Fuel Consumption and Emission Values For Traffic Models

U.S. Department
of Transportation

**Federal Highway
Administration**

FOREWORD

This report describes a new methodology used in the assessment of fuel consumption and emissions which reflects the "real-world" operating conditions of passenger vehicles. As a result of the study, tables and graphs which show the relationship between fuel consumption and emissions as a function of speed and acceleration were developed.

This study was conducted for the Federal Highway Administration (FHWA), Office of Safety and Traffic Operations Research and Development under contract DTFH61-82-Y-30005, and covers the period of research from January 1982 to May 1985.

Although this study was initiated with the objective of updating the fuel consumption and emission algorithms embedded in traffic models, the quality and uniqueness of the study's results have numerous applications.

Acknowledgement is given to Dr. G. F. Roberts and Mr. B. E. Peterson who provided consultation to the project. A special thanks is given to Captain Sapp and Sergeant Caldwell and other personnel at the Arnold Air Force Station for making their facility available which made the on-road testing possible.

Because of the limited publication of this report, distribution is limited to one copy to each FHWA Regional and Division Office.

Stanley R. Byington, Director
Office of Safety & Traffic
Operations R&D

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16. Abstract

This report documents the methodologies used in the development of fuel consumption and emission maps for 15 passenger vehicles representative of 64 percent of the 1980-1992 population.

From the results of this study, the Federal Highway Administration is currently updating the fuel consumption and emission estimation algorithms in traffic models such as NETSIM and TRANSYT-7F. These results include tables and graphs which relate fuel consumption and emissions to vehicle speed and acceleration.

The major achievement of this study was the capability of combining laboratory (dynamometer) testing with on-road testing to assess the energy and environmental characteristics of passenger vehicles as they operate in "real-world" conditions.

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TABLE OF CONTENTS

iii

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (Continued)

PHYSICAL UNITS NOMENCLATURE

cc	cubic centimeters
CID	cubic inch displacement
°F	degrees fahrenheit
ft	foot
ft/s	feet per second
ft/s^2	feet per second squared
g	acceleration of gravity (32.2 ft/s^2)
gal/h	gallons per hour
gal/hr	gallons per hour (used in fuel consumption tables)
kPa	kilo-Pascals (6.9 kPa = 1 psi pressure)
km/h	kilometers per hour
km/ℓ	kilometers per liter
ℓ	liter
mg/s	milligrams per second
mℓ	milliliter
mℓ/s	milliliters per second
mpg	miles per gallon
mph	miles per hour
ppm	parts per million
rpm	revolutions per minute
µg/s	micrograms per second

1.0 INTRODUCTION

1.1 BACKGROUND AND OBJECTIVES

Since the early 1970's the assessment of the energy and environmental impacts of highway transportation has been a national need and concern. Breakthroughs in technology, achieved by automotive engineers, have provided in the market-place more energy-efficient vehicles. Today, automobiles averaging 25 to 35 miles per gallon (10.6 to 14.8 km/£) are common. However, problems relative to the new fleet of cars still remain for the transportation engineer, e.g., how to assess and predict vehicular fuel consumption in any given operating environment and how to enhance roadway designs and traffic control strategies in order to provide an environment where vehicles can operate more efficiently.

In order to maximize the efficiency and minimize the costs of such assessments, most transportation engineering agencies resort to the use of computer simulations. If one can carry out a study using accurate computer models, he obviously will save considerable time and money as opposed to conducting experiments to achieve the same objectives. The Federal Highway Administration (FHWA) and others have developed computer programs which evaluate geometric designs and traffic control strategies (primarily for urban areas) from environmental and energy conservation standpoints. Use of these models by many users has demonstrated their potential as effective tools in the development of traffic engineering measures that reduce motorist operating costs, fuel consumption, cost associated with planning, designing, and implementing new traffic control strategies, and costly and inconvenient retrofits when problems in a strategy are detected only after implementation. Although most of these computer programs have been developed sporadically over the last 10—15 years, most of them still utilize fuel consumption models which represent the fuel consumption characteristics of the 1960's and/or early 1970's vehicle fleet.

The energy crises of 1973—1974 and 1979, in addition to the 1977 Clean Air Act Amendments, triggered changes in the vehicle manufacturing policy. New vehicles are small, lighter, cleaner, and most importantly, more energy-efficient. In a short time, these policy changes have made the existing fuel consumption models obsolete. Furthermore, the present fuel consumption models were developed in a laboratory environment using computer simulations. As a result, they have not reflected "real world" operating conditions.

The Federal Highway Administration, recognizing the need for more realistic and representative data on post-1980 vehicles with regard to their fuel consumption and emissions performance, sponsored the "Vehicle Testing Project" at the Oak Ridge National Laboratory (ORNL) in order to generate a new data base for the various computer models used by transportation engineers. Specific objectives of the project for ORNL were as follows:

1. Test fifteen modern vehicles for fuel consumption and create data-based simulators of those vehicles (i.e. computer models of the fuel consumption characteristics of the fifteen vehicles) from which the fuel consumption tables required for the FHWA highway models could be generated. Addtionally, correction factors for road grade and ambient temperature effects that can be applied to the base fuel consumption tables were to be determined.

2. For each of the fifteen test vehicles, measure the difference in fuel consumed by stopping and restarting the engine as opposed to letting the engine idle. From these results, determine for how long the vehicle would have to idle before it uses more fuel than it would if the engine were shut off and restarted.

3. From the fifteen vehicles above test six of them for hydrocarbon (HC), carbon monoxide (CO), and oxides of nitrogen (NO_x) emissions. In the same fashion as with fuel consumption, create data-based simulators and tables for use in FHWA's computer programs.

4. For each of the six vehicles tested for emissions, measure the difference in emissions resulting from stopping and restarting the engine as opposed to letting it idle. From these results, determine for how long the vehicle would have to idle before it produces more emissions than if the engine were shut off and restarted.

Following this section is a discussion on the general approach and rationale used in order to achieve the above objectives. Then specific procedures will be discussed in some detail, followed by a general discussion of the results with sample results used to demonstrate the product of the work.

1.2 GENERAL APPROACH

Recognizing the need not only for an improved and updated data base for fuel consumption and emissions but also a need for the results of this project to have relevance to the U.S. passenger vehicle population, the FHWA carefully selected the fifteen vehicles to be tested. Based on an exhaustive study by the FHWA, it was determined that a judicious choice of the fifteen vehicles to be tested could have great significance in terms of the representation of those fifteen from the domestic fleet. In particular, it was determined that the fifteen vehicles (engine-drivetrain combinations) could represent between 57 and 66 percent of the 1979–1985 passenger vehicle population. The procedures and rationale for this selection are provided by Santiago [1983]. Vehicles to be tested in this project were obtained from local rental agencies with the exception of one, which was a government car in service at ORNL.

Because the approach used in this project to develop data-based models of fuel consumption and emissions from "real world" conditions is unique (i.e. the authors are unaware of previous uses of the same procedure for such large data bases), it is appropriate to elaborate on the details of the approach. A requirement of this project is that the fuel consumption data developed <u>must</u> reflect the fuel consumption of the vehicle as it operates in <u>realistic</u>, "real world," conditions. This requirement is accomplished only by the inclusion of on-road testing within the approach.

In the past, research has been oriented toward developing fuel consumption and emission data from computer simulations of engine performance or chassis dynamometer testing. These approaches produce accurate maps that describe the performance of the engine <u>exclusively</u> and not the performance of the vehicle as it operates on the <u>road</u>. This, then, justifies developing data from field experimentation.

The engine and the vehicle must be analyzed as two separate systems because the engine is the element that actually consumes fuel and the vehicle is the medium by which loads are applied to the engine. Accordingly, then, there are two basic premises upon which the entire approach to this project and all of the procedures are based:

(1) Fuel consumption (or emissions rate) is a unique function of engine speed and intake manifold vacuum (or throttle/rack position in the case of diesel engines).

(2) Engine speed and intake manifold vacuum are determined by the vehicle's operating condition, i.e. vehicle speed and acceleration and transmission gear.

Two data bases, then, are required for each vehicle in order to produce the final desired data-based simulators which yield fuel consumption (or emissions) as a function of vehicle speed and acceleration:

(1) A data base developed from chassis dynamometer tests, which relates fuel consumption to engine speed and intake manifold vacuum. This data base describes only the engine's performance.

(2) A data base, developed from road tests, which relates engine speed and manifold vacuum to vehicle speed and acceleration and ambient temperature. This data base describes how the vehicle's performance imposes loads and operating conditions on the engine.

Note that the common factors between the two data bases are the engine speed and intake manifold vacuum. It is this commonality that allows one to bring the two separate data bases together into one. The final operation in this approach uses the computer to merge the two data sets in order to produce the final result, i.e. fuel consumption (or emissions) as a function of vehicle speed and acceleration.

As an aid to the reader in understanding the general approach, Figure 1 is offered as a block diagram which illuminates the approach as well as some of the details of when and where parts of the procedures took place in the testing of a single vehicle.

Following the logic presented in the block diagram of Figure 1, one can see that the two data bases referred to above are generated in the middle portion of the work on each vehicle. The University of Tennessee (UT), operating under subcontract to ORNL, carried out all chassis dynamometer work on their own facilities. In addition, UT performed the functions of installing the instrumentation and data acquisition systems on each vehicle as well as helping with the road tests when necessary.

On-road tests were carried out on an Air Force runway at Arnold Air Force Station in Tullahoma, Tennessee. Using the runway was attractive for many reasons: the tests required high speeds and high accelerations as well as decelerations from high speeds, all of which would be dangerous if carried out on public roads; the smooth and level pavement of the runway increased the accuracy of the data from the fifth wheel (vehicle velocity and acceleration). The runway used was 6000 ft in length with zero grade thereby precluding any influence of hills or grades on the data. The testing on the runway introduces the "real world" character to this project because the data were obtained on the vehicles while they were being exercised through actual driving with aerodynamic drag and real rolling resistance being factors in the tests rather than being simulated or approximated during dynamometer tests.

An obvious question which should occur to the reader at this point is the following: as long as on-road tests are necessary to characterize the "real world" situation, then why not measure the fuel consumption on the runway and omit the chassis dynamometer tests entirely? There are two very good answers to this question:

(1) Emissions testing must be carried out in a chassis dynamometer laboratory because good portable emissions analyzers simply do not exist.

(2) On vehicles with mechanical carburetors, it is nearly impossible to measure the instantaneous fuel flow rate from the carburetor to the engine under most on-road operating conditions. This is a result of the combined effects of fuel sloshing in the carburetor bowl and the time lags induced by the filtering effects of the bowl. The chassis dynamometer, on the other hand, allows one to reach a steady-state engine operating condition and then measure the fuel flow to the carburetor while holding the steady-state condition. The measured fuel flow will then equal the flow from the carburetor to the engine.

It should be pointed out that although the logic in Figure 1 suggests that the dynamometer and road tests are parallel events, they can be parallel only in terms of the logic. Obviously, in the testing of a vehicle the dynamometer and road tests had to be performed sequentially.

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┌─────────────────┬──────────┐
│  Obtain Use of  │ Rental · │
│     Vehicle     │ Agency   │
└─────────────────┴──────────┘
          │
          ▼
┌────────────────────┬──────────────┐
│ Install Instrumentation │ University of │
│  and Vehicle Data     │ Tennessee (UT) │
│  Acquisition Systems  │              │
└────────────────────┴──────────────┘
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┌──────────────────────────────────┬────┐   ┌──────────────────────────────┬────────────┐
│ Test on Chassis Dynamometer to   │ UT │   │ Test On-Road to Establish   │ Air Force │
│ Establish Fuel Consumption   │   │   │ Vehicle Performance/   │ Runway at │
│ (Emissions) — Engine Speed   │   │   │ Engine Performance Data   │ Arnold Air │
│ and Vacuum Data Base   │   │   │ Base   │ Force   │
│   │   │   │   │ Station   │
└──────────────────────────────────┴────┘   └──────────────────────────────┴────────────┘

┌────────────────┬────────────┐
│ Merge Two Data │ ORNL   │
│ Bases   │ Computers │
└────────────────┴────────────┘

┌──────────────────────┬────────────┐
│ Produce Final Simulator │ ORNL   │
│ of Vehicle — i.e. Maps, │ Computers │
│ Tables, and Computer   │   │
│ Tapes of Simulators   │   │
└──────────────────────┴────────────┘

Figure 1. Block diagram of logic used in the approach for
                      vehicle testing.

The following sections deal with the experimental and analytical procedures utilized in this approach. Additionally, samples of the detailed results will be presented as well as some of the more global features of the results. The procedure and results for objectives 1 and 3 mentioned in the previous section are discussed in the body of the report, while those for objectives 2 and 4 are discussed in separate appendices.

2.0 PROCEDURES

2.1 EXPERIMENTAL PROCEDURES

Experimental procedures for both the dynamometer testing and the road testing are discussed below. A list of equipment used as well as detailed discussion of instrumentation installation is provided in Appendix B.

2.1.1 Dynamometer Testing

The dynamometer testing phases of this project involved several separate operations: (1) fuel consumption testing, (2) emissions testing, (3) restart testing for fuel consumption, and (4) restart testing for emissions. Each operation is discussed and summarized separately below.

2.1.1.1 Fuel consumption testing procedure

After installation of the necessary equipment, some preliminary checks were conducted, for example, the idle fuel flow rate was checked. It was discovered early in the project that if difficulties were to occur with the fuel measuring system, they would show up at the lowest flow rates (idle). In some cases the indicated idle flow rates were verified by actual volumetric measurements of the fuel consumed during a given time period.

The engine was "warmed up" by allowing it to operate until the coolant thermocouple indicated that the thermostat had opened, then testing began. The following sequence of tests was run:

Idling in Neutral: The transmission was placed in neutral and the engine speed was varied (by changing the throttle position). At each engine speed the datalogger was allowed to scan (and the data recorded) for about ten seconds. A manual plot of the resulting engine speed and manifold vacuum combinations was prepared as the data were being collected. The range of engine speeds required was determined either by examining the engine speed vs. manifold vacuum envelope generated from the road testing, or by making an informed estimate regarding the range of these variables that would be encountered on the road.

Locked Drive Axle: In this test the engine was loaded to the maximum possible continuous load by locking the drive axle and thus forcing the entire output of the engine to be absorbed by the torque converter. This test established the minimum attainable engine speed for a given throttle position (manifold vacuum). Care had to be exercised to ensure that the automatic transmission fluid temperature did not overheat.

Other Load Tests: The particular chassis dynamometer used features a control mode in which the operator can select a roller speed that the dynamometer will maintain so long as the absorption capacity of the unit is not exceeded. This feature was very useful in that the operator could set a given roller speed (and thus an engine speed) and manipulate the accelerator pedal to generate a range of intake manifold vacuums for that given engine speed. At each manifold vacuum setting the datalogger would scan the data for about ten seconds. Once the engine had been exercised over the desired range of manifold vacuums at a given engine speed, the roller speed would be increased and the process repeated for the new engine speed. Each speed-manifold vacuum combination was plotted on a graph to give immediate feedback regarding the adequacy of the coverage.

Coastdown Tests: The dynamometer used also featured a brake testing mode in which the rolls were powered at a speed of 77 miles-per-hour by two electric motors. By using this feature, the vehicle drive wheels were rotated at a speed equivalent to 77 mph, the throttle position was adjusted to give the desired intake manifold vacuum, and then the drive motors were turned off. In this fashion the engine gradually slowed down through a range of speeds for the given initial manifold vacuum — thus simulating a coastdown on the road. The process was repeated for different initial intake manifold vacuums ranging from the maximum (throttle completely closed) to the minimum (no coastdown occurred when the drive motors were turned off). These tests yielded engine speed/manifold vacuum profiles for engine coastdowns at various constant throttle settings.

