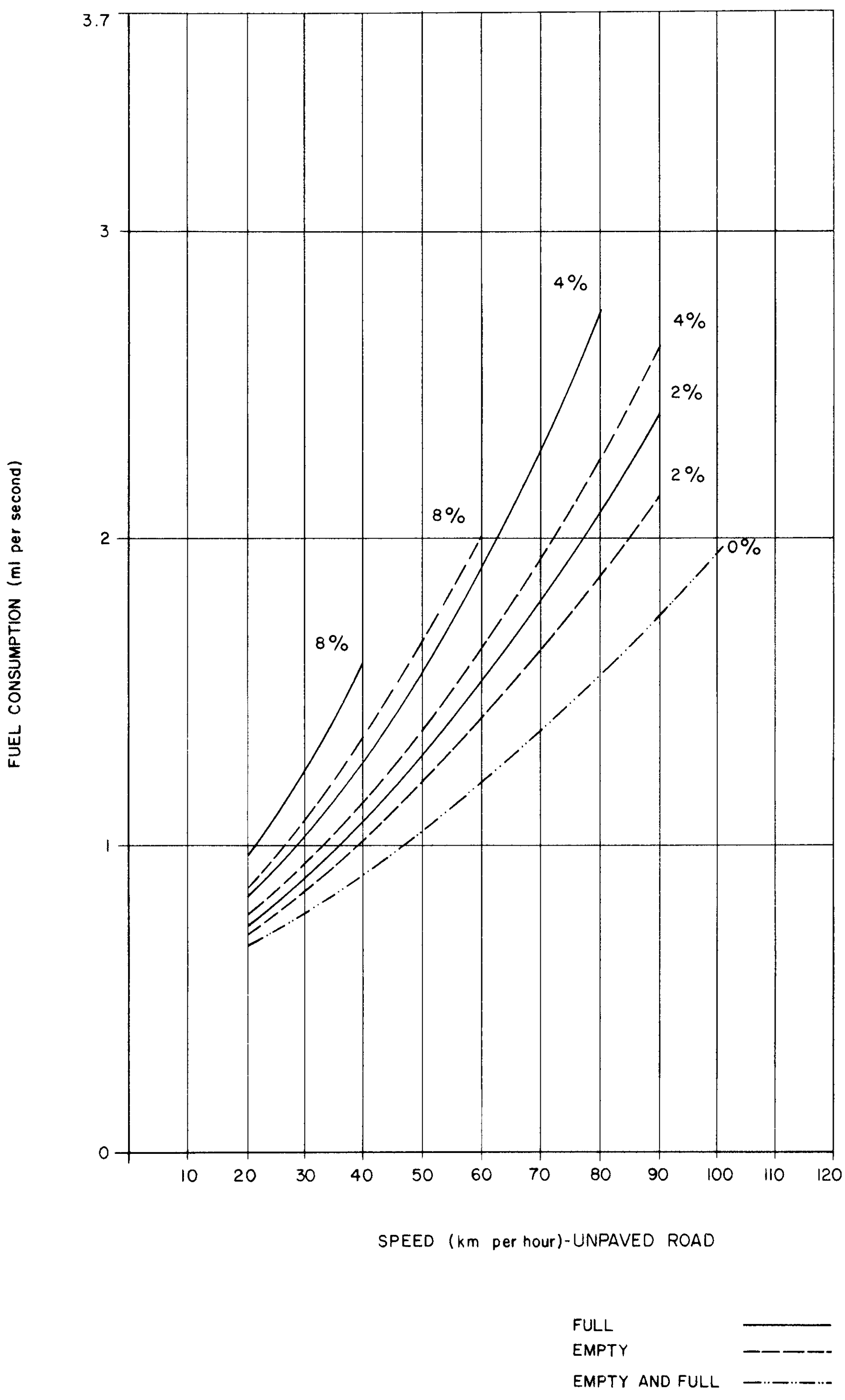


FIG. 22

FUEL CONSUMPTION - VOLKSWAGEN 1300 - POSITIVE GRADE

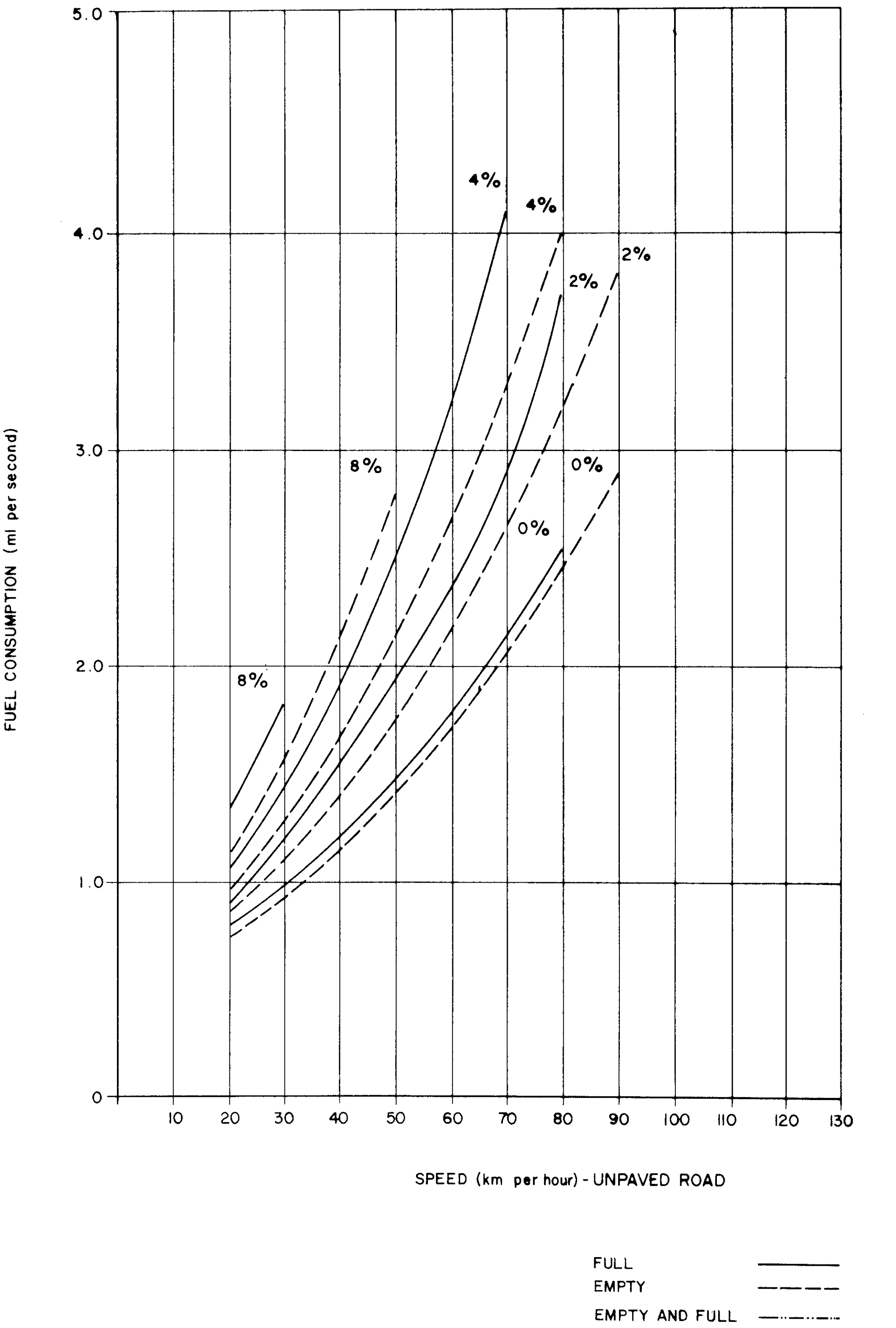


FIG. 23

FUEL CONSUMPTION - KOMBI - POSITIVE GRADE

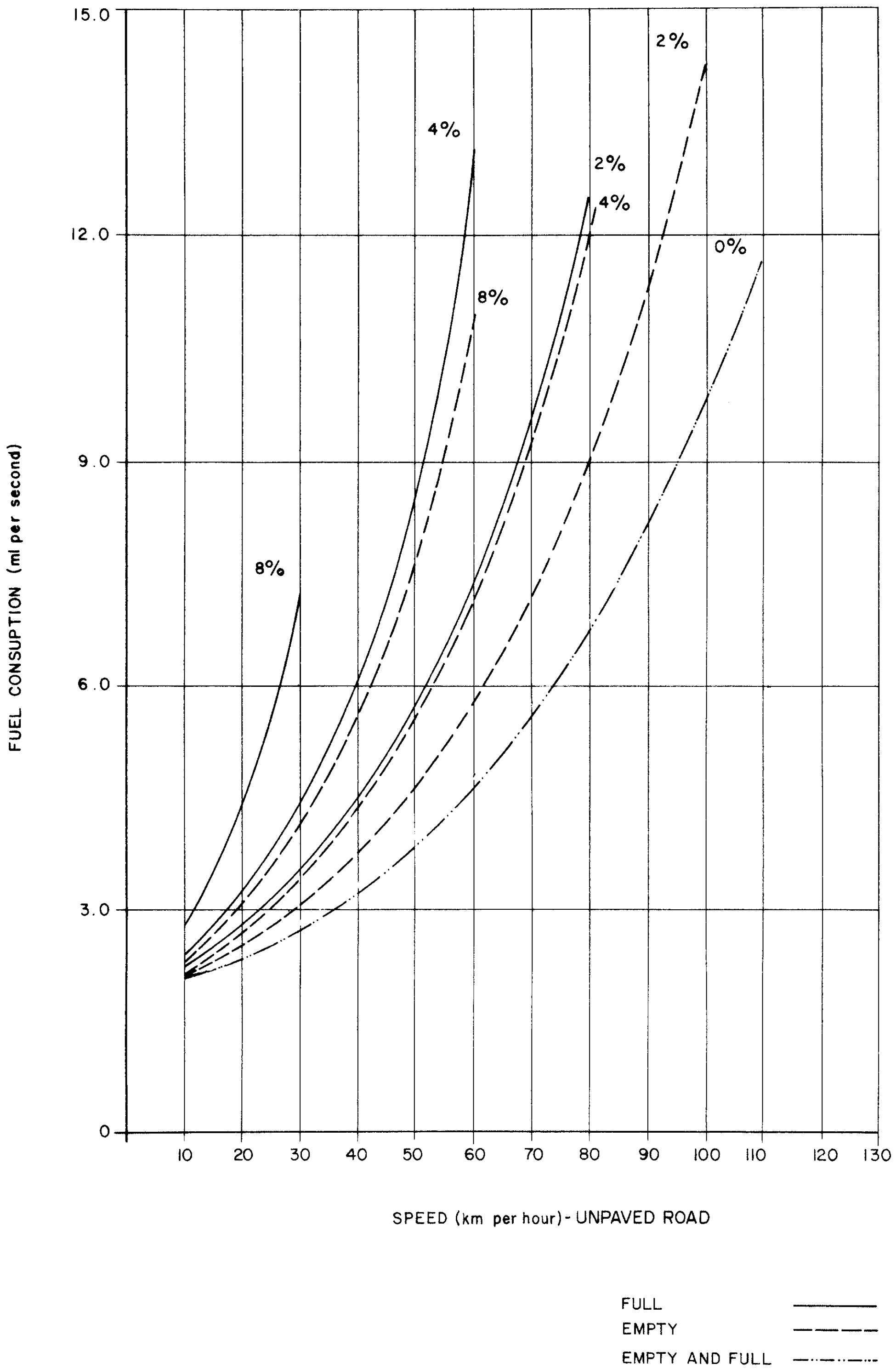


FIG. 24

## FUEL CONSUMPTION - FORD 400 - POSITIVE GRADE

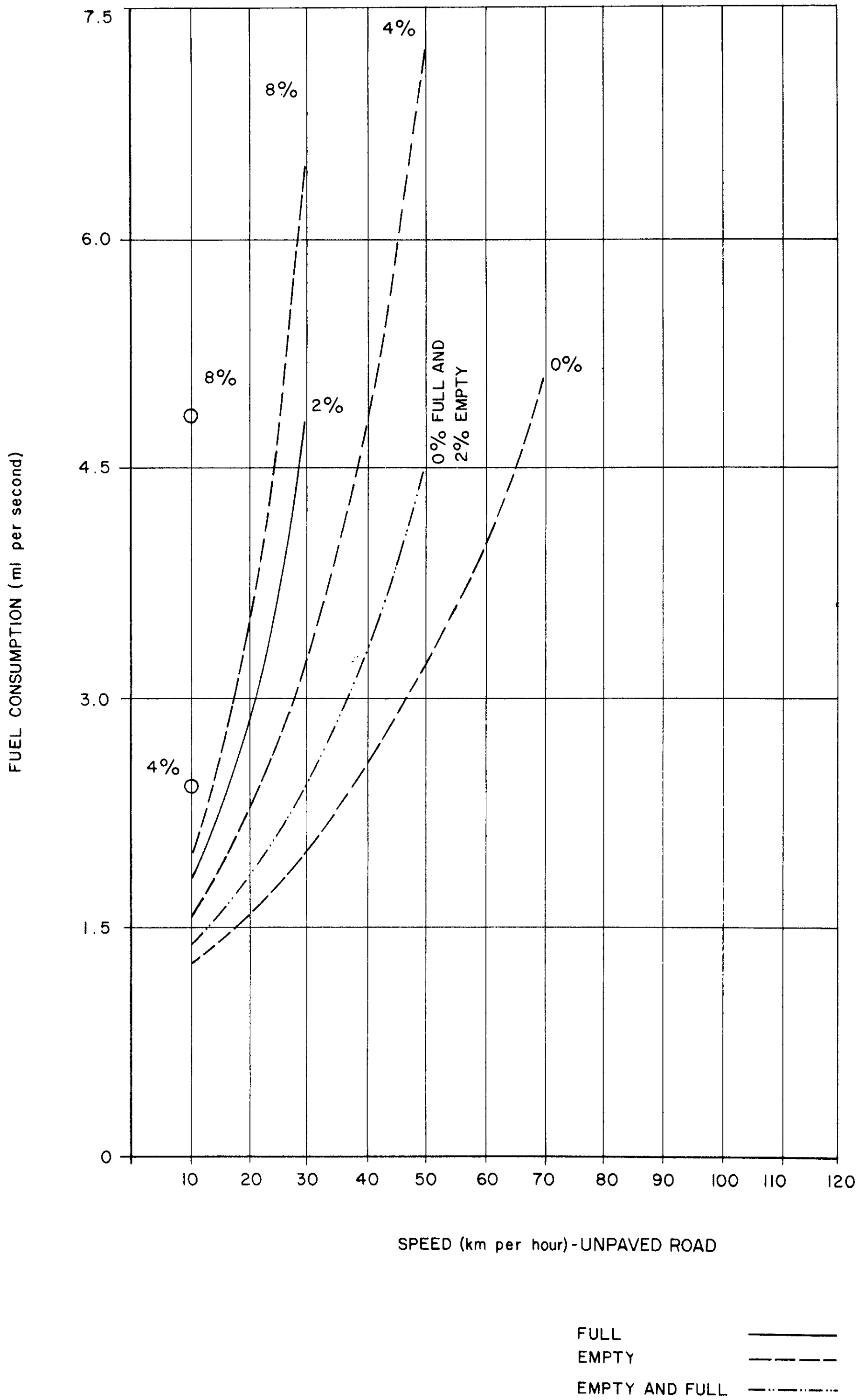


FIG. 25

**FUEL CONSUMPTION - BUS MERCEDES 0-362 - POSITIVE GRADE**

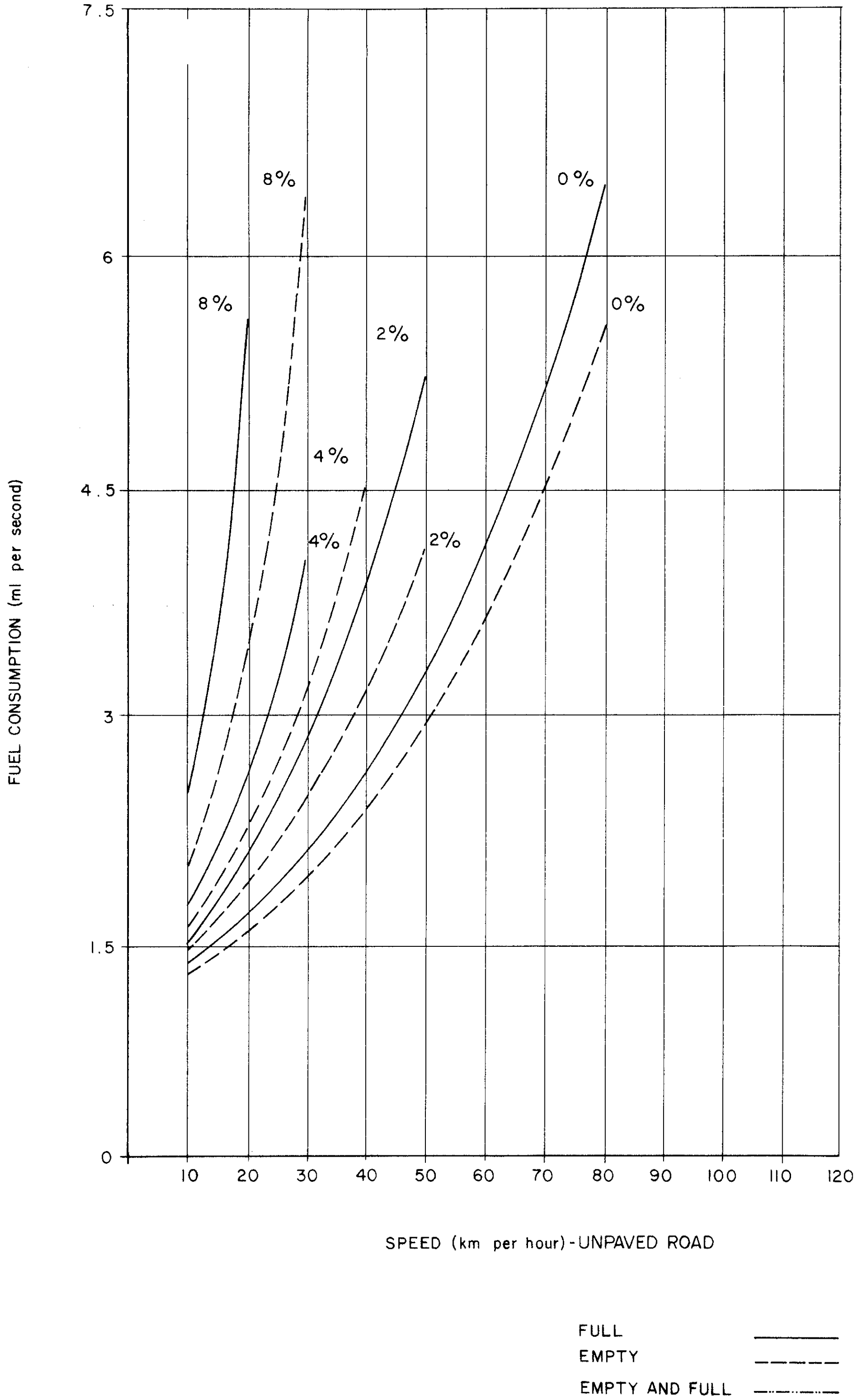


FIG. 26

FUEL CONSUMPTION - BUS MERCEDES O-362 - POSITIVE GRADE

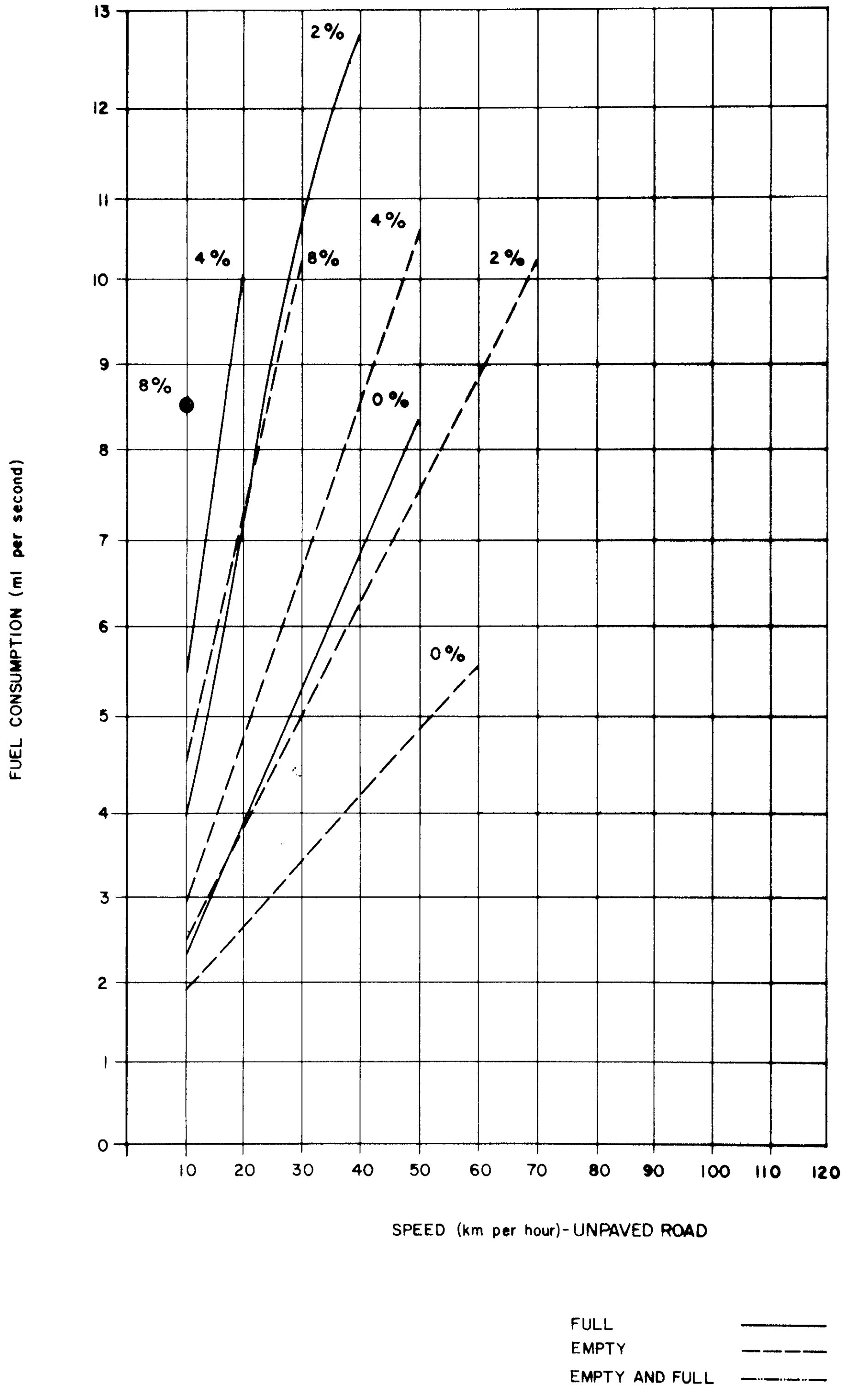


FIG. 27