2.1.1.2 Emissions testing procedure

The procedures used for the emissions testing are almost identical to those used in the fuel consumption testing and, in fact, the two tests could be (but seldom were) run simultaneously. The additional complexity of the emissions testing results from the additional instrumentation required: three emissions analyzers — one each for HC, CO, and NO_x and an air flow meter. The response times of the emission testers is such that a significantly longer period of time must elapse between the time that a vehicle operating point is established and the time that the readings on the emission testers have stabilized. Primarily because of this factor, the emission testing is much slower than the fuel consumption testing. The vehicle operation is essentially the same, but an assistant must monitor the emission testers and signal when the readings have stabilized. This assistant must also set the proper scale on each emission tester and set another couple of switches to "tell" the datalogger which scales are being used. Operation of the vehicle is the same as in the fuel consumption testing except that additional time must be allotted during the coastdown tests before the drive motors are turned off.

2.1.1.3 Restart tests (fuel consumption)

The restart tests for fuel consumption are normally conducted after the regular fuel consumption tests are finished. These tests consist of establishing the fuel flow rate with the engine idling in neutral (and also in "drive" for vehicles equipped with automatic transmissions); then stopping and starting the engine using the manufacturer's recommended procedure for starting a warm engine. Each restart cycle consists of idling for about six seconds, turning the ignition off, monitoring the fuel flow rate until it goes to zero, restarting the engine, and then another idling period of about ten seconds. The sequence was repeated for a total of ten cycles. The idle flow rates were then recorded again.

2.1.1.4 Restart tests (emissions)

The emission restart test was conducted only once per vehicle. In this test the exhaust from the vehicle tailpipe was collected for two identical periods of time: the first time with the engine idling in "drive" and the second with the engine idling in drive but with a shutdown and immediate restart conducted during the time period. The bag used to collect the emissions was initially evacuated and at time zero the exhaust hose carrying the engine exhaust was directed into the bag. At the end of the allotted time (usually about 60 seconds) the bag was sealed off. A sample of the bag's contents was then directed through the emission testers to determine the composition and then the volume of the bag was determined by pumping the contents out through a wet test meter. The results of the test consisted of the time, the concentrations of the emissions, and the bag volume. From these data the penalty (or benefit) from emissions considerations of stopping and restarting versus continuous idling can be determined.

2.1.1.5 Cautions during the experimental program

Dynamometer testing

Most of the precautions required during the dynamometer testing are associated with good safety practices in a typical vehicle testing laboratory and would be recognized as such by those accustomed to working in such an environment. At the risk of appearing too simplistic, however, the following list is offered:

1. Fire is an obvious hazard. Since fuel lines have to be broken, it is imperative that good workmanship and the proper materials be used to plumb the fuel meters into the system.

2. Damage to the vehicle is a real possibility when exercising it on a chassis dynamometer. Care must therefore be taken to make sure that the engine and/or transmission components are not thermally stressed beyond what is considered "normal" and that

full power runs are made taking into account the engine's expected speed operating range. Tires are stressed more heavily when contacting a set of rolls than when in contact with a relatively flat roadway and care must be taken to make sure that the drive tires are not overheating.

3. Care must also be exercised to make sure that the vehicle does not come out of the dynamometer rolls. This requires chocking the wheels not in the rolls and making sure that the vehicle operator uses smooth transitions to avoid rocking the vehicle out of the rolls. Front wheel drive vehicles are particularly vulnerable to oscillating from side to side and can come out of the rolls in this mode if care is not exercised. The University of Tennessee laboratory uses chains to restrain the vehicles so that this type of accident does not occur.

4. Another caution that falls in the safety area relates to the possibility of an engine throwing a drive belt or even losing a fan blade. The only way to guard against this to make sure no bystanders are in line with the front of the vehicle while it is being run.

5. Precautions related to the quality of the data require that the data be examined periodically to make sure that it "makes sense" in light of what is known about the behavior of engines. For example, any idle fuel flow rates in excess of 0.5 cc/second were immediately suspect. Any significant discrepancy between the engine speed as registered on the dynamometer's engine analyzer and the speed being displayed by the datalogger required some remedial action. At the completion of a test sequence the data tape was reviewed in the laboratory to make sure that the data was being recorded completely.

6. The success of the present program has to be attributed to a combination of elements. For the data-gathering phase of the project to be successful it was essential that a knowledgeable engineer be actively involved in the data-gathering. To support this effort required a flexible support structure of technicians who were able to assist in putting out "fires" as they occurred. In particular, it was gratifying to have access to a well-qualified electronics technician who could diagnose and repair electronic components.

2.1.2 Road Tests

2.1.2.1 Preliminary road tests

Prior to running the road tests on the runway at Tullahoma, preliminary tests were run on each vehicle for the purpose of gathering data used in a computer program which developed the runway test plan. These

preliminary tests were carried out on a state highway near ORNL with a straight, level stretch of about one mile in length. The cars, outfitted for the road tests, were taken to this stretch of highway, set up in a data-taking mode for road tests, and run in two procedures. First, data were recorded for wide-open-throttle operation from zero to about 60 mph on the level stretch. These data were taken twice — once in each direction. Then two coastdowns were recorded — again, one in each direction — from highway speed to a low speed of about 20 mph with the transmission in drive. All necessary precautions were taken during these runs on a public highway to ensure that our testing did not impose unsafe conditions on the normal traffic on the road. The data from these preliminary tests then served as the basis for creating a test plan for the runway tests, the description of which follows.

2.1.2.2 Development of a road test plan

A computer program generates the sequence of acceleration, deceleration and constant-speed test runs necessary to get data of adequate density in all parts of the simulated car's non-braking operating range. The maximum and coasting acceleration of the car at each speed are first approximated from the preliminary test runs, so as to delimit the operating region on the speed/acceleration plane. The computer program then calculates how many passes the car must make through each of many small portions of the operating region to achieve the desired density. Since data are sampled at a constant rate of about 20 readings per second, more passes are needed in high-acceleration parts of the operating region, through which the car passes very rapidly in a given test run. The computer program then determines a series of test runs that results in the desired number of passes through each portion of the operating region, each run specified by the initial and terminal speeds and the relative throttle opening. Special care is taken to observe the car's behavior at very low speeds, where it tends to accelerate at engine idle. The test runs are printed in random order to factor out the effects of engine temperature, wind, fuel tank load, etc. These procedures are described in greater detail in Rose et al. [1982].

An example of a computer-generated road test plan with associated driving instructions is given in Table 1. The particular example shown is for the Toyota Corolla with 1.8ℓ 4-cylinder engine. It shows that for this particular car 37 runs, including accelerations, decelerations, and steady speeds are sufficient to map the vehicle's on-road performance. Note that throttle position 8 is wide-open throttle, while 0 is closed throttle. Throttle positions be-tween 0 and 8 represent, of course, incremental fractions of wide-open throttle.

2.1.2.3 Road test procedures

In order to carry out the road tests on the runway, several conditions had to be met first:

Table 1. Sample road test plan.

Run	Throttle position	Speed range			
		km/h		mph	
1.	8	0.	80.	0.	50.
2.	?†	110.	110.	68.	68.*
3.	4	0.	90.*	0.	56.*
4.	1	0.	30.*	0.	19.*
5.	4	140.	130.*	87.	81.*
6	?	80.	80.	50.	50.
7.	6	0.	30.	0.	19.
8.	?	20.	20.	12.	12.
9.	?	0.	0.	0.	0.
10.	0	0.	0.*	0.	0.*
11.	0	140.	40.*	87.	25.*
12.	?	100.	100.	62.	62.
13.	8	0.	40.	0.	25.
14.	?	40.	40.	25.	25.
15.	3	140.	100.*	87.	62.*
16.	?	130.	130.	81.	81.
17.	?	10.	10.	6.	6.
18.	?	60.	60.	37.	37.
19.	7	0.	130.*	0.	81.*
20.	8	0.	50.	0.	31.
21.	6	0.	130.*	0.	81.*
22.	5	0.	40.	0.	25.
23.	?	90.	90.	56.	56.
24.	7	0.	70.	0.	43.
25.	?	50.	50.	31.	31.
26.	?	120.	120.	75.	75.
27.	8	0.	130.*	0.	81.*
28.	2	140.	80.*	87.	50.*
29.	3	0.	70.*	0.	43.*
30.	5	0.	120.*	0.	75.*
31.	7	0.	40.	0.	25.
32.	?	30.	30.	19.	19.
33.	2	0.	50.*	0.	31.*
34.	1	140.	60.*	87.	37.*
35.	6	0.	50.	0.	31.
36.	4	0.	30.	0.	19.
37.	?	70.	70.	43.	43.

*Throttle position should be such that steady state speed is approximately the final speed indicated. In any case, the run should continue until steady state speed is approached, although it is not necessary to go all the way to steady state, since it is covered by the constant speed runs.

†A question mark indicates that throttle position is unknown but should be such that the indicated steady speed is maintained.

(1) A road test plan (discussed in the previous section) had to be generated.

(2) Weather conditions in central Tennessee had to be expected to be within the acceptable limits during the day(s) that tests were planned. This meant rain- and snow-free days with temperatures between 30° and 70°F with no high wind conditions. (Unexpected weather conditions prevented testing or voided plans to test only two or three times during the course of the project.)

(3) Clearance to use the runway had to be obtained from the Air Force Operations Office at Arnold Center. There were only a few occasions when air traffic pre-empted testing.

With a car prepared for testing and with the above three conditions met then road testing could commence. The description of the routine that follows represents that which was most typical for the fifteen cars tested.

With the car outfitted properly, with equipment checked out, and with a test plan prepared for the vehicle, the trip to Tullahoma would begin around 9:00 am. Care was taken to fill the car's fuel tank just before the drive to Tullahoma in order to obtain gross data for the car's on-highway fuel economy. The drive to Tullahoma — about 160 miles — generally required about four hours including rest stops and lunch. Upon arrival in the Tullahoma area, the car would again be fueled so as to isolate the on-highway fuel economy from everything else. Generally, arrival at the runway area after all check-ins, clearances, etc. would occur at about 2:00 pm. Thus, the timing was appropriate for obtaining the hot afternoon road data which would be used in the temperature sensitivity study reported in Appendix E.

Once at the runway, all excess equipment (tools, spare equipment, etc.) had to be unloaded from the vehicle, and performance checks of all equipment were made. Generally, the equipment was checked out using AC power available at an outlet near the runway. This was done in order to preserve battery power as much as possible since, once on the runway, the on-board batteries would have to power all of the equipment.

The road test plan was run simply by following the instructions on the plan (Table 1 is a sample). Many times it was easy to "miss" the throttle setting called for in the test plan. Those occasions were simply noted and repeated later on when familiarity with the car's performance capabilities was at a higher level.

The most common problem encountered during these road tests were with the tape recorder and its erratic performance at times. Thus, the most important precaution that the driver had to exercise was to make sure that the tape recorder was operating properly at all times. This required almost constant attention. It was also important to take frequent looks at the data either by watching a particular channel

displayed continuously on the datalogger screen or by taking frequent "logs" on the datalogger which is a printout of the last data recorded in all channels. Anytime that a parameter was found to be out of nominal or expected limits, then it was necessary to stop the car, investigate, and adjust or repair as necessary. There were fairly frequent "mishaps" with equipment in the early stages of the project with the first few cars. But, as experience was gained, mishaps with any equipment other than the tape recorder were nearly nonexistent.

Another serious precaution that had to be exercised was diligent attention to the car's speed relative to the distance remaining on the runway. With many runs requiring coastdowns and given the fact that the cars had to be accelerated to the coastdown speed before the coastdown could begin, it was a real challenge with many of the cars to avoid running off the end of the runway while still obtaining the coastdown data.

After completing the test plan for the car, a series of coastdowns was run starting from about 80 mph (130 km/h) and coasting down to about 20 mph (32 km/h) with the transmission in neutral. These tests were performed in order to obtain data on the vehicle's drag coefficient and rolling resistance.

The time required to complete the test plan plus the additional coastdowns was about 2 1/2 hours — if no. problems were encountered. Typical length of time on the runway, including solving problems, was about 3 1/2 hours. Once the data-taking was finished, various checks were made to ensure that the data had, indeed, been recorded. Several times a computer terminal was taken along, and various portions of the data tape were played on the terminal as a check. But, eventually, it was found that if one were confident that the datalogger was programmed properly, and if all the tape marks could be found at the appropriate points on the tape, then one could be assured that the data had been recorded properly.

After the afternoon tests were finished, the vehicle was weighed at the Tennessee weigh station on I-24 near Tullahoma, and arrangements were made to have the batteries recharged during the night. The following morning, the goal was to get started on the runway by 7:00 am in order to capture most of the data during the cool morning hours. The procedures and routines in the morning were the same as for the previous afternoon. After completion of the morning tests, the return trip to the Oak Ridge-Knoxville area was made. Again, the car's fuel tank was carefully filled just before the highway trip in order to get a good measure of actual highway fuel economy.

2.1.2.4 Comparison of road and dynamometer tests

One of the most important objectives which had to be achieved with each vehicle was to ensure that the road test data set and dynamometer

data set were complementary and consistent. In other words, the dynamo-meter data must cover all of the same engine operating areas as encoun-tered in the road tests so that the computer mapping and merging of the two data sets could be successful. In order to accomplish this objec-tive plots of the engine manifold vacuum versus engine speed for both road tests and dynamometer tests were routinely compared very soon after the data were obtained. Such a plot from the road tests defines the actual operating regions of the engine. Therefore, data from the dyna-mometer had to cover the same areas of engine operation. This was a factor and consideration which received considerable attention during the course of testing of all of the vehicles. Figures 2 and 3 are plots of manifold vacuum versus engine speed for the Toyota Corolla from the road and dynamometer, respectively. Notice the good comparison of coverage between the two plots; which is the kind of good comparison that was necessary.

2.2 ANALYTICAL PROCEDURES

2.2.1 Analytical Procedures for Fuel Consumption Maps and Tables

Maps of fuel consumption as a function of vehicle speed and accel-eration are constructed for each transmission gear. The development of these maps has three main stages: use of chassis dynamometer tests to build a map of fuel flow vs. engine speed and intake manifold vacuum, preparation of data gathered on the road, and merger of the dynamometer and road data to produce maps of fuel flow vs. vehicle speed and accel-eration.

Since it is possible to measure instantaneous fuel flow rates only during steady-state operation, the rates are measured while the car to be simulated is mounted on a chassis dynamometer. In this first stage, the aim is to relate fuel flows to engine speed and manifold vacuum (or throttle opening, in the case of diesel engines). A few thousand obser-vations of fuel flow rate (corrected volumetrically for fuel temperature) at various speeds and vacuums are fitted with about 200 overlapping quadratic surfaces, each covering a portion of the speed/vacuum plane. The centers of the surfaces form a rectangular array when projected on the plane, and cubic splines parallel to either axis are run through these centers so as to determine a smooth, piecewise cubic surface. This surface represents fuel flow as a function of engine speed and vacuum and is stored in the computer as about 200 cubic polynomials in two variables. The operating region boundary is stored as about 50 cubic polynomials in one variable. See Figure 4 for an example of such a surface for the Toyota Corolla.

The second stage involves processing road test data so as to yield observations of engine speed and manifold vacuum at each of several thousand speed/acceleration pairs. This requires differentiating a smoothed speed reading to obtain acceleration, smoothing the other readings as necessary, adjusting for the fact that the four types of

15
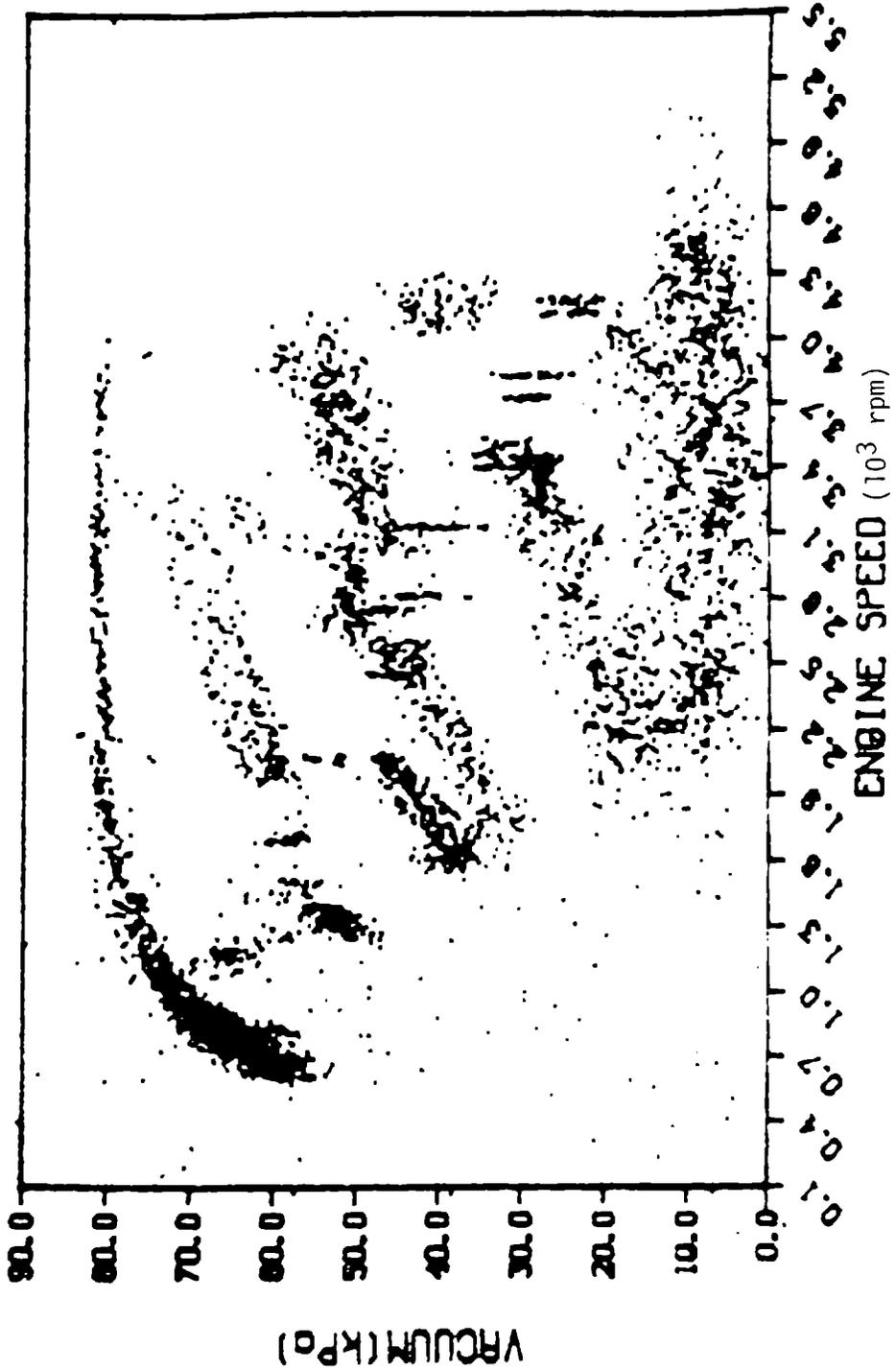
Figure 2. Manifold vacuum versus engine speed for Toyota Corolla — road tests.
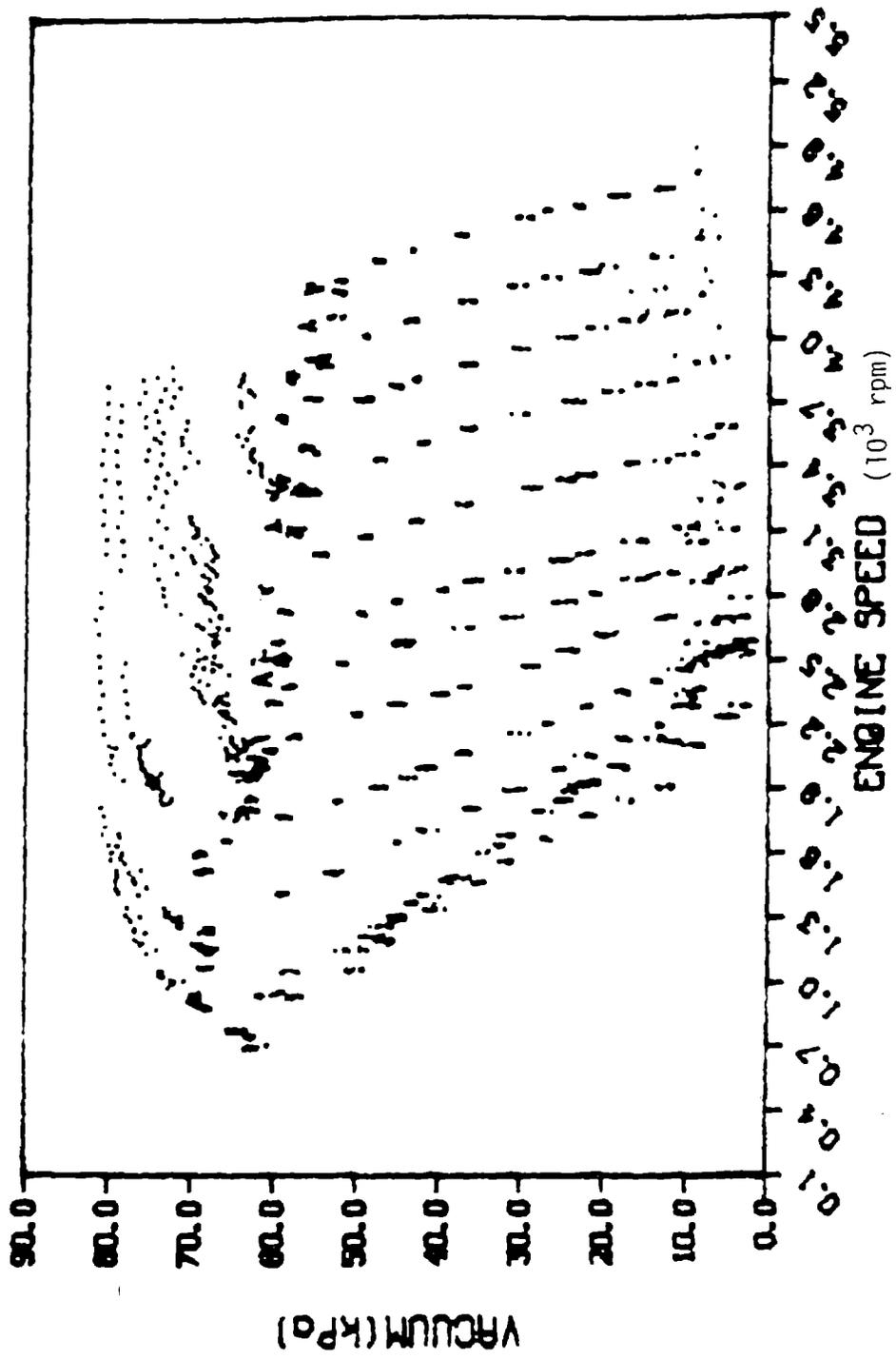
Figure 3. Manifold vacuum versus engine speed for Toyota Corolla — dynamometer tests.
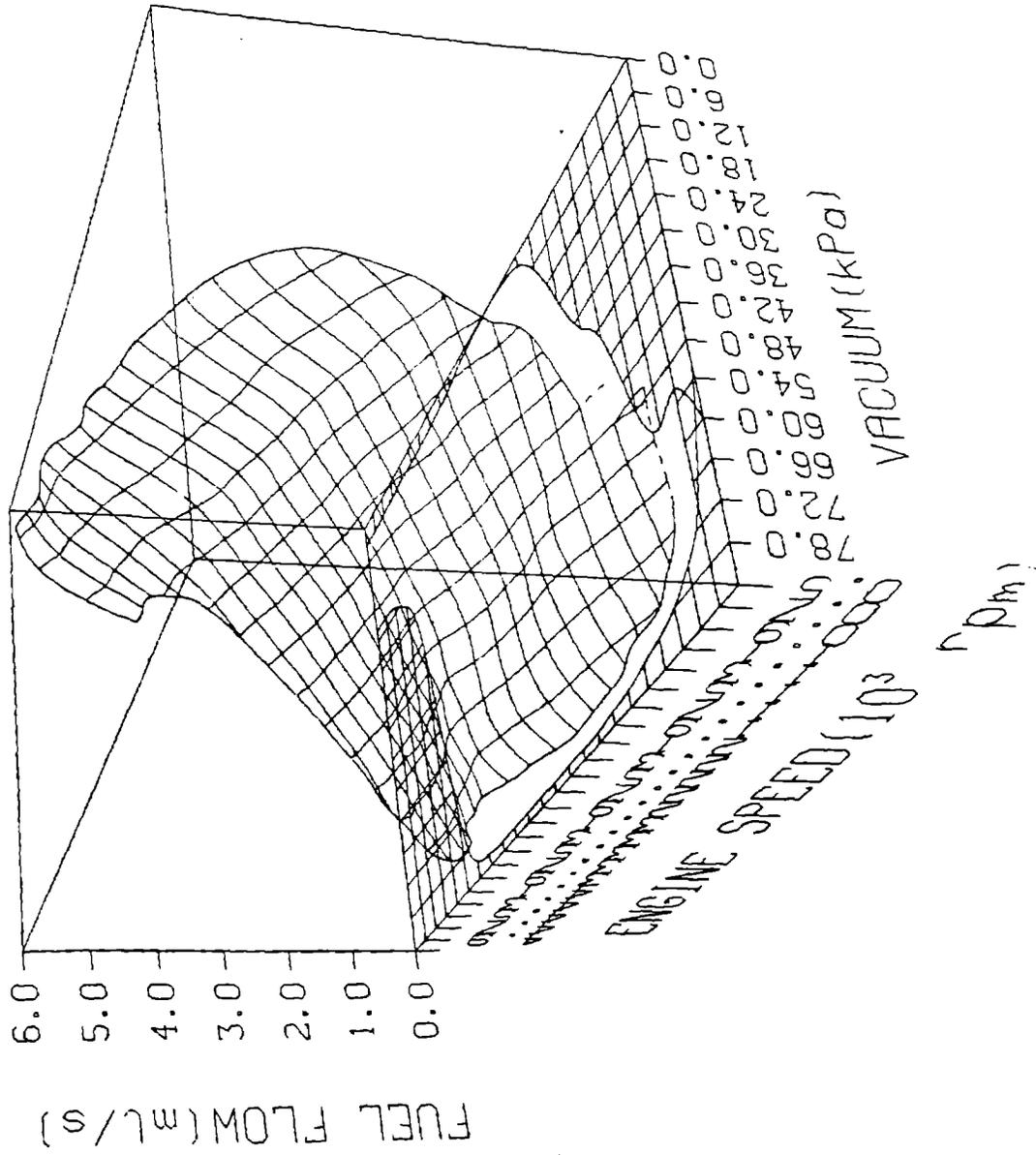
Figure 4. Fuel flow as a function of engine speed and manifold vacuum for the Toyota Corolla.

observations are made sequentially rather than simultaneously, and detecting gearshifts based on the behavior of vehicle speed, engine speed and manifold vacuum. The operating region of the car in each gear is inferred from the distribution of observations in the speed/acceleration plane. Figure 5 shows such inferences for the Toyota Corolla.

The final stage begins with a replacement of each engine/manifold vacuum measurement taken on the road with the corresponding fuel flow rate predicted by the cubic surface obtained in the first stage. The resulting data are used to construct for each gear a piecewise cubic surface that shows fuel flow rate as a function of vehicle speed and acceleration, using essentially the same technique as in the first stage. This time, however, the ambient temperature is made a third independent variable in the quadratic regression, so as to correct for its effect. The resulting surfaces yield predictions of fuel flow rate at the average ambient temperature during the test period. Figures 6, 7, and 8 are samples of such surfaces for each gear for the Toyota Corolla. Regression analysis is then used to relate the difference between actual and predicted fuel flow rate to the ambient temperature, with the aim of providing an ambient temperature correction for the predicted fuel flow. In addition, tables of fuel flow rates are made by evaluating the appropriate cubic polynomials at a number of desired speeds and accelerations. A nonzero grade is simulated by adding to the desired acceleration (i.e. the table value of acceleration desired) the acceleration due to gravity times the sine of the angle of road slope. These procedures for constructing fuel consumption maps are more adequately described in Hooker, Rose and Roberts [1983a, 1983b]. Documentation of the simulation routines is found in Hooker [1984a, 1984b, 1984c].

2.2.2 Analytical Procedures for Emissions Maps and Tables

Maps of steady-state emissions as a function of vehicle speed and acceleration are made in much the same way as fuel consumption maps. Fuel flow and air intake rates and temperatures are monitored during chassis dynamometer tests, as are the concentrations of hydrocarbons (HC), carbon monoxide (CO) and oxides of nitrogen (NO_x) in the exhaust gases. The partial pressures of nitrogen, oxygen and water vapor in the intake air are calculated, and a chemical equation is balanced to infer the mass flow rates (mg/s) of HC, CO and NO_x in the exhaust. The dependence of these flow rates on engine speed and manifold vacuum (or throttle opening) is captured in three piecewise cubic surfaces. On-road measurements of engine speed and vacuum are replaced with the emissions flow rates predicted by these surfaces so as to derive, for each gear, maps of HC, CO and NO_x mass flow rates vs. vehicle speed and acceleration. As before, these maps can be used to generate tables of flow rates for any desired road grade.