FUEL CONSUMPTION - SCANIA - POSITIVE GRADE

TABLE D.11 - FUEL CONSUMPTION REGRESSION EQUATIONS FOR NEGATIVE GRADES

Volkswagen and Kombi Unpaved

$$F = -.87 + (1+1.88(C + .5)(e^{(.214\ G)}))^{.009\ V}$$

S = .04

Volkswagen and Kombi Paved

$$F = -1 + (1+(.065 + .042\ C)(e^{(-.016\ G^2)}) + .003(3-G)\frac{L}{C})^{.107\ V}$$

S = .07

Ford-400 Unpaved

$$F = \frac{1.77}{(1+G)^{.5}} - 1 + (1+e^{(.814\ +\ .07(L+1)^2(.827-G))})^{.0178\ V}$$

S = .56

Ford-400 Paved

$$F = \frac{1.91}{(1+G)^{.5}} - 1 + (1+e^{(1.38\ +\ .1(L+1)^2(1.26-G))})^{.01\ V}$$

S = .27

MB-1113 Unpaved

$$F = \frac{1.264}{(1+G)} - 1 + (1+e^{(.597\ +\ .253(L+1)^2(.684-G))})^{.02\ V}$$

S = .11

MB-1113 Paved

$$F = \frac{1.09}{(1+G)} - 1 + (1+e^{(.519\ +\ .213(L+1)^2(1.08-G))})^{.0180\ V}$$

S = .14

Scania Unpaved

$$F = \frac{2.068}{(G+1)^{.5}} (e^{(1.765\ +\ .522(L+1)(.863-G))})^{.0091\ V}$$

S = .36

Scania Paved

$$F = \frac{2.343}{(G+1)^{.5}} (e^{(.879\ +(L+1)(.79-G))})^{.0086\ V}$$

S = .14

where C = Class, 1=Volkswagen, 2=Kombi
G = Grade in Percent
V = Velocity in km per hour
L = Load 0=Empty 1=Full
F = Fuel in ml per second
S = Standard error of the equation