19
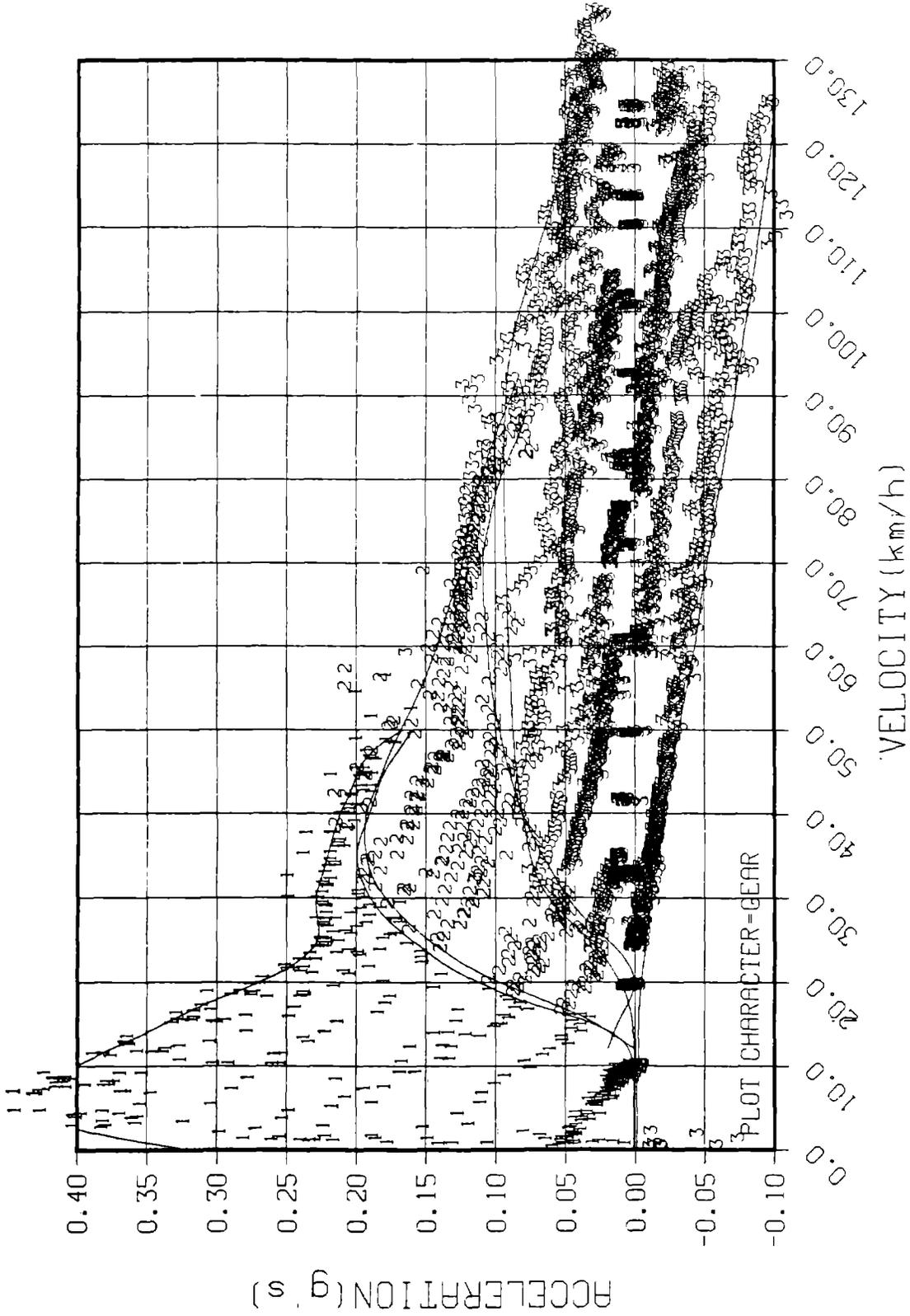
Figure 5. Vehicle speed versus acceleration for the Toyota Corolla with transmission ranges inferred and exhibited.
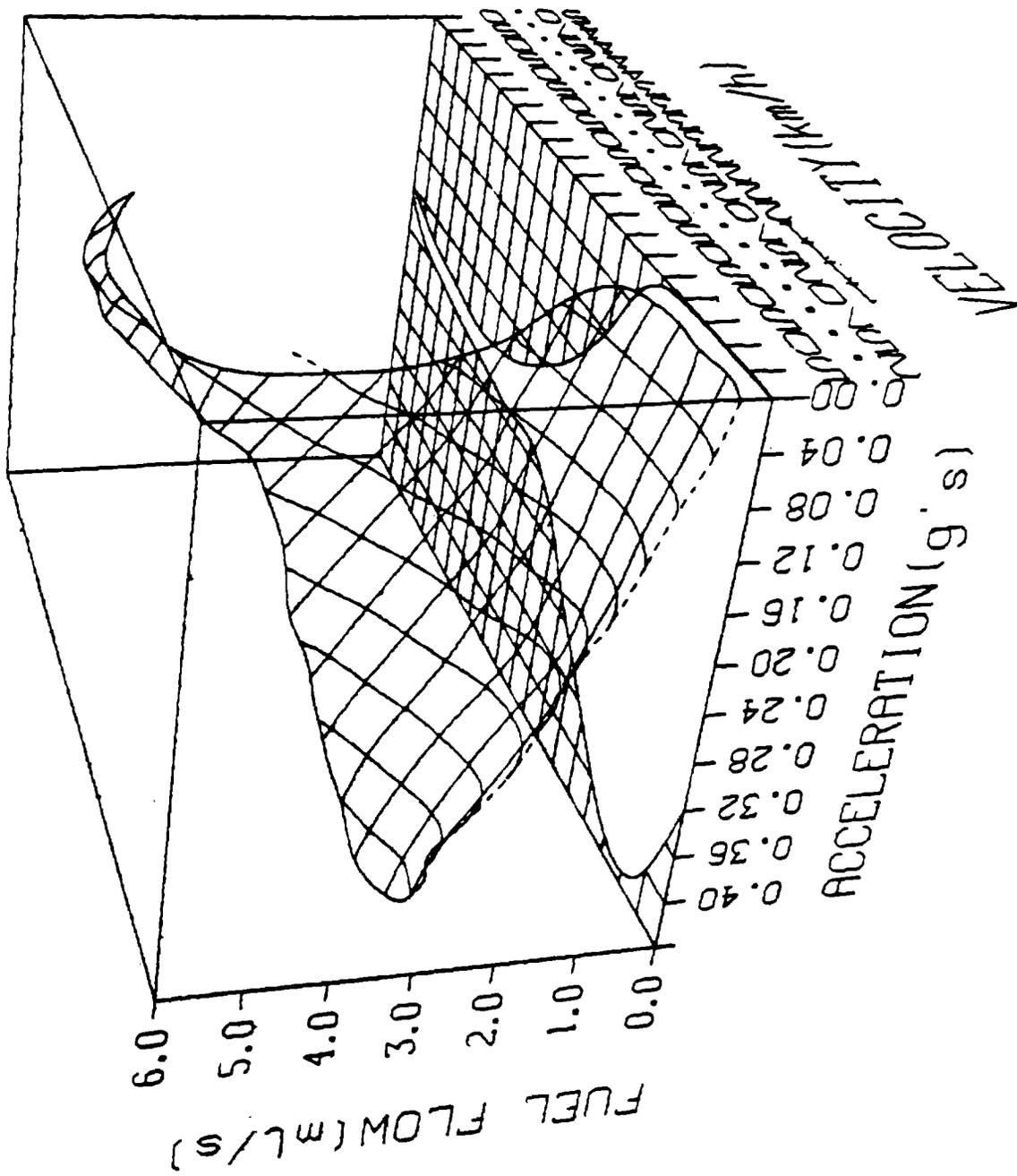
Figure 6. Fuel flow as a function of vehicle speed and acceleration — gear 1, Toyota Corolla.
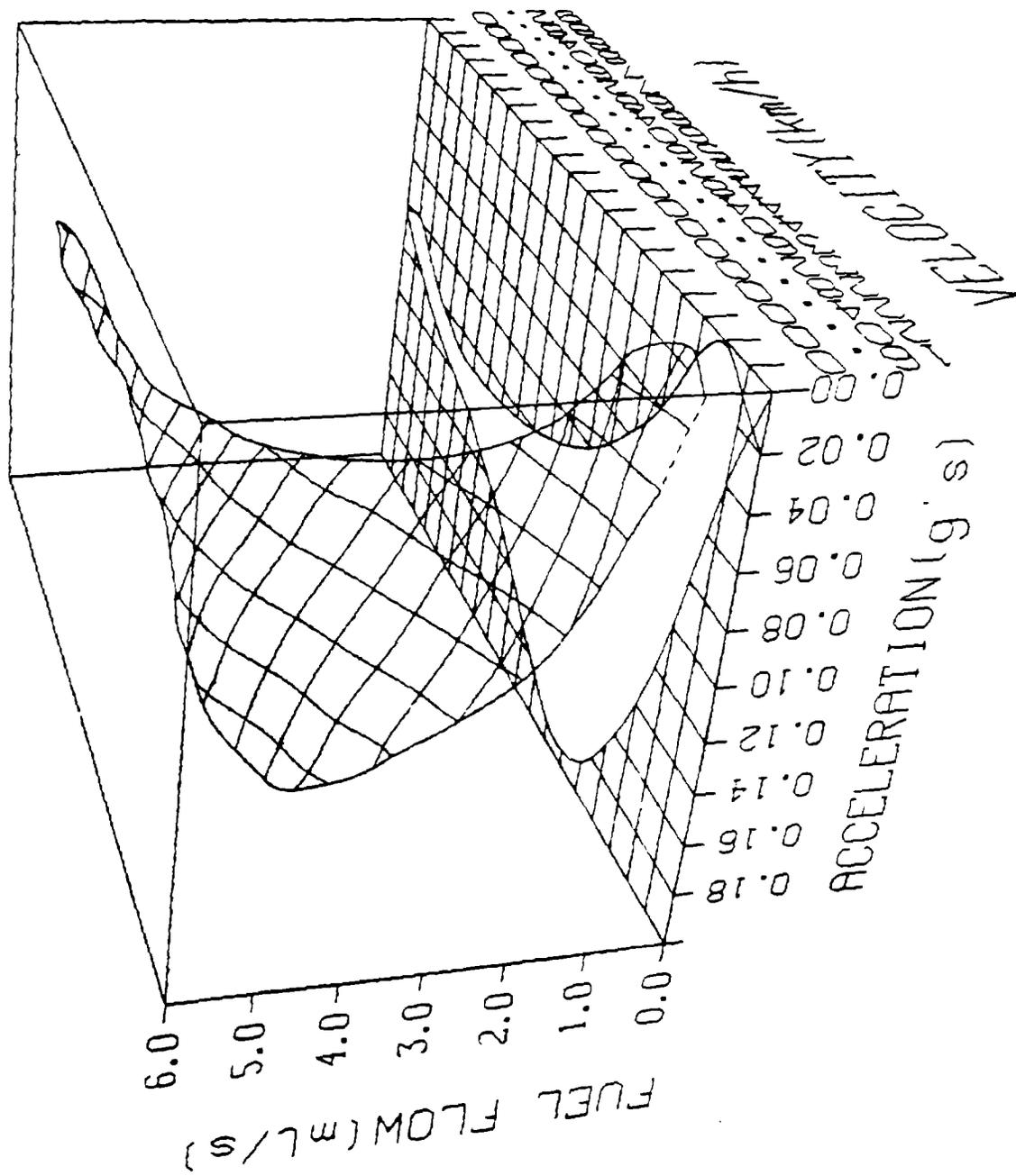
Figure 7. Fuel flow as a function of vehicle speed and acceleration – gear 2, Toyota Corolla.
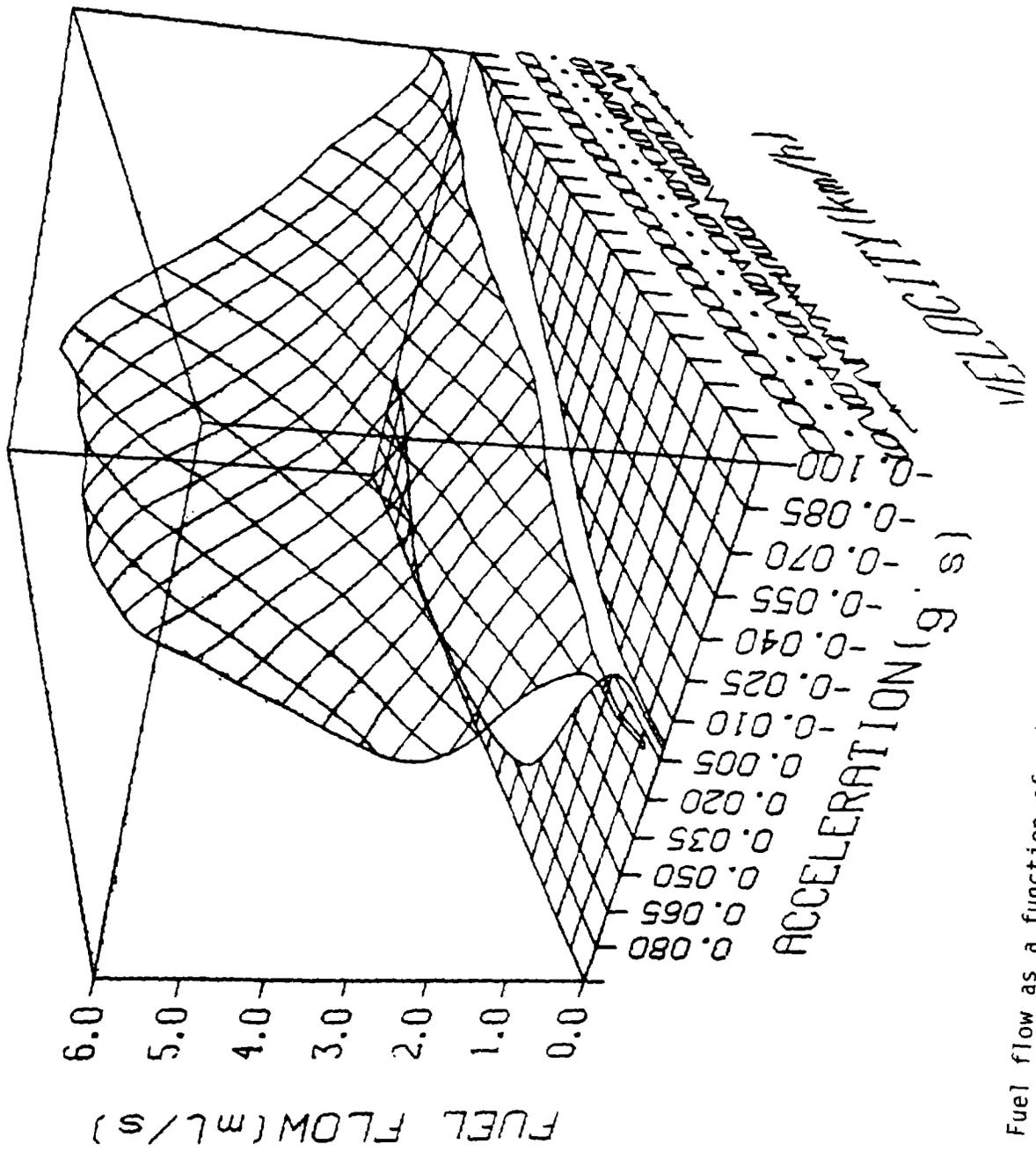
Figure 8. Fuel flow as a function of vehicle speed and acceleration — gear 3, Toyota Corolla.

23

Representation of the fuel consumption and emissions maps for a typical 4-speed automobile requires about 3000 cubic polynomials, containing some 45,000 coefficients. The software written to generate these polynomials consists of 22,000 lines of Fortran. The polynomials serve as input to the simulation software submitted to FHWA, which consists of another 7700 lines of Fortran. This brings the total body of software to nearly 30,000 lines.

Samples of the emissions results represented in three-dimensional surfaces will be presented in the next section on results.

3.0 RESULTS

Since it would require about 300 pages to present all of the
figures and tables that represent the results of this project, and since
all of those results plus computer tapes of the results have been deli-
vered to FHWA, no attempt will be made in this report to include all of
the results. Rather, only samples of the results will be presented. In
addition, some comparisons of general results from this project with
some other common measures of fuel consumption will be made in order to
demonstrate the validity of the data-based simulators developed for this
project.

All figures representing results from this project are contained in
Appendix F along with a "key to the plots," i.e. a legend for helping to
interpret the plots as well as their captions. All tables representing
results from this project are presented in Appendix G. Again, the
results to be presented in the body of this report represent only
samples of the wealth of results contained in Appendices F and G, while
those appendices themselves are not included here. Those readers
wishing to obtain copies of Appendices and F and G should request them
from FHWA.

Table 2 contains information about each of the vehicles tested
including model year and style of vehicle, engine type and size,
transmission type, and a notation as to which were tested for emissions.
Although it had been intended originally to test one or two vehicles
with manual transmissions, it turned out to be practically impossible to
rent any vehicle with manual transmission and much less likely to rent
one that was in the test plan. So, all of the vehicles had automatic
transmissions. The order in which the vehicles were tested is also
included in Table 2.

3.1 DESCRIPTION OF DELIVERABLE RESULTS

3.1.1 Fuel Consumption Simulators and Tables

As indicated previously, the real product of this project is a
data-based simulator of the fuel consumption of each vehicle as a func-
tion of vehicle speed and acceleration. These are piecewise continuous
cubic surfaces with vehicle fuel consumption as the dependent variable
and vehicle speed and acceleration as the independent variables for an
average ambient temperature. Figures 6, 7, and 8 were examples of these
surfaces for each gear for the Toyota Corolla, and other examples need
not be presented at this point. Suffice it to say that for each vehicle
tested the data-based simulators of the same type were created, stored
on tape, and sent to FHWA.

Table 2. List of vehicles tested.