MT-GEIPOT

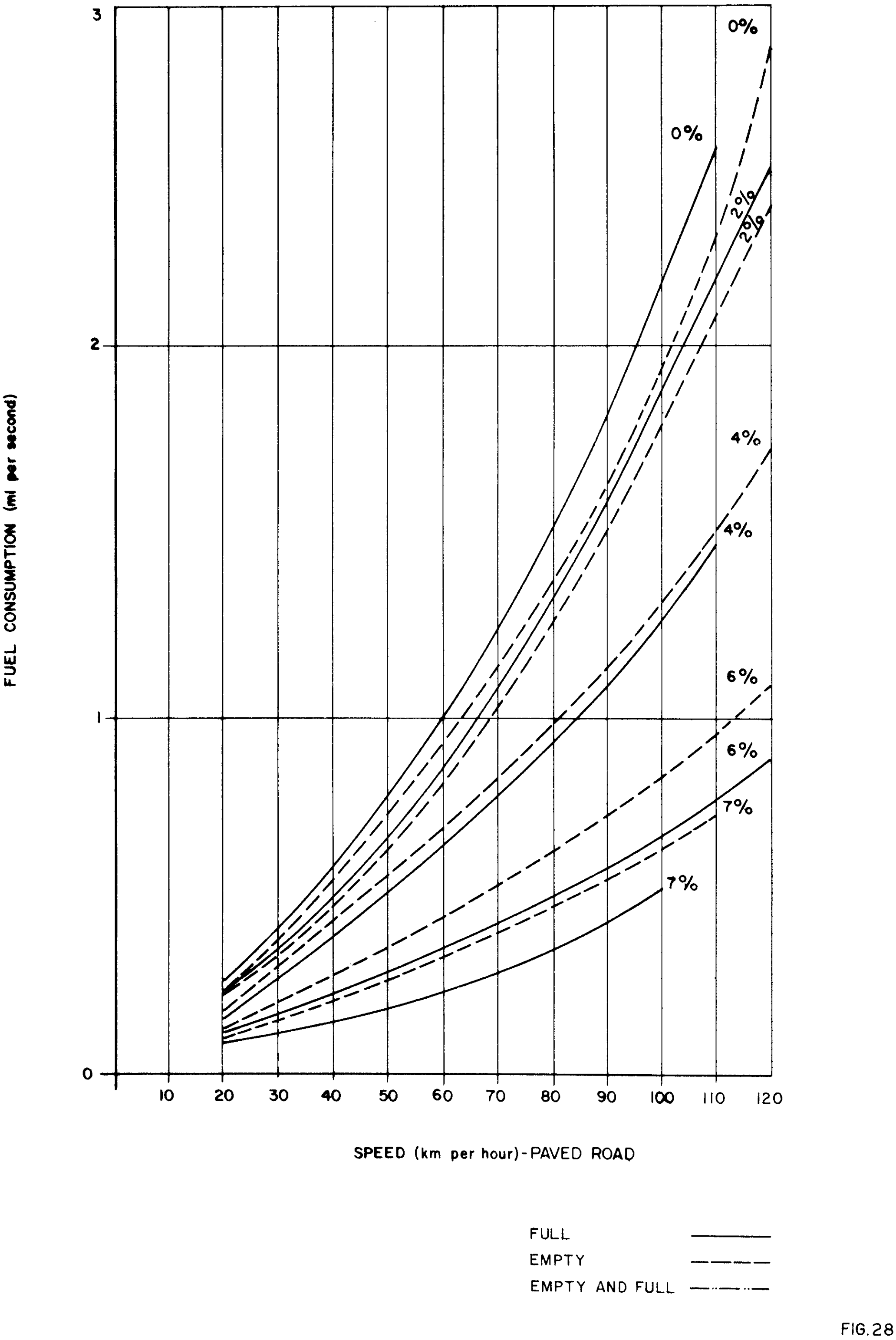


FIG. 28

FUEL CONSUMPTION - VOLKSWAGEN 1300 - NEGATIVE GRADE

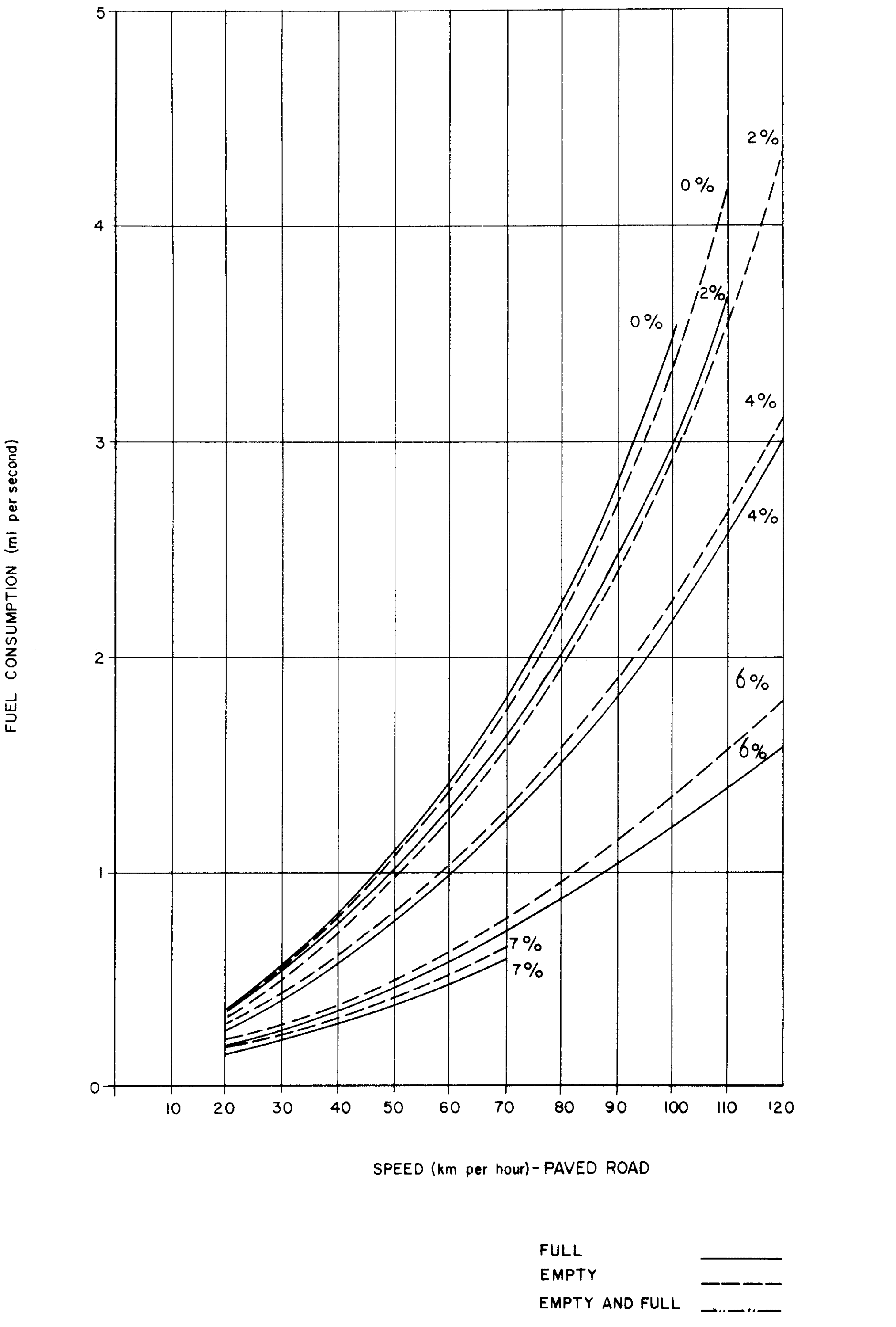


FIG. 29

FUEL CONSUMPTION - KOMBI - NEGATIVE GRADE

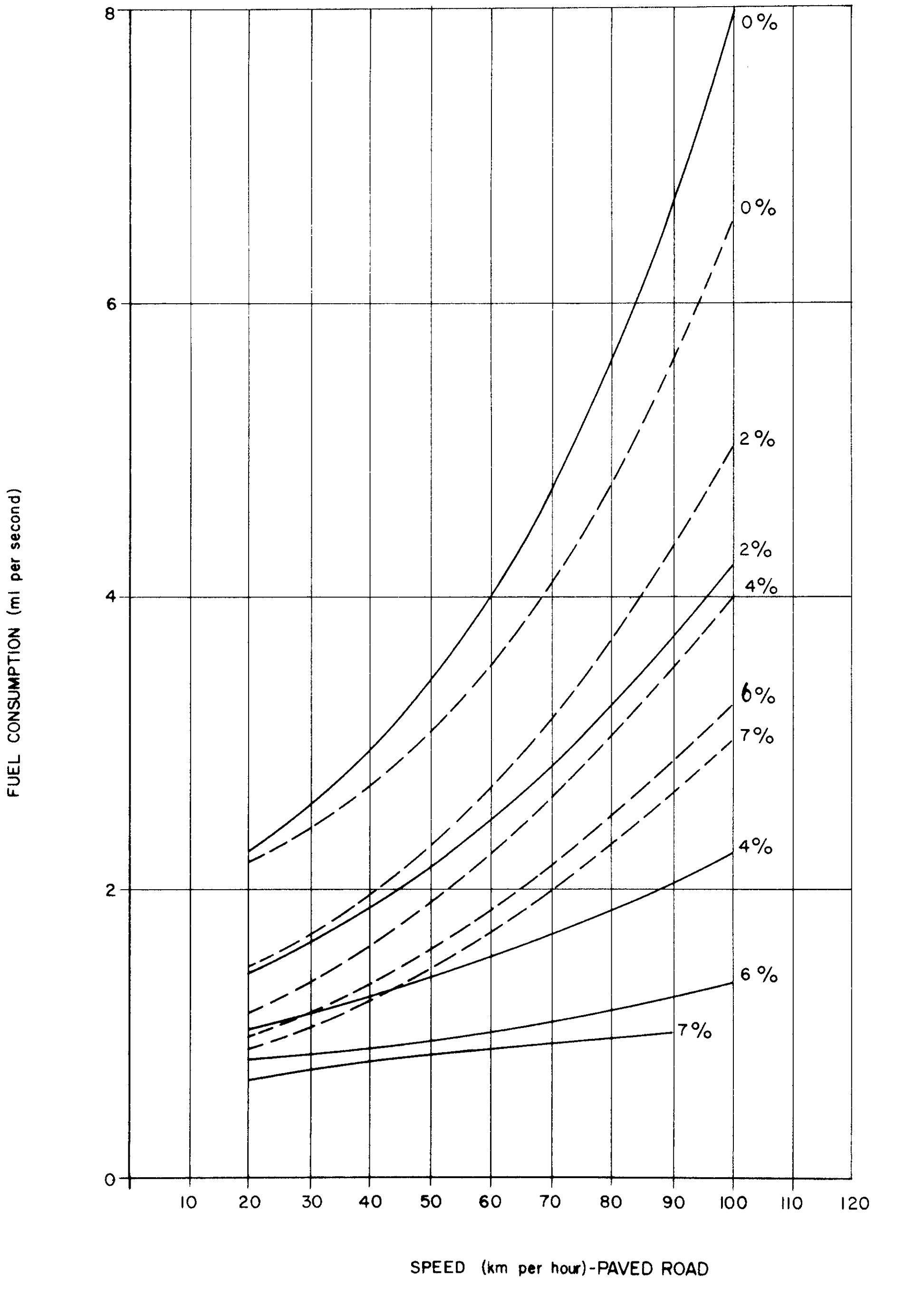


FIG.30

FUEL CONSUMPTION - FORD 400 - NEGATIVE GRADE

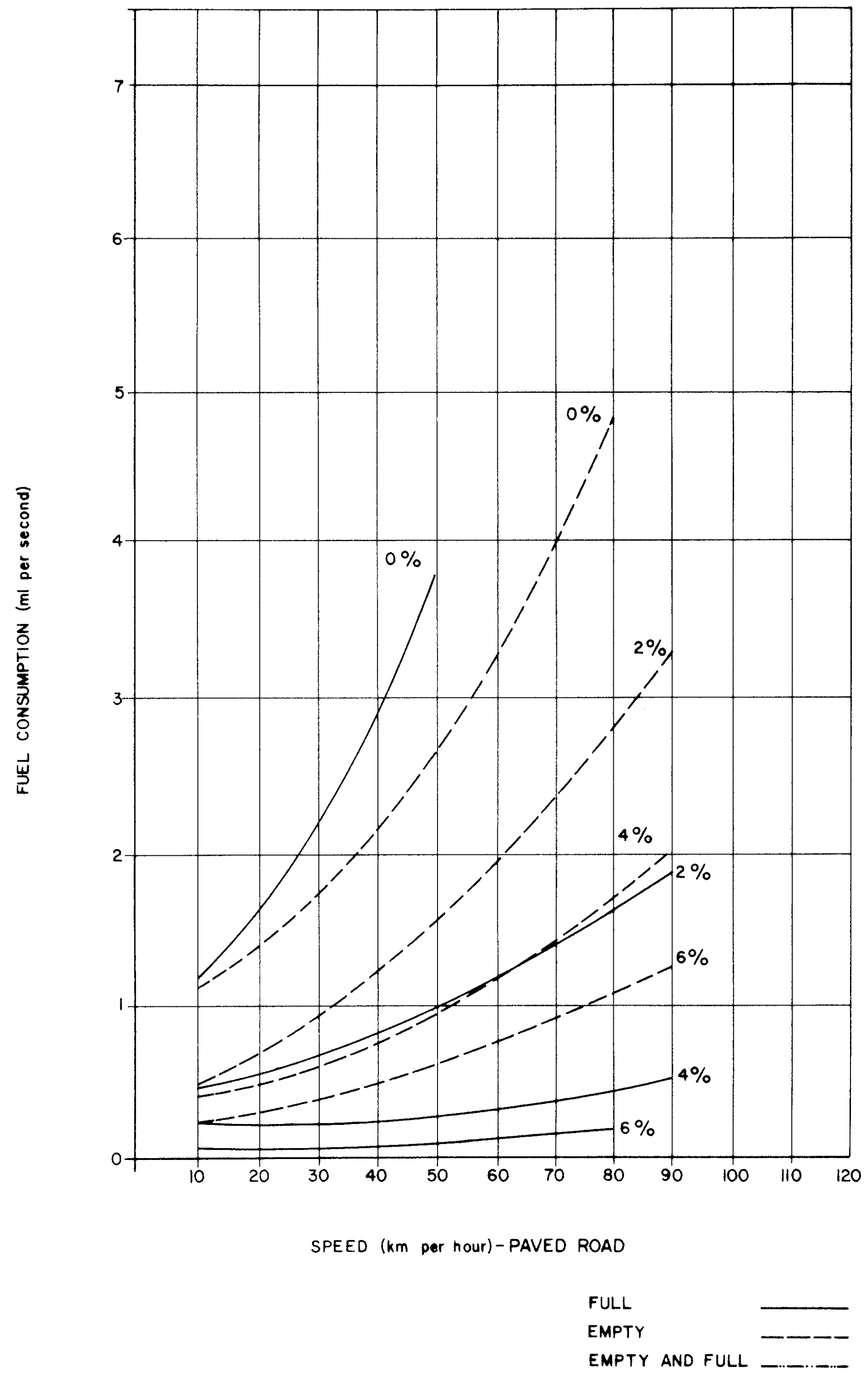


FIG. 31

FUEL CONSUMPTION - MERCEDES BENZ - 1 113 - NEGATIVE GRADE

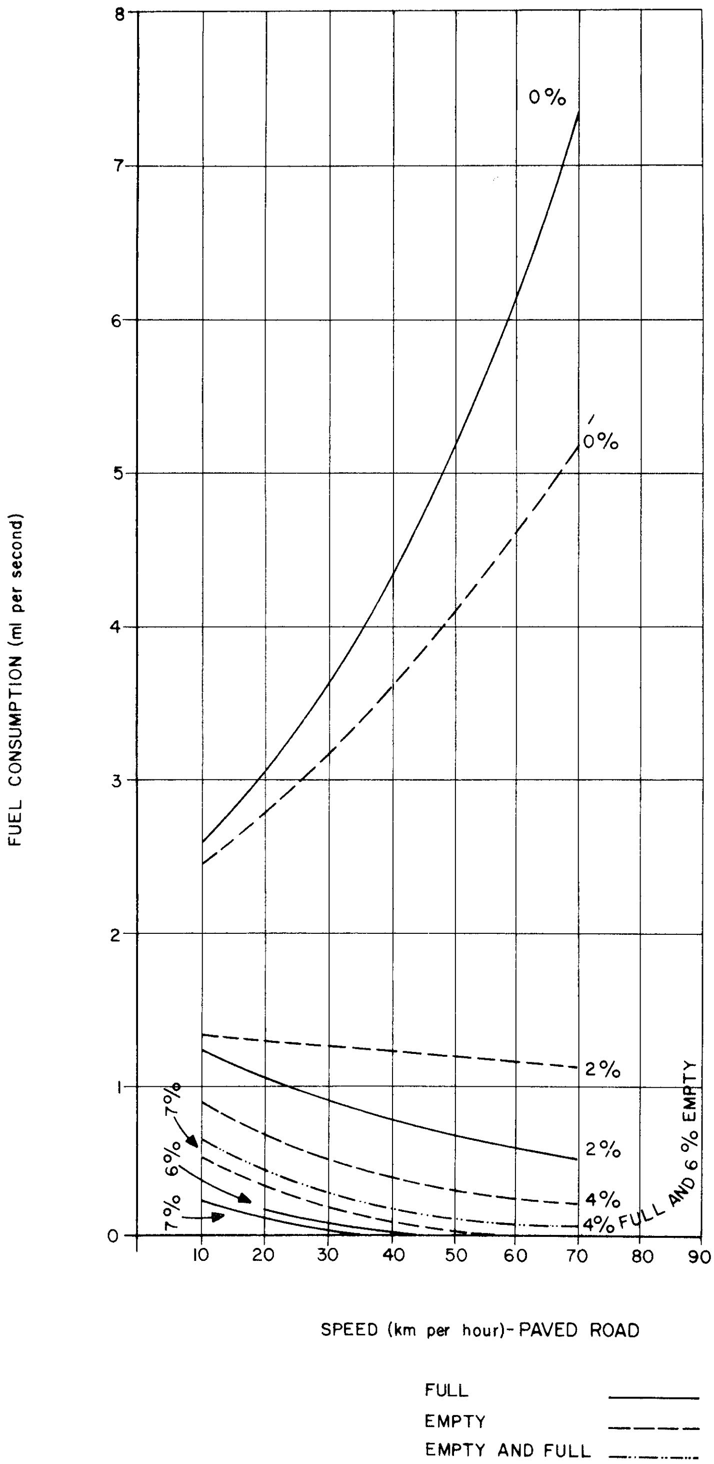


FIG. 32

FUEL CONSUMPTION - SCANIA - NEGATIVE GRADE

MT-GEIPOT

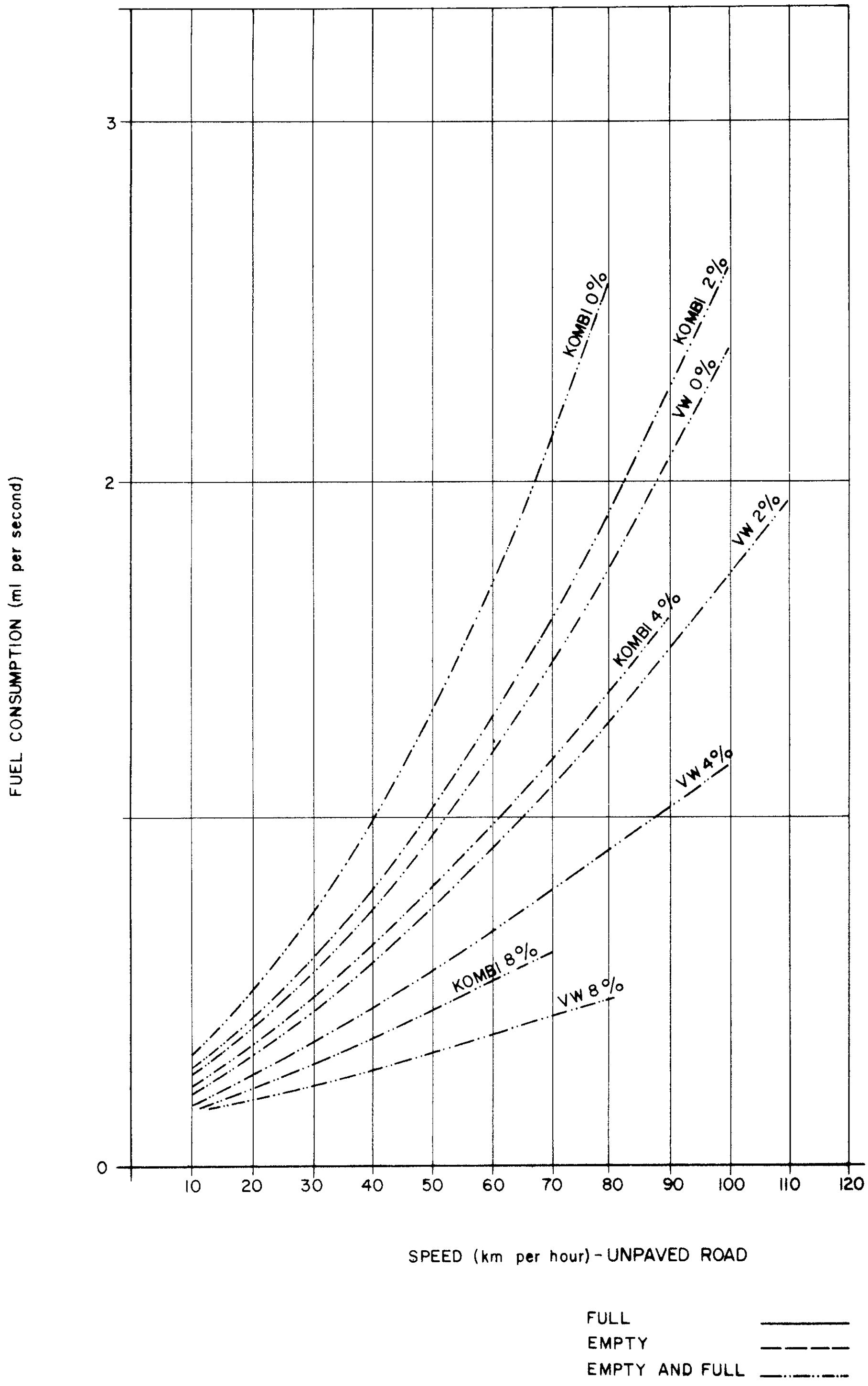


FIG. 33

FUEL CONSUMPTION - VOLKSWAGEN AND KOMBI - NEGATIVE GRADE

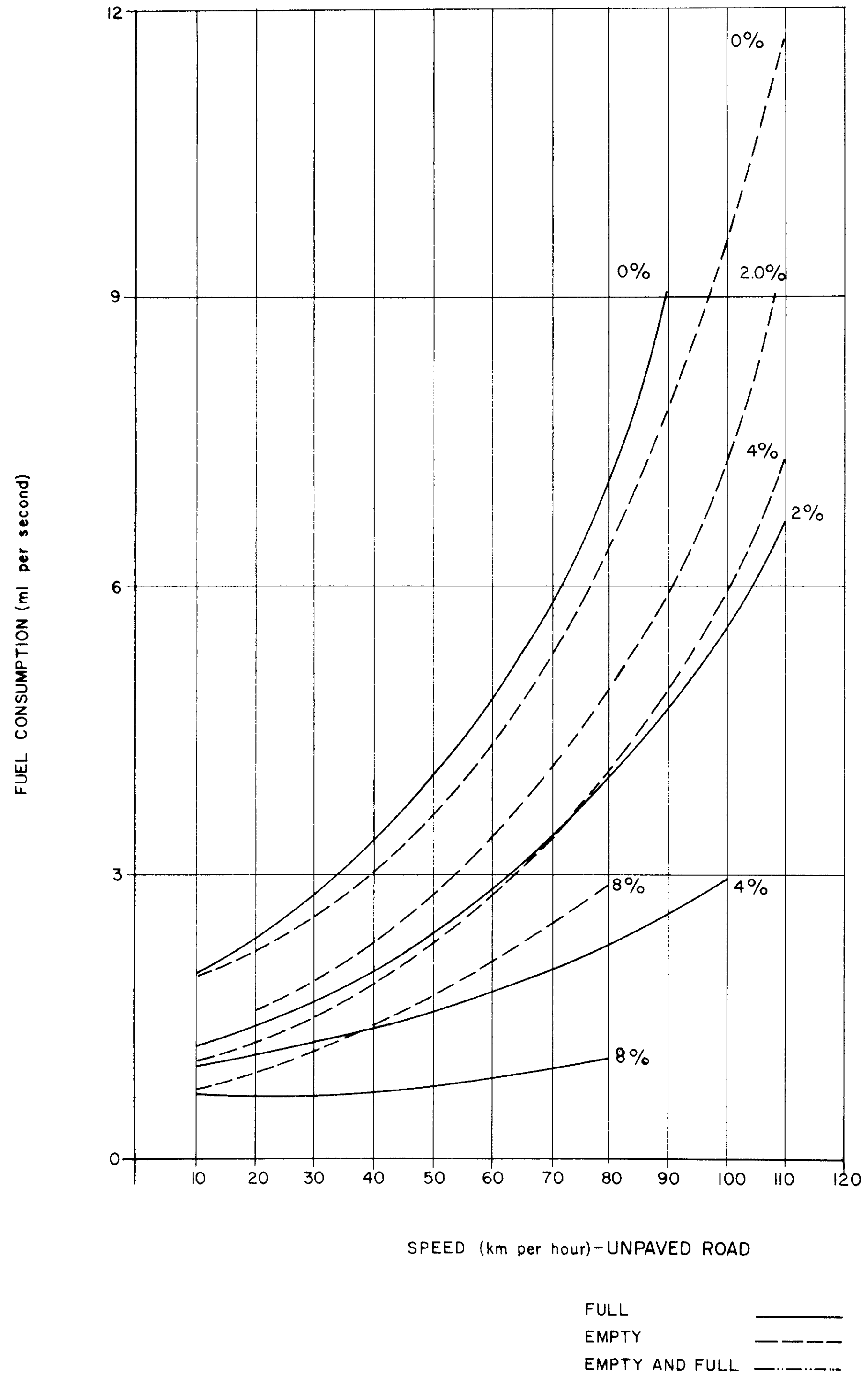


FIG. 34

## FUEL CONSUMPTION - FORD 400 - NEGATIVE GRADE

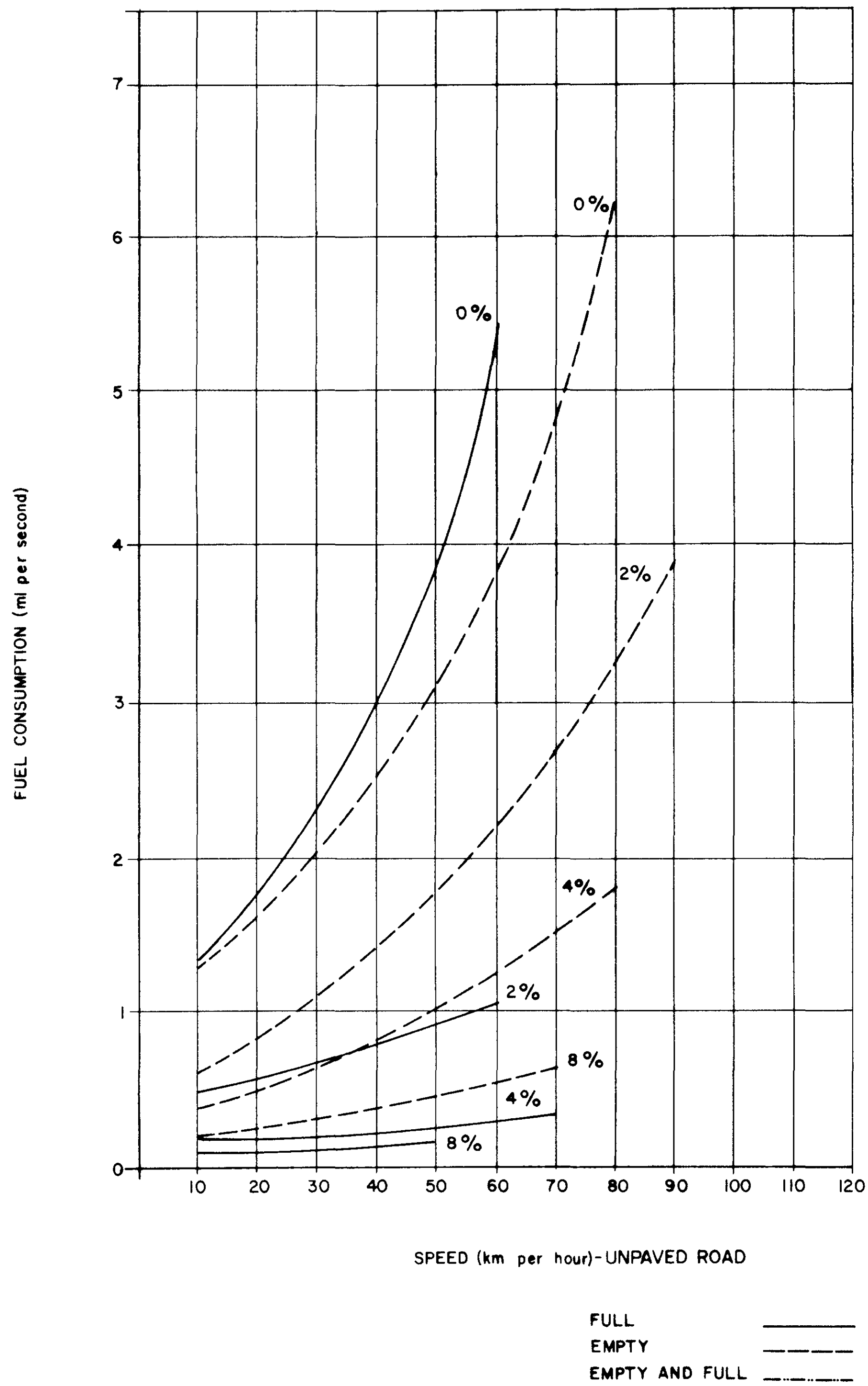


FIG. 35

FUEL CONSUMPTION - MERCEDES BENZ 1113 - NEGATIVE GRADE

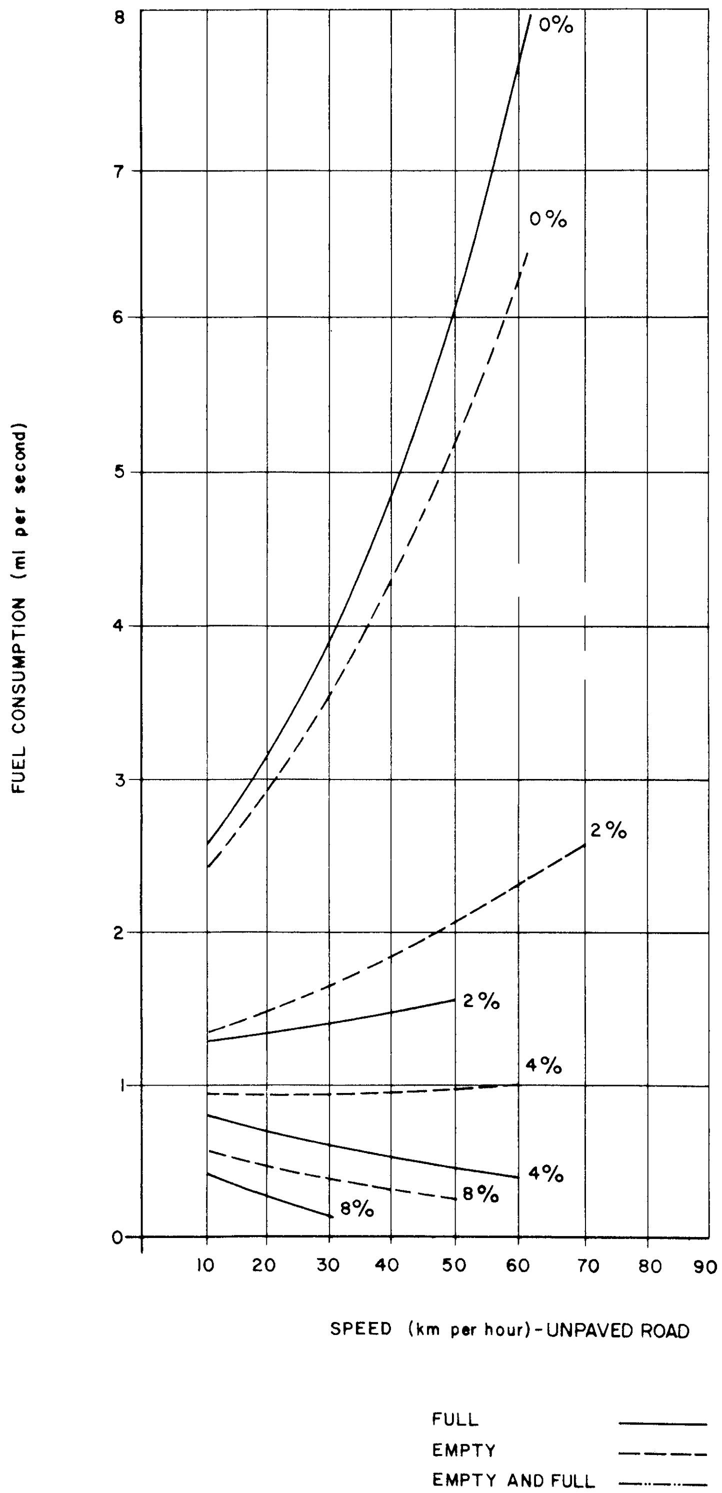


FIG. 36