Vehicle number	Make and model	Engine type	Engine size (ℓ)	Transmission type*	Emissions tests?
1	'82 Ford Fairmont	4 cyl.	2.3	A3	Yes
2	'82 Chevrolet Citation	4 cyl.	2.5	A3	No
3	'82 Ford Futura	6 cyl.	3.3	A3	No
4	'83 Plymouth Reliant	4 cyl.	2.6	A3	No
5	'82 Toyota Corolla	4 cyl.	1.8	A3	No
6	'83 Ford Escort	4 cyl.	1.6	A3	No
7	'83 Pontiac Firebird	V-6	2.8	A4	Yes
8	'83 Chevrolet Monte Carlo	V-6	3.75	A3	No
9	'82 Chevrolet Chevette	4-cyl. Diesel	1.8	A3	No
10	'81 Chevrolet Caprice	V-8 Diesel	5.7	A3	No
11	'83 Chevrolet Silverado Pickup	V-8 Diesel	6.2	A4	No
12	'82 Datsun 210	4 cyl.	1.5	A3LT	Yes
13	'82 Chevrolet Caprice Station Wagon	V-8	5	A4	Yes
14	'81 Buick Century	V-6	3.8	A3	Yes
15	'84 Chevrolet S-10 Pickup	4 cyl.	2	A4	Yes

*A3 = three-speed automatic,
A4 = four-speed automatic or three-speed with automatic overdrive,
A3LT = three-speed automatic with lock-up torque converter (must be treated as four-speed).

26

Tables of fuel consumption as a function of vehicle speed and acceleration were made for each vehicle by evaluating the appropriate cubic polynomials at a number of desired speeds and accelerations. A sample of one of these tables is presented as Table 3 — again, illustrating the results for the Toyota Corolla. (English units are used in these tables at the request of FHWA.) Fuel consumption is presented in gallons per hour for each speed and acceleration combination. Speed is subdivided in one foot/second increments from zero to 110 ft/s, while acceleration is subdivided in one foot per second squared increments from minus 5 ft/s^2 to 12 ft/s^2. Thus, for example, fuel flow rate for the condition of 20 ft/s velocity and 5 ft/s^2 acceleration is 2.33 gal/hr. For additional information, the cruise fuel economy figure in miles per gallon is listed for each speed (cruise equals zero acceleration). Also, a legend along the right side of the table called "Gear Distribution" indicates whether the vehicle is in a braking mode, or which gear the vehicle must be in, or whether the condition is outside the limits of operation of the vehicle (indicated by an A). Numerical values for fuel consumption are listed even in the areas where the vehicle cannot operate. Instead, the last accurate fuel consumption value in the vehicle's operating range in the same row of values is simply repeated. The symbols under the gear distribution are indexed to the acceleration columns — eighteen columns of acceleration corresponding with eighteen columns under gear distribution.

3.1.2 Emissions Simulators and Tables

Emissions simulators for each of the six vehicles tested were produced in the same way as fuel simulators except that considerably more data had to be handled for each vehicle as compared to one tested for fuel consumption alone. The cubic surfaces had to be created for each gear and for each exhaust emissions constituent — hydrocarbons, carbon monoxide, and oxides of nitrogen. Again, tables were generated just as for fuel consumption which presented emission rate as a function of vehicle speed and acceleration. Again, only samples of the results will be presented in this report. Figures 9 through 20 show results for the 1982 Chevrolet Station Wagon for each of the measured emissions and with each divided into transmission gear operating regions. Thus, four plots — for 1st, 2nd, 3rd, and 4th gears — are presented for each of the three emissions. Note that the emissions scales are logarithmic. This is to reduce the size of the plot but it also reduces the visual impact of just how much the emissions increase at very high loads. Basically, the emissions are nil at low and moderate engine loads, but when the high load regions are encountered (high acceleration and low speed) the emissions increase dramatically. For the sake of example, the table for HC emissions for this car (similar to the fuel consumption table example of Table 3) is presented as Table 4.

Table 3. Fuel consumption table for Toyota Corolla.

FUEL CONSUMPTION (GAL/HR) FOR 4-CYL TOYOTA COROLLA

BRAKE, GEARSHIFT AND MAX ACCEL BOUNDARIES INDICATED

B = BRAKE APPLIED   A = ACCELERATION OR SPEED EXCEEDS MAXIMUM

SPEED (FT/S)	ACCELERATION (FT/S/S) -5.	-4.	-3.	-2.	-1.	0.	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	CRUISE MPG	GEAR DISTRIBUTION
0.	.233	.233	.233	.233	.233	.233)	.456	.65	.86	1.03	1.23	1.52	1.73	1.89	2.14	2.50	2.63	2.63	0.00	BBBBB311111111111AA
1.	.239	.239	.239	.239	.239	.239)	.397	.57	.76	.92	1.09	1.31	1.50	1.67	1.91	2.24	2.64	2.77	2.85	BBBBB311111111111A
2.	.255	.255	.255	.255	.256	.256)	.368	.53	.70	.86	.98	1.17	1.33	1.51	1.77	2.06	2.38	2.64	5.33	BBBBB311111111111
3.	.276	.276	.276	.276	.278	.278)	.358	.51	.68	.82	.92	1.08	1.22	1.41	1.69	1.97	2.27	2.54	7.36	BBBBB311111111111
4.	.299	.299	.299	.299	.302	.302)	.362	.52	.68	.80	.93	1.03	1.15	1.36	1.67	1.98	2.26	2.51	9.02	BBBBB311111111111
5.	.319	.319	.319	.319	.324	.324)	.380	.53	.68	.80	.92	1.03	1.14	1.35	1.65	2.02	2.31	2.55	10.52	BBBBB311111111111
6.	.313	.313	.313	.313	.347	.347)	.409	.55	.69	.83	.94	1.06	1.19	1.39	1.72	2.08	2.38	2.64	12.04	BBBBB311111111111
7.	.339	.339	.339	.339	.347	.347)	.441	.57	.72	.87	.97	1.13	1.29	1.48	1.80	2.16	2.48	2.75	13.75	BBBBB311111111111
8.	.339	.339	.339	.339	.348	.348)	.473	.61	.75	.91	1.03	1.20	1.40	1.64	1.91	2.25	2.58	2.84	15.65	BBBBB311111111111
9.	.335	.335	.335	.335	.346	.346)	.51	.65	.80	.96	1.10	1.27	1.52	1.80	2.06	2.37	2.69	2.94	17.75	BBBBB311111111111
10.	.329	.329	.329	.329	.341	.341)	.54	.70	.86	1.03	1.19	1.34	1.60	1.92	2.20	2.51	2.82	3.06	19.99	BBBBB311111111111
11.	.323	.323	.323	.320	.337	.337)	.58	.76	.92	1.10	1.28	1.41	1.67	2.02	2.33	2.65	2.95	3.20	22.27	BBBBB311111111111
12.	.320	.320	.320	.319	.335	.335)	.63	.80	.98	1.17	1.34	1.51	1.78	2.13	2.46	2.78	3.09	3.25	24.40	BBBBB311111111111
13.	.319	.319	.319	.319	.337	.337)	.68	.85	1.04	1.24	1.39	1.64	1.95	2.27	2.59	2.90	3.21	3.28	26.28	BBBBB321111111111A
14.	.319	.319	.319	.319	.342	.342)	.66	.92	1.12	1.32	1.48	1.78	2.12	2.43	2.76	3.06	3.29	3.29	27.93	BBBBB321111111111A
15.	.321	.321	.321	.321	.340	.340)	.66	.99	1.20	1.41	1.61	1.94	2.29	2.61	2.95	3.20	3.36	3.16	29.37	BBBBB321111111111A
16.	.323	.323	.323	.323	.344	.356)	.691	1.12	1.25	1.48	1.74	2.08	2.44	2.79	3.06	3.29	3.44	3.44	30.65	BBBBB321111111111A
17.	.323	.323	.323	.323	.364	.364)	.73	.92	1.28	1.53	1.83	2.20	2.58	2.95	3.12	3.44	3.44	3.44	31.84	BBBBB322111111111A
18.	.319	.313	.319	.319	.371	.371)	.76	.94	1.16	1.62	1.93	2.33	2.73	3.10	3.43	3.43	3.43	3.43	33.08	BBBBB322111111111AAA
19.	.313	.313	.313	.313	.378	.378)	.80	.96	1.21	1.79	2.11	2.51	2.93	3.31	3.46	3.46	3.46	3.46	34.29	BBEBB322111111111AAA
20.	.306	.306	.306	.306	.385	.385)	.82	.99	1.26	2.08	2.33	2.72	3.14	3.52	3.52	3.52	3.52	3.52	35.40	BBEBB322111111111AAA
21.	.299	.299	.299	.299	.394	.394)	.85	1.03	1.32	1.73	2.50	2.90	3.31	3.57	3.57	3.57	3.57	3.57	36.32	BBEBB322221111AAAA
22.	.295	.295	.295	.293	.406	.406)	.88	1.07	1.38	1.82	2.60	3.02	3.44	3.61	3.61	3.61	3.61	3.61	36.97	BBEBB322221111AAAA
23.	.293	.293	.293	.293	.420	.420)	.82	1.12	1.44	1.90	2.18	3.13	3.56	3.67	3.67	3.67	3.67	3.67	37.37	BBBBB322221111AAAA
24.	.295	.295	.295	.295	.435	.435)	.84	1.16	1.51	1.98	2.62	3.27	3.68	3.78	3.78	3.78	3.78	3.78	37.60	BBBBB322221111AAAA
25.	.299	.299	.299	.299	.452	.452)	.86	1.20	1.58	2.05	2.68	3.42	3.79	3.90	3.90	3.90	3.90	3.90	37.68	BBBBB322221111AAAA
26.	.305	.305	.305	.305	.471	.471)	.88	1.25	1.65	2.18	2.74	3.57	3.87	3.97	3.97	3.97	3.97	3.97	37.64	BBBBB322221111AAAA
27.	.312	.312	.312	.312	.49	.49)	.90	1.30	1.73	2.22	2.84	3.74	3.95	4.02	4.02	4.02	4.02	4.02	37.50	BBBBB322221111AAAA
28.	.319	.319	.319	.319	.51	.51)	.93	1.25	1.81	2.32	2.96	3.90	4.04	4.10	4.10	4.10	4.10	4.10	37.29	BBBBB332221111AAAA
29.	.325	.325	.325	.325	.53	.53)	.95	1.30	1.89	2.42	3.07	4.08	4.16	4.20	4.20	4.20	4.20	4.20	37.02	BBBBB332221111AAAA
30.	.329	.329	.329	.329	.56	.56)	.98	1.35	1.98	2.51	3.16	3.77	4.27	4.31	4.31	4.31	4.31	4.31	36.72	BBBBB332222111AAAA
31.	.331	.331	.331	.331	.58	.58)	1.01	1.40	2.06	2.61	3.24	3.67	4.37	4.40	4.40	4.40	4.40	4.40	36.41	BBBBB332222111AAAA
32.	.329	.329	.329	.329	.60	.60)	1.04	1.44	2.13	2.71	3.30	3.77	4.45	4.47	4.47	4.47	4.47	4.47	35.86	BBBBB332222111AAAA
33.	.327	.327	.327	.327	.63	.63)	1.07	1.49	2.21	2.79	3.34	3.75	4.51	4.54	4.54	4.54	4.54	4.54	35.62	BBBBB332222AAAAAA
34.	.325	.325	.325	.325	.65	.65)	1.10	1.53	2.28	2.88	3.43	3.80	4.63	4.63	4.63	4.63	4.63	4.63	35.38	BBBBB332222AAAAAA
35.	.325	.325	.325	.325	.67	.67)	1.13	1.57	2.35	2.96	3.52	3.87	4.72	4.72	4.72	4.72	4.72	4.72	35.13	BBBBB332222AAAAAA
36.	.324	.324	.324	.324	.70	.70)	1.16	1.61	2.43	3.06	3.61	3.95	4.82	4.82	4.82	4.82	4.82	4.82	34.89	BBBBB332222AAAAAA
37.	.325	.325	.325	.325	.72	.72)	1.19	1.65	2.53	3.16	3.71	4.05	4.87	4.87	4.87	4.87	4.87	4.87	34.68	BBBBB333222AAAAAA
38.	.328	.328	.328	.328	.75	.75)	1.22	1.69	2.64	3.27	3.82	4.16	4.87	4.87	4.87	4.87	4.87	4.87	34.38	BBBBB333222AAAAAA
39.	.331	.331	.331	.331	.77	.77)	1.24	1.72	2.75	3.38	3.93	4.18	4.90	4.90	4.90	4.90	4.90	4.90	34.14	BBBBB333222AAAAAA
40.	.335	.335	.335	.335	.80	.80)	1.26	1.75	2.85	3.48	4.03	4.26	4.93	4.93	4.93	4.93	4.93	4.93	33.94	BBBBB333222AAAAAA
41.	.338	.338	.338	.338	.82	.82)	1.27	1.79	2.93	3.56	4.11	4.26	4.92	4.92	4.92	4.92	4.92	4.92	33.82	BBBBB333222AAAAAA
42.	.340	.340	.340	.340	.85	.85)	1.29	1.86	3.00	3.62	4.18	4.71	4.86	4.86	4.86	4.86	4.86	4.86	33.80	BBBBB333222AAAAAA
43.	.337	.337	.337	.337	.87	.87)	1.31	1.90	3.17	3.78	4.28	4.71	4.71	4.71	4.71	4.71	4.71	4.71	33.92	BBBBB333222AAAAAA
44.	.330	.330	.330	.330	.88	.88)	1.32	1.94	3.26	3.81	4.32	4.48	4.48	4.48	4.48	4.48	4.48	4.48	34.15	BBBBB333222AAAAAA
45.	.330	.330	.330	.330	.90	.90)	1.34	1.95	3.26	3.81	4.48	4.48	4.48	4.48	4.48	4.48	4.48	4.48	34.15	BBBBB333222AAAAAA
46.	.321	.321	.321	.321	.91	.91)	1.37	2.00	3.35	3.88	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.50	34.47	BBBBB333222AAAAAA
47.	.311	.311	.311	.311	.343	.92)	1.39	2.06	3.44	3.98	4.49	4.49	4.49	4.49	4.49	4.49	4.49	4.49	34.84	BBBBB333222AAAAAA

28

Table 3. Fuel consumption table for Toyota Corolla. (Continued)