## FUEL CONSUMPTION - SCANIA - NEGATIVE GRADE

### (3) *Summary of FC-1 Analysis*

Eighteen regression models are presented. They are the result of preliminary analysis of 20,000 steady-state fuel-consumption measurements. The equations are not in final form since the analysis reflects only a portion of the overall steady-state fuel-consumption experiment. The preliminary analysis using non-linear regression techniques offered a range of possible regression models. However,further refinements and modifications are required on the equations. Due to lack of actual analysis time, many possible improvements could not be accomplished. Certain problems with high coefficient correlations and large coefficient errors have not been satisfactorily eliminated from some of these preliminary non-linear equations. Such problems should be addressed before any of the functions are utilized for predictions.

The preliminary analysis effort has been very useful. The final analysis objective are much closer to realization due to the analysis performed on the data presented here.

## d *Fuel Consumption on Curves (FC-3)*

It has been demonstrated in previous literature (Sawhill,Ref. 6) that small radius curves can significantly affect fuel consumption. The purpose of this experiment is to examine the effects of extreme curvelinear alignment on fuel consumption. Eight test vehicles provided the data collected on the two 8% gravel sections. Test runs were made in both directions in the empty and laden condition. Since one of the sections was a tangent and the other had a very small radius curve, fuel consumption differences could be compared between the two horizontal curvature extremes. The factors and levels of the experiment are presented in Table D.12.

### (1) *Analysis-of-Variance Approach*

Data collected from the four gasoline and the four diesel vehicles operating in the positive and negative directions provided four groups of data. These four groups were analyzed separately. Since a limited number of vehicles were tested, various error terms must be separated within each analysis. The assumption was made that Volkswagen,

TABLE D.12 - FACTORS AND LEVELS OF THE EXPERIMENT

| Factors | Levels |
|---|---|
| Vehicles | Volkswagen 1300, 2 Kombies, Ford-400, 2 Mercedes Benz 1113, Mercedes Benz O-362 Bus, Scania |
| Loads | Empty and Full |
| Horizontal Curvature | 70-meter radius curve and tangent |
| Speeds | 10-50 km/h |
| Grades | +8%, -8% |

Kombi and Ford-400 repeat errors are homogeneous and that Mercedes Benz O-362 bus, and Scania repeat errors are homogeneous. Two Kombis and two Mercedes Benz 1113 trucks provided estimates of these errors. The Kombi errors were therefore used to test differences in the gasoline vehicle group and the Mercedes Benz 1113 errors were used to test differences in the diesel vehicle groups. Table D.13 presents an example of an Analysis-of-Variance layout.

Restrictions must be placed on the inferences of this experiment because only four gasoline vehicles and four diesel vehicles were tested. In addition, since only two vehicles provide error estimates, the error terms have very few degrees of freedom. Therefore, whenever possible, error terms are pooled and the appropriate pooled errors are used to test the main effects and interactions.

(2) *Analysis of Results*

In the positive grade case for gasoline vehicles, the error terms RH, RHL(c), RH5L(c) were not significantly defferent. Therefore, the pooled error with four degrees of freedom was used to test all horizontal curvature effects. None of the horizontal curvature effects were significant at the 10% confidence level. For the negative grades the various error terms of the gasoline vehicles were not homogeneous. The two repeat Kombis operated very similarly on the two sections. For each vehicle the mean fuel consumption on the curved section was about 3% above the fuel consumption on the tangent section. These similar statistics produced an extremely small RH error term. Other error terms, although larger than RH were also relatively small. The factors and interactions were tested without pooling the error terms. The F statistic calculated for each case, therefore, contains only one degree of freedom in the denominator. With this limitation, the tests showed that all intercation terms that contained horizontal curvature were not significant at the 10% level. But the main factor horizontal curvature was tested by the RH interaction and was significant at the 5% level.

The repeat error from the two Mercedes Benz trucks was used to test the horizontal curvature factor and interactions for the diesel vehicles. For both the positive and negative grades, the repeat errors were relatively large in comparison to other effects. One of the Mercedes trucks consumed less fuel on the tangent than on the curved

TABLE D.13 - EXAMPLE ANALYSIS-OF-VARIANCE TABLE USED TO ANALYZE FUEL CONSUMPTION FOR GAS AND DIESEL VEHICLES

| Source | df | |
|---|---|---|
| Class (C) | 2 | |
| Repeat Vehicle (R) | 1 | |
| Load within Class L(C) | 3 | |
| RL | 1 | |
| Speeds (S) | 4 | (depending on the direction of the grade this value could be as low as 1) |
| CS | 8 | |
| RS | 1 | |
| SL (C) | 12 | |
| RLS | 1 | |
| Horizontal Curve (H) | 1 | |
| CH | 2 | |
| RH | 1 | |
| HL (C) | 3 | |
| RHL | 1 | |
| ʃSH | 4 | |
| CSH | 8 | |
| SHR | 1 | |
| HSL (C) | 12 | |
| HSLR | 1 | |

section and the other vehicle consumed less on the curved section than the tangent. The influence of the horizontal curvature was therefore reversed from one vehicle to the next, causing the repeat errors to be relatively large. Pooling was performed where possible, and all the main effects and interactions of horizontal curvature were not significant at the 10% level for positive and negative grades.

### (3) *Summary of FC-3 Analysis*

It is difficult to make firm conclusions about the results of the analysis-of-variance procedures because of the limited degrees of freedom in the error term and because of the inference restrictions. The experiment cannot be viewed as a definitive study of the effect of horizontal curves on grades. However, within the scope of this experiment, the effect of horizontal curves appears to be minimal. Since this test was conducted using extreme conditions of horizontal curvature and grade, and for these conditions the largest mean difference in fuel consumption was only 3%, it may be concluded that it is not economical to experiment further on the effects of curves on fuel consumption. Therefore, the satellite study to further investigate the effect of horizontal curves on fuel consumption, FCS-2, will not be conducted.

## 5 SUMMARY

The road user costs and traffic experiments have been in progress for 16 months. During this time, over 130,000 pieces of data have been collected. Currently, there are five traffic-behavior and two fuel-consumption experiments in progress. One fuel-consumption main experiment and one satellite study have been completed. However, as explained earlier, there is still a lot of work to be performed. One fuel-consumption and three traffic-behavior main experiments have not been started.

Figure 37 shows the work schedule proposed for finishing the experimental program. The fuel consumption testing is scheduled to be completed by May 1978. At this time, it will be necessary to train the fuel-consumption crew to perform three of the traffic-behavior experiments. Since radar units are not required for performing these experiments, the radar crew can simultaneously perform other traffic-

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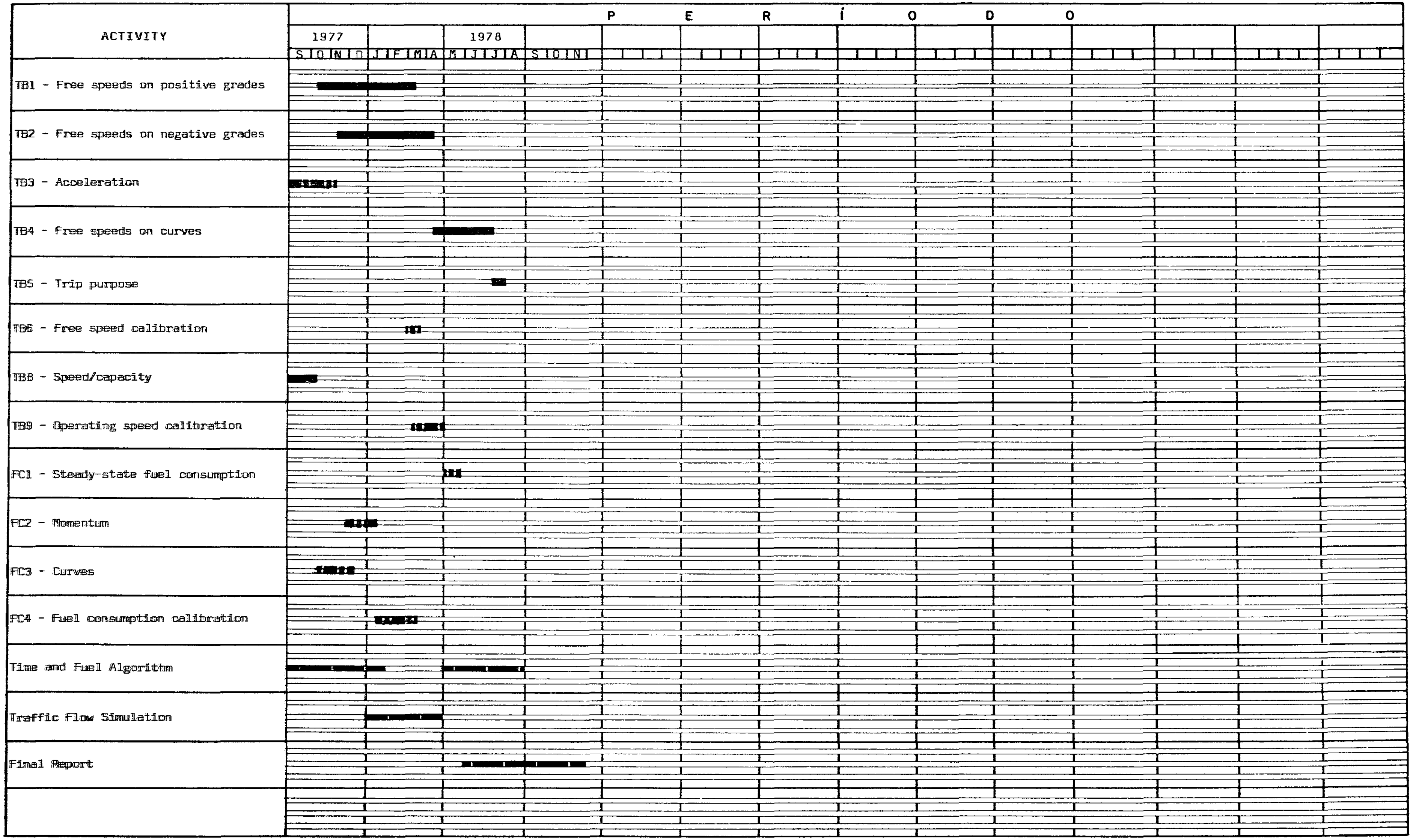
WORK PLAN AND SCHEDULE




LEGEND RADAR CREW ▬ FUEL CREW ▬ SENIOR STAFF ▬

FIG. 37

behavior experiments. By using both crews to work on these experiments, it should be possible to complete the traffic-behavior experiments by the end of July 1978. This time schedule does not allow for the performance of satellite studies.

As shown by the schedule, the senior staff of the group has three main activities scheduled. Modeling of the Time and Fuel Algorithm is scheduled in two phases. The first phase, ending in January 1978, will be the basic development and programing. Because the results from the traffic-flow simulation model and the analysis of some of the experiments will not be completed by this time. a second phase is scheduled for incorporating these results into the algorithm.

Implementation of the traffic-flow simulation model is scheduled for the first four months of 1978. At this time, it will be necessary to have Mr. Russ Kaesehagen return to the project for a period of about one month. This is necessary because Mr. Kaesehagen has done some development work on the model since leaving the project.

Six months have been scheduled for writing the final report. As the work plan shows, there is overlap between the end of the experiments, the modeling of TAFA, and the writing of the final report. This indicates that the Road User Costs and Traffic Experiments Group is working on a very tight schedule and that minor delays in the collection or analysis of the data will lead to the elimination or reduction in scope of some of the later experiments.