SPEED (FT/S)	-5.	-4.	-3.	-2.	-1.	0.	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	CRUISE MPG	GEAR DISTRIBUTION
48.	.303	.303	.303	.303	.353	.93	1.42	2.11	3.53	3.99	4.47	4.46	4.46	4.46	4.46	4.46	4.46	4.46	35.23	BBBB3333222AAAAAAA
49.	.298	.298	.298	.298	.364	.94	1.44	2.17	3.60	4.04	4.45	4.45	4.45	4.45	4.45	4.45	4.45	4.45	35.62	BBBB3333222AAAAAAA
50.	.296	.296	.296	.296	.378	.95	1.47	2.22	3.66	4.07	4.45	4.45	4.45	4.45	4.45	4.45	4.45	4.45	35.96	BBBB3333322AAAAAAA
51.	.295	.295	.295	.295	.396	.96	1.49	2.28	3.72	4.10	4.45	4.45	4.45	4.45	4.45	4.45	4.45	4.45	36.23	BBBB3333322AAAAAAA
52.	.294	.294	.294	.294	.415	.97	1.52	2.39	3.77	4.13	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	36.41	BBBB3333322AAAAAAA
53.	.293	.293	.293	.293	.437	.99	1.55	2.39	3.82	4.15	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	36.51	BBBB3333322AAAAAAA
54.	.293	.293	.291	.291	.459	1.01	1.58	2.45	3.87	4.18	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	36.52	BBBB3333322AAAAAAA
55.	.296	.296	.296	.296	.482	1.03	1.61	2.50	3.92	4.22	4.46	4.46	4.46	4.46	4.46	4.46	4.46	4.46	36.43	BBBB3333322AAAAAAA
56.	.302	.302	.302	.302	.51	1.05	1.64	2.56	3.97	4.27	4.49	4.49	4.49	4.49	4.49	4.49	4.49	4.49	36.26	BBBB3333322AAAAAAA
57.	.312	.312	.312	.312	.53	1.08	1.68	2.61	4.04	4.34	4.52	4.52	4.52	4.52	4.52	4.52	4.52	4.52	36.00	BBBB3333322AAAAAAA
58.	.328	.328	.328	.324	.56	1.11	1.72	2.67	4.12	4.39	4.54	4.54	4.54	4.54	4.54	4.54	4.54	4.54	35.69	BBBB3333322AAAAAAA
59.	.338	.338	.338	.338	.59	1.14	1.75	2.73	4.20	4.44	4.54	4.54	4.54	4.54	4.54	4.54	4.54	4.54	35.34	BBBB3333322AAAAAAA
60.	.353	.353	.353	.353	.62	1.17	1.79	2.78	4.27	4.48	4.53	4.53	4.53	4.53	4.53	4.53	4.53	4.53	34.98	BBBB3333322AAAAAAA
61.	.367	.367	.367	.367	.65	1.20	1.84	2.84	4.34	4.51	4.54	4.54	4.54	4.54	4.54	4.54	4.54	4.54	34.61	BBEB3333322AAAAAAA
62.	.382	.382	.382	.382	.68	1.23	1.88	2.90	4.39	4.54	4.55	4.55	4.55	4.55	4.55	4.55	4.55	4.55	34.24	BBEB3333322AAAAAAA
63.	.397	.397	.397	.397	.71	1.27	1.92	2.95	4.03	4.56	4.56	4.56	4.56	4.56	4.56	4.56	4.56	4.56	33.86	BBBB3333322AAAAAAA
64.	.413	.413	.413	.413	.74	1.30	1.97	3.01	4.45	4.56	4.56	4.56	4.56	4.56	4.56	4.56	4.56	4.56	33.49	BBBB3333322AAAAAAA
65.	.430	.430	.430	.430	.77	1.34	2.01	3.07	4.47	4.56	4.56	4.56	4.56	4.56	4.56	4.56	4.56	4.56	33.12	BBEB3333 3AAAAAAAA
66.	.447	.447	.447	.447	.81	1.37	2.05	3.13	4.49	4.56	4.56	4.56	4.56	4.56	4.56	4.56	4.56	4.56	32.77	BBBB3333 3AAAAAAAA
67.	.465	.465	.465	.465	.85	1.41	2.10	3.20	4.51	4.55	4.55	4.55	4.55	4.55	4.55	4.55	4.55	4.55	32.42	BBBB3333 3AAAAAAAA
68.	.483	.483	.483	.483	.89	1.44	2.14	3.26	4.56	4.56	4.56	4.56	4.56	4.56	4.56	4.56	4.56	4.56	32.09	BBBB3333 3AAAAAAAA
69.	.50	.50	.50	.50	.93	1.48	2.18	3.32	4.61	4.61	4.61	4.61	4.61	4.61	4.61	4.61	4.61	4.61	31.78	BBBB3333 3AAAAAAAA
70.	.52	.52	.52	.52	.97	1.52	2.22	3.38	4.67	4.67	4.67	4.67	4.67	4.67	4.67	4.67	4.67	4.67	31.50	BBBB3333 3AAAAAAAA
71.	.54	.54	.54	.54	1.01	1.55	2.26	3.44	4.73	4.73	4.73	4.73	4.73	4.73	4.73	4.73	4.73	4.73	31.25	BBBB3333 3AAAAAAAA
72.	.56	.56	.56	.56	1.04	1.58	2.30	3.50	4.78	4.78	4.78	4.78	4.78	4.78	4.78	4.78	4.78	4.78	31.02	BBBB3333 3AAAAAAAA
73.	.57	.57	.57	.57	1.07	1.62	2.34	3.56	4.81	4.81	4.81	4.81	4.81	4.81	4.81	4.81	4.81	4.81	30.81	BBBB3333 3AAAAAAAA
74.	.58	.58	.58	.58	1.10	1.65	2.38	3.62	4.84	4.84	4.84	4.84	4.84	4.84	4.84	4.84	4.84	4.84	30.63	BBBB3333 3AAAAAAAA
75.	.58	.58	.58	.58	1.12	1.68	2.41	3.68	4.86	4.86	4.86	4.86	4.86	4.86	4.86	4.86	4.86	4.86	30.48	BBBB3333 3AAAAAAAA
76.	.58	.58	.58	.58	1.14	1.71	2.45	3.74	4.89	4.89	4.89	4.89	4.89	4.89	4.89	4.89	4.89	4.89	30.38	BBBB3333 3AAAAAAAA
77.	.59	.59	.59	.59	1.16	1.73	2.49	3.80	4.95	4.95	4.95	4.95	4.95	4.95	4.95	4.95	4.95	4.95	30.33	BBBB3333 3AAAAAAAA
78.	.60	.60	.60	.60	1.19	1.75	2.54	3.87	5.02	5.02	5.02	5.02	5.02	5.02	5.02	5.02	5.02	5.02	30.32	BBBB3333 3AAAAAAAA
79.	.60	.60	.60	.60	1.21	1.78	2.55	3.93	5.09	5.09	5.09	5.09	5.09	5.09	5.09	5.09	5.09	5.09	30.32	BBBB3333 3AAAAAAAA
80.	.62	.62	.62	.62	1.23	1.80	2.63	4.00	5.12	5.12	5.12	5.12	5.12	5.12	5.12	5.12	5.12	5.12	30.31	BBBB3333 3AAAAAAAA
81.	.63	.63	.63	.63	1.24	1.82	2.68	4.06	5.11	5.11	5.11	5.11	5.11	5.11	5.11	5.11	5.11	5.11	30.30	BBBB3333 3AAAAAAAA
82.	.65	.65	.65	.65	1.26	1.85	2.73	4.12	5.10	5.10	5.10	5.10	5.10	5.10	5.10	5.10	5.10	5.10	30.24	BBBB3333 3AAAAAAAA
83.	.66	.66	.66	.66	1.28	1.88	2.79	4.18	5.09	5.09	5.09	5.09	5.09	5.09	5.09	5.09	5.09	5.09	30.16	BBBB3333 3AAAAAAAA
84.	.67	.67	.67	.67	1.29	1.91	2.84	4.23	4.82	4.82	4.82	4.82	4.82	4.82	4.82	4.82	4.82	4.82	30.06	BBBB3333 3AAAAAAAA
85.	.67	.67	.67	.67	1.30	1.94	2.89	4.27	4.82	4.82	4.82	4.82	4.82	4.82	4.82	4.82	4.82	4.82	29.95	BBBB3333 3AAAAAAAA
86.	.66	.66	.66	.66	1.32	1.97	2.94	4.32	4.84	4.84	4.84	4.84	4.84	4.84	4.84	4.84	4.84	4.84	29.80	BBBB3333 3AAAAAAAA
87.	.64	.64	.64	.64	1.33	2.00	3.00	4.36	4.83	4.83	4.83	4.83	4.83	4.83	4.83	4.83	4.83	4.83	29.63	BBBB3333 3AAAAAAAA
88.	.63	.63	.63	.63	1.35	2.04	3.06	4.40	4.83	4.83	4.83	4.83	4.83	4.83	4.83	4.83	4.83	4.83	29.44	BBBB3333 3AAAAAAAA
89.	.61	.61	.61	.61	1.36	2.08	3.12	4.43	4.85	4.85	4.85	4.85	4.85	4.85	4.85	4.85	4.85	4.85	29.22	BBBB3333 3AAAAAAAA
90.	.60	.60	.60	.60	1.38	2.12	3.18	4.62	4.87	4.87	4.87	4.87	4.87	4.87	4.87	4.87	4.87	4.87	28.98	BBBB3333 3AAAAAAAA
91.	.59	.59	.59	.58	1.40	2.16	3.25	4.75	4.89	4.89	4.89	4.89	4.89	4.89	4.89	4.89	4.89	4.89	28.72	BBBB3333 3AAAAAAAA
92.	.58	.58	.58	.58	1.42	2.20	3.31	4.84	4.88	4.88	4.88	4.88	4.88	4.88	4.88	4.88	4.88	4.88	28.45	BBBB3333 3AAAAAAAA
93.	.60	.60	.60	.60	1.44	2.25	3.38	4.79	4.87	4.87	4.87	4.87	4.87	4.87	4.87	4.87	4.87	4.87	28.17	BBBB3333 3AAAAAAAA
94.	.59	.59	.59	.59	1.46	2.30	3.45	4.81	4.84	4.84	4.84	4.84	4.84	4.84	4.84	4.84	4.84	4.84	27.87	BBBB3333 3AAAAAAAA
95.	.60	.60	.60	.60	1.48	2.35	3.51	4.84	4.85	4.85	4.85	4.85	4.85	4.85	4.85	4.85	4.85	4.85	27.55	BBBB3333 3AAAAAAAA
96.	.61	.61	.61	.61	1.51	2.41	3.58	4.85	4.85	4.85	4.85	4.85	4.85	4.85	4.85	4.85	4.85	4.85	27.21	BBBB3333 3AAAAAAAA
97.	.62	.62	.62	.62	1.53	2.46	3.65	4.87	4.85	4.85	4.85	4.85	4.85	4.85	4.85	4.85	4.85	4.85	26.86	BBBB3333 3AAAAAAAA
98.	.62	.62	.62	.62	1.56	2.52	3.72	4.84	4.84	4.84	4.84	4.84	4.84	4.84	4.84	4.84	4.84	4.84	26.49	BBBB3333 3AAAAAAAA
99.	.61	.61	.61	.61	1.59	2.59	3.79	4.84	4.85	4.85	4.85	4.85	4.85	4.85	4.85	4.85	4.85	4.85	26.10	BBBB3333 3AAAAAAAA
100.	.61	.61	.61	.61	1.63	2.65	3.86	4.84	4.85	4.85	4.85	4.85	4.85	4.85	4.85	4.85	4.85	4.85	25.71	BBBB3333 3AAAAAAAA
101.	.59	.59	.59	.59	1.67	2.72	3.94	4.87	4.88	4.88	4.88	4.88	4.88	4.88	4.88	4.88	4.88	4.88	25.31	BBBB3333 3AAAAAAAA

Table 3. Fuel consumption table for Toyota Corolla. (Continued)

SPEED (FT/S)	ACCELERATION (FT/S/S)																			CRUISE MPG	GEAR DISTRIBUTION
	-5.	-4.	-3.	-2.	-1.	0.	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.		
102.	.58	.58	.58)	.97	1.71	2.79	a.01)a.91	a.91	a.91	a.91	a.91	a.91	a.91	a.91	a.91	a.91	a.91	a.91	24.92	BBB3333AAAAAAAAAA
103.	.56	.56	.56)	.99	1.75	2.86	a.09)a.93	a.93	a.93	a.93	a.51	a.93	a.93	a.93	a.93	a.93	a.93	a.93	24.56	BBE3333AAAAAAAAAA
104.	.55	.55	.55)1.02	1.80	2.93	a.16)a.95	a.95	a.95	a.95	a.95	a.95	a.95	a.95	a.95	a.95	a.95	a.95	a.95	24.23	BBF3333AAAAAAAAAA
105.	.54	.54)	.54)1.04	1.84	2.99	a.28)a.95	a.95	a.95	a.95	a.95	a.95	a.95	a.95	a.95	a.95	a.95	a.95	a.95	23.94	BB3333AAAAAAAAAA
106.	.54	.54)	.54 1.07	1.89	3.05	a.31)a.94	a.94	a.94	a.98	a.98	a.98	a.94	a.98	a.94	a.94	a.94	a.94	a.94	23.67	BB3333AAAAAAAAAA
107.	.54	.54)	.54 1.11	1.98	3.11	a.39)a.93	a.93	a.93	a.93	a.93	a.93	a.93	a.93	a.93	a.93	a.93	a.93	a.93	23.42	BB3333AAAAAAAAAA
108.	.54	.54)	.54 1.14	1.99	3.18	a.47)a.93	a.93	a.93	a.93	a.5?	a.93	a.93	a.93	a.93	a.93	a.93	a.93	a.93	23.18	BB3333AAAAAAAAAA
109.	.55	.55)	.55 1.18	2.05	3.24	a.58)a.95	a.95	a.95	a.95	a.95	a.95	a.95	a.95	a.95	a.95	a.95	a.95	a.95	22.92	BB3333AAAAAAAAAA
110.	.56	.56)	.56 1.23	2.10	3.31	a.61)a.97	a.97	a.97	a.97	a.97	a.97	a.97	a.97	a.97	a.97	a.97	a.97	a.97	22.66	BB3333AAAAAAAAAA

30

Figure 9. Hydrocarbon emissions — Chevrolet Station Wagon, gear 1.

Figure 10. Hydrocarbon emissions — Chevrolet Station Wagon, gear 2.
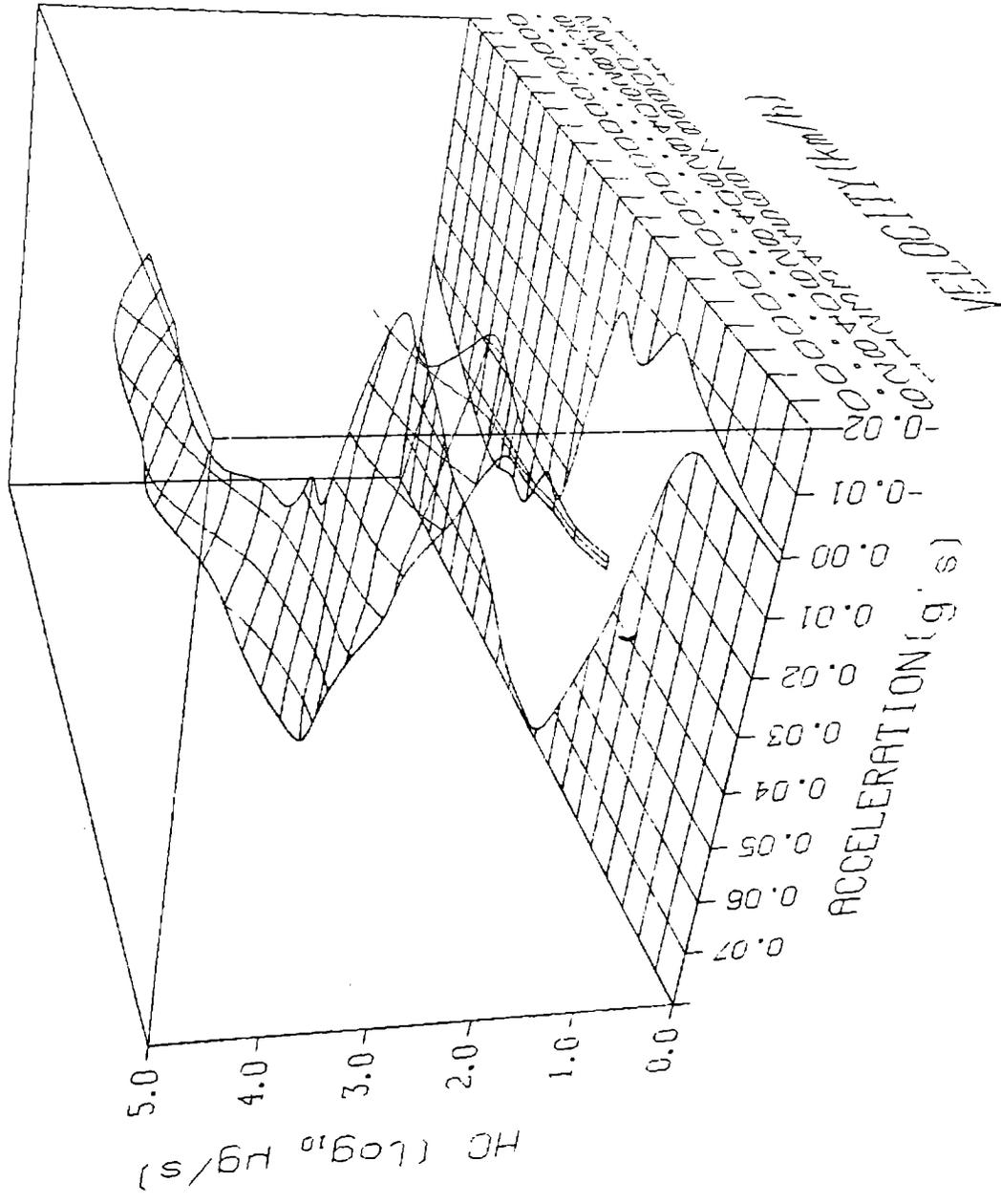
Figure 11. Hydrocarbon emissions — Chevrolet Station Wagon, gear 3.
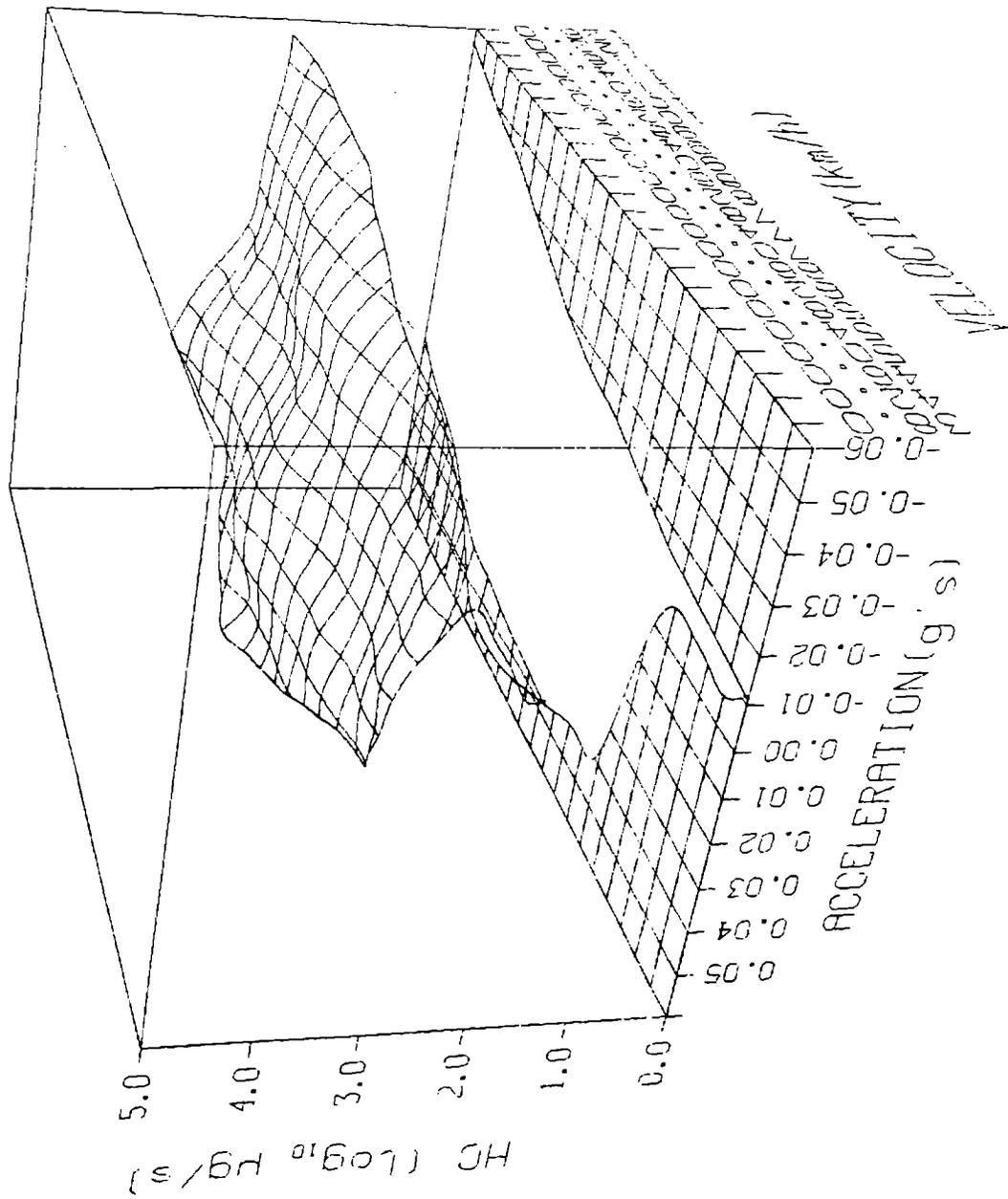
Figure 12. Hydrocarbon emissions — Chevrolet Station Wagon, gear 4.

Figure 13. Carbon monoxide emissions — Chevrolet Station Wagon, gear 1.

Figure 14. Carbon monoxide emissions — Chevrolet Station Wagon, gear 2.

Figure 15. Carbon monoxide emissions — Chevrolet Station Wagon, gear 3.

Figure 16. Carbon monoxide emissions — Chevrolet Station Wagon, gear 4.

38

Figure 17. Oxides of nitrogen emissions — Chevrolet Station Wagon, gear 1.

Figure 18. Oxides of nitrogen emissions — Chevrolet Station Wagon, gear 2.

40

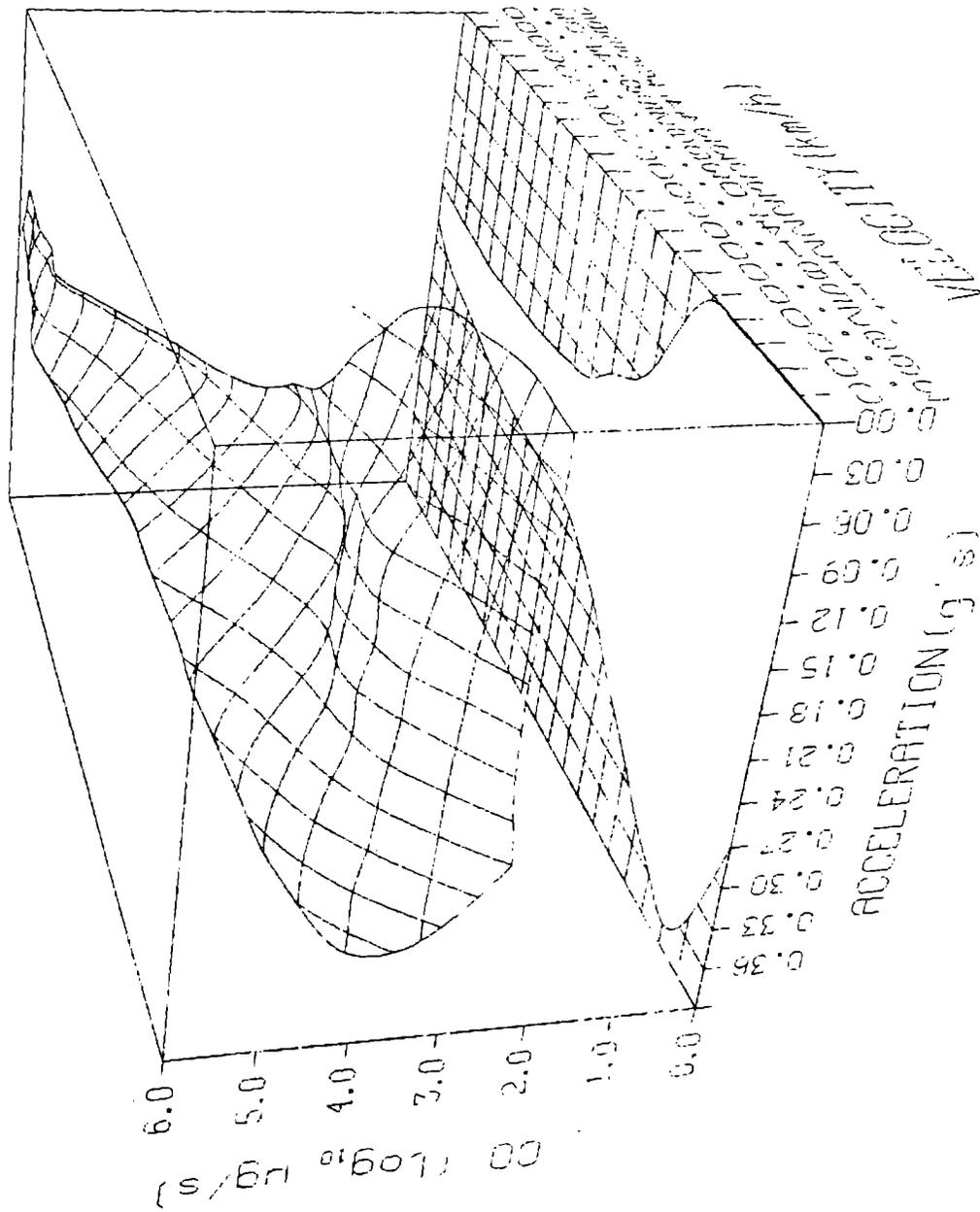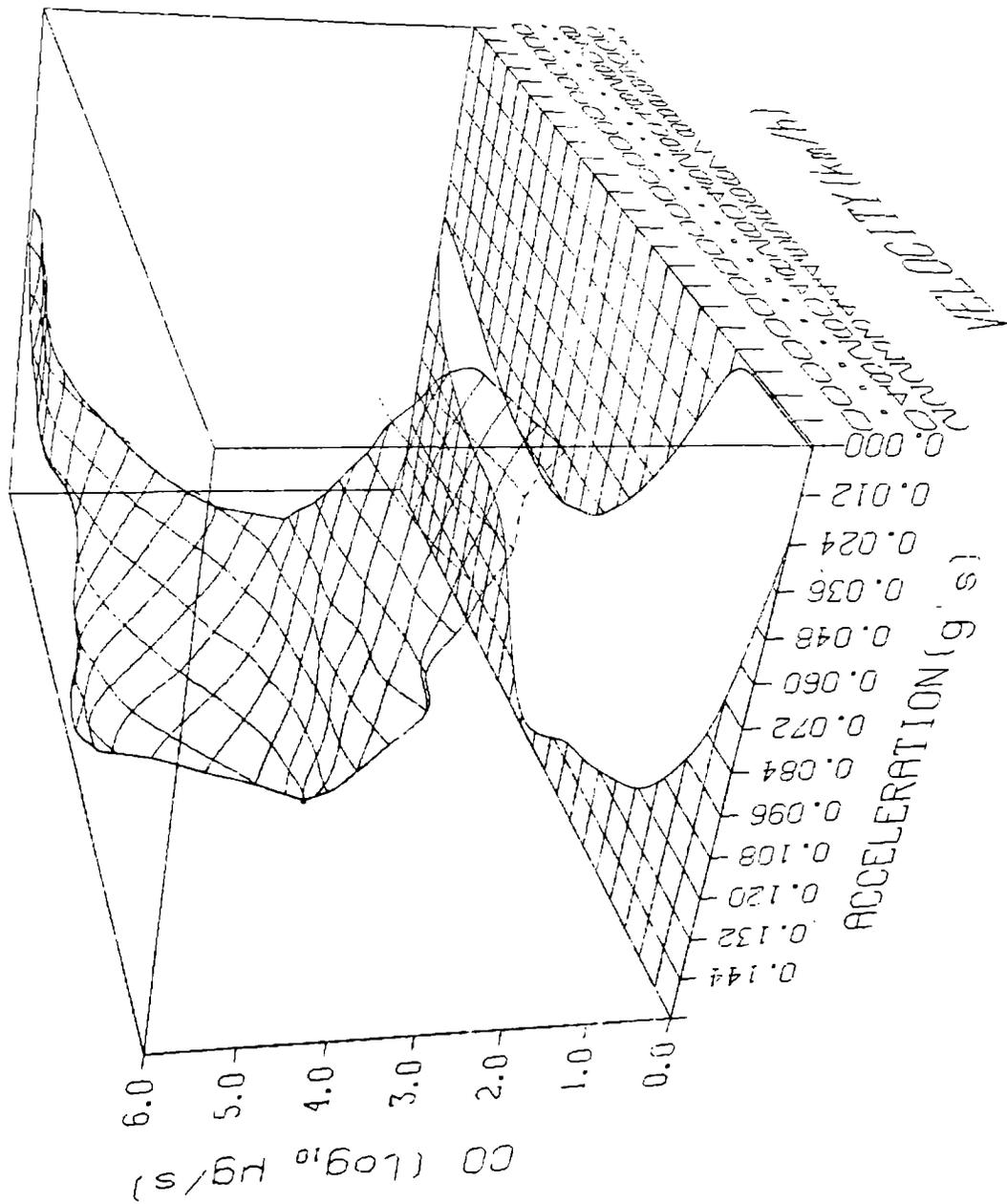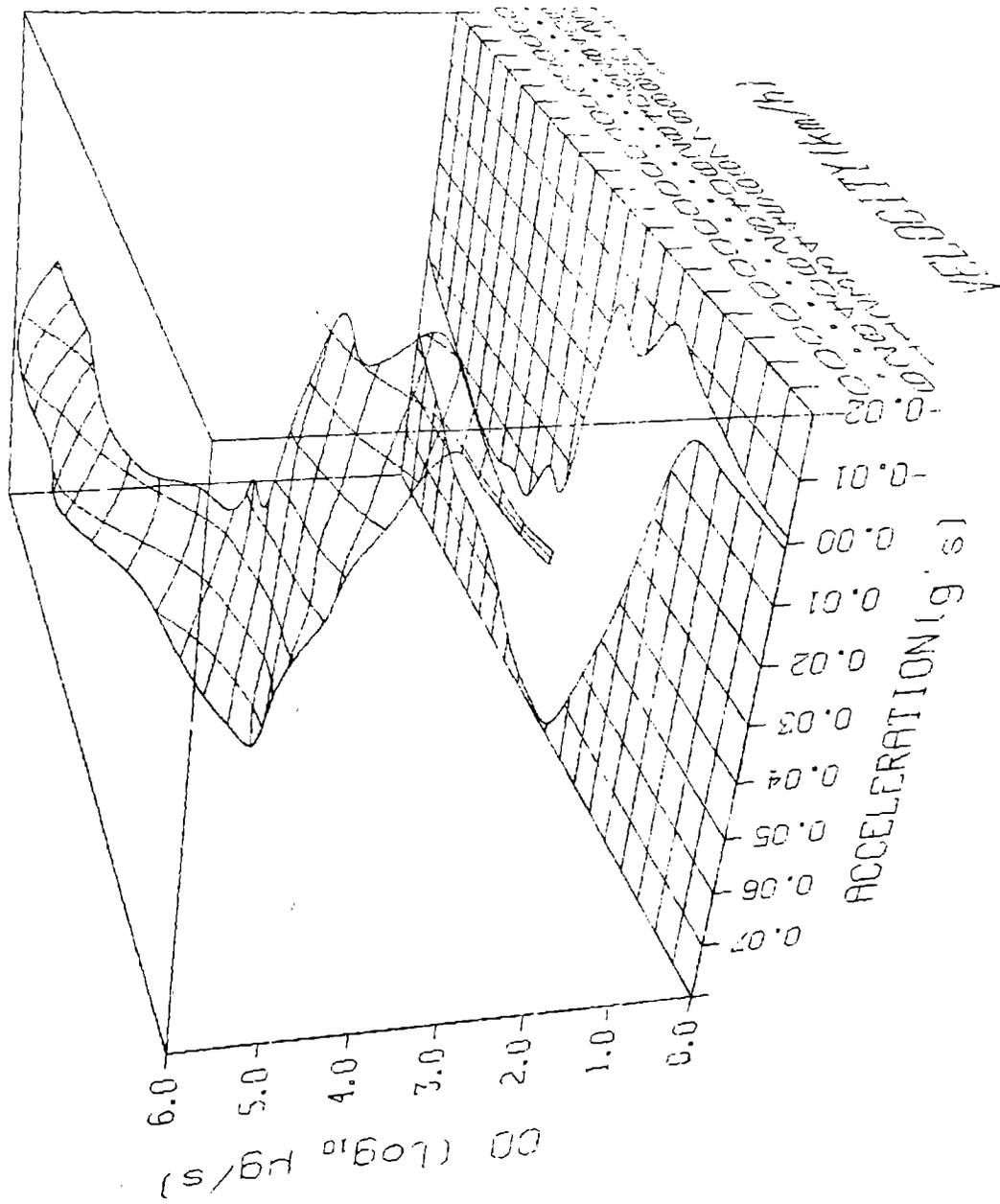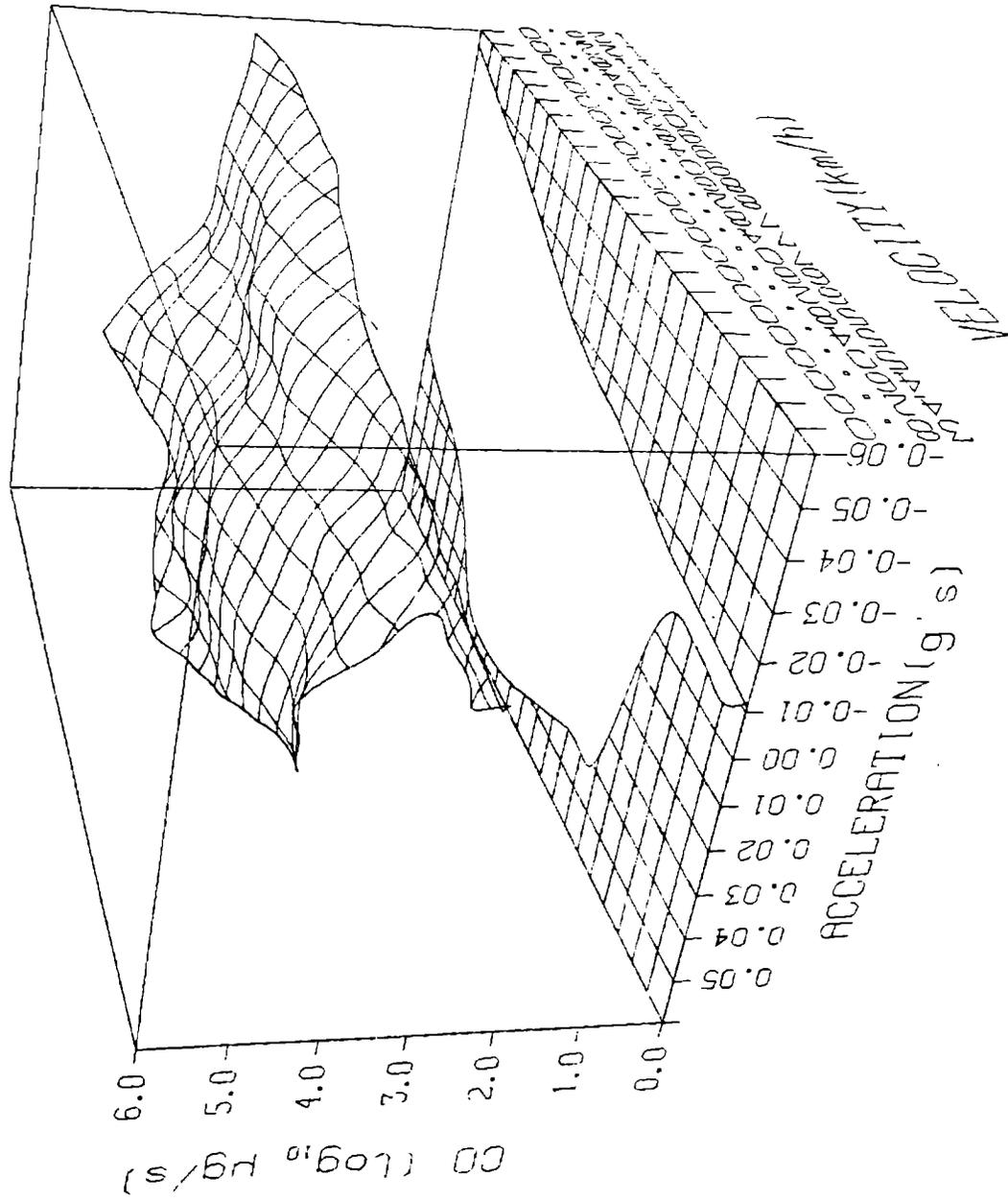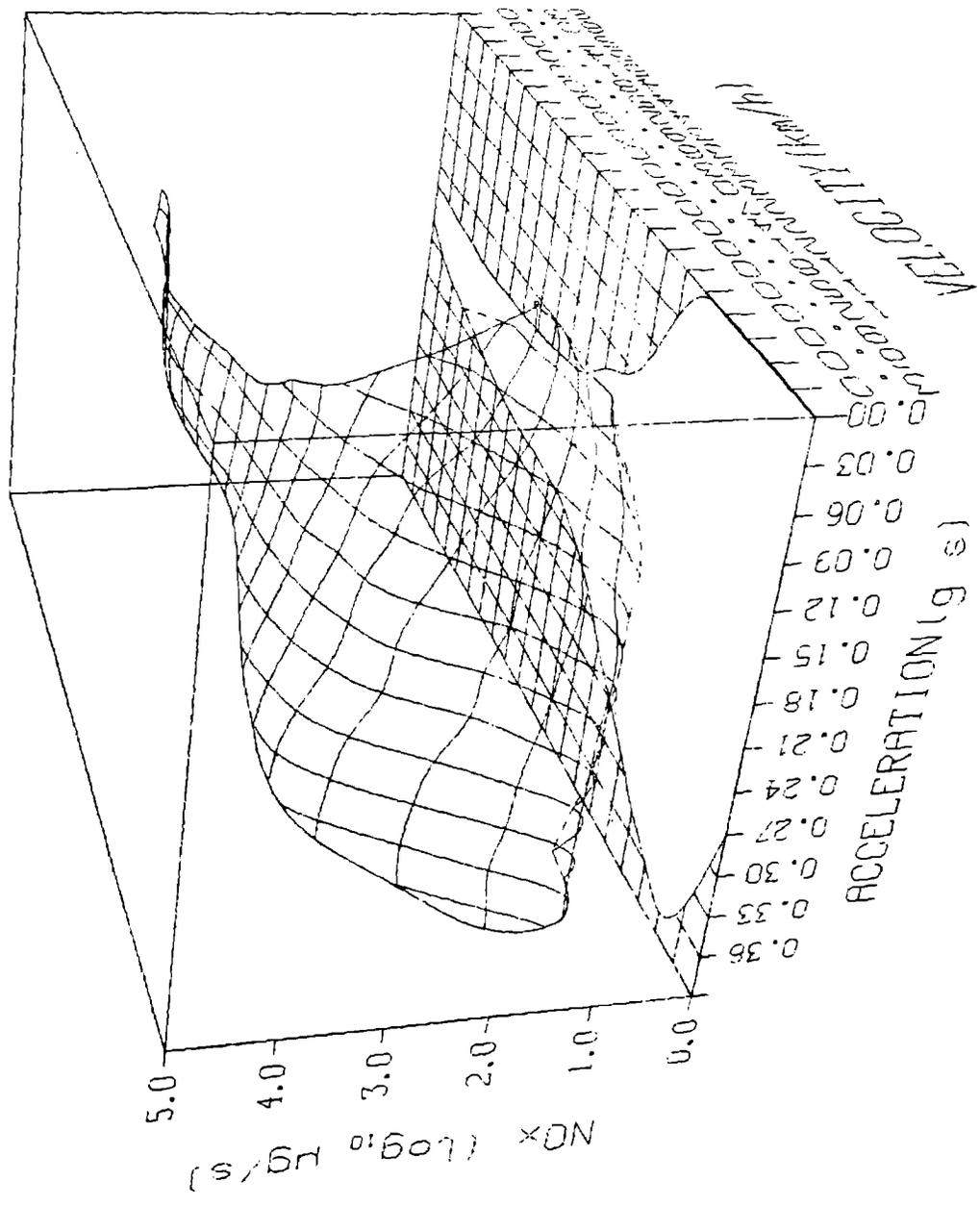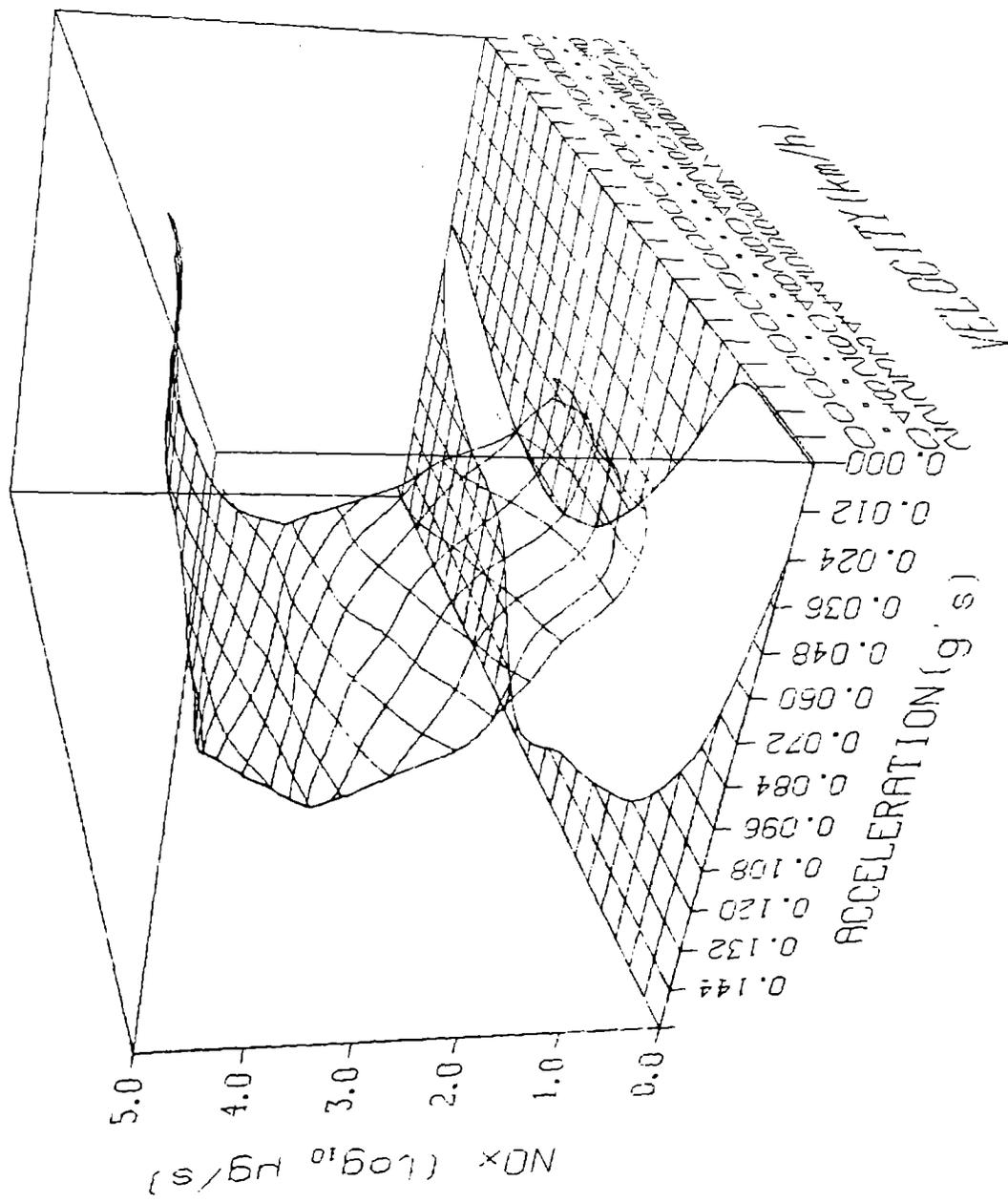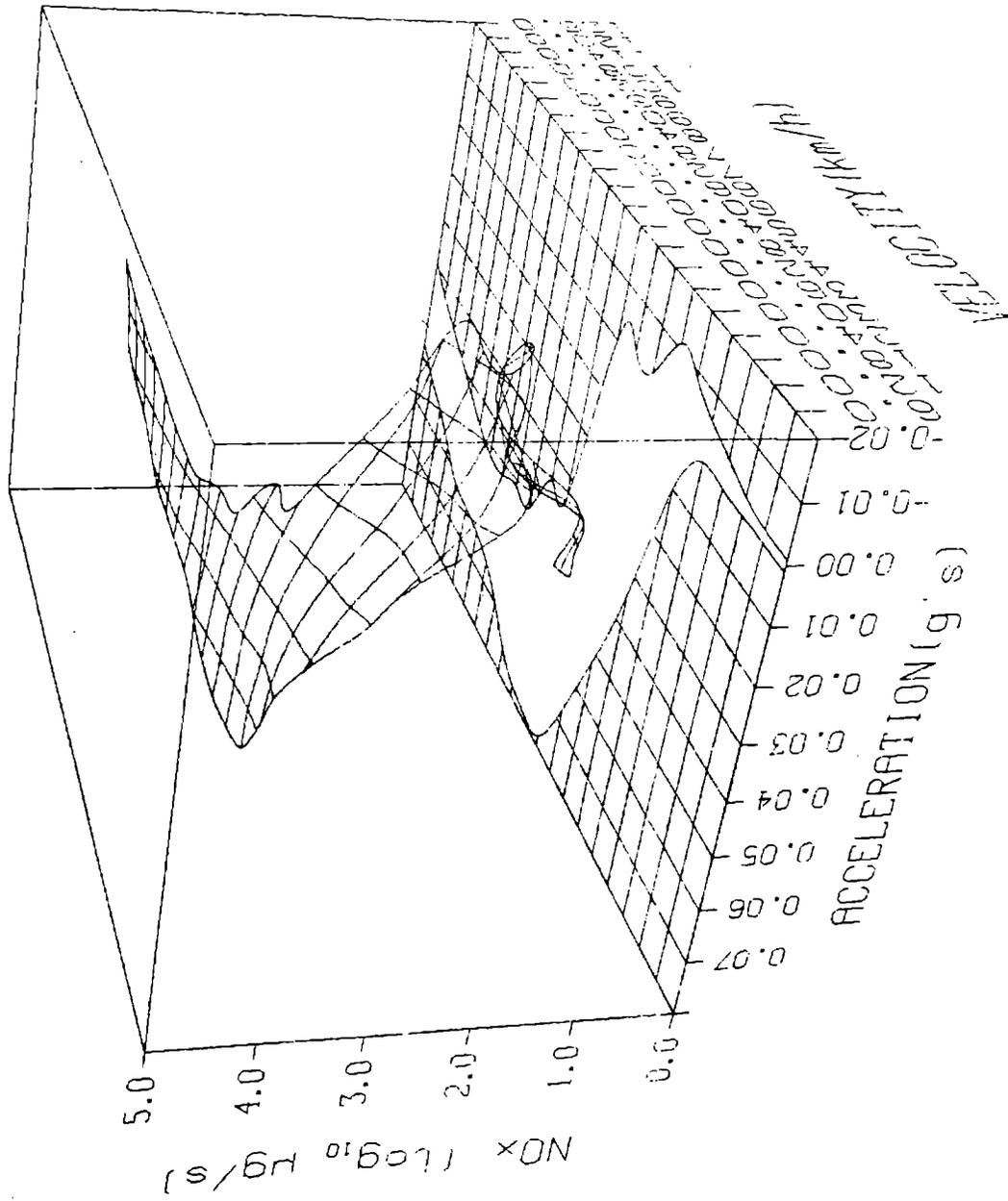Figure 19. Oxides of nitrogen emissions — Chevrolet Station Wagon, gear 3.

41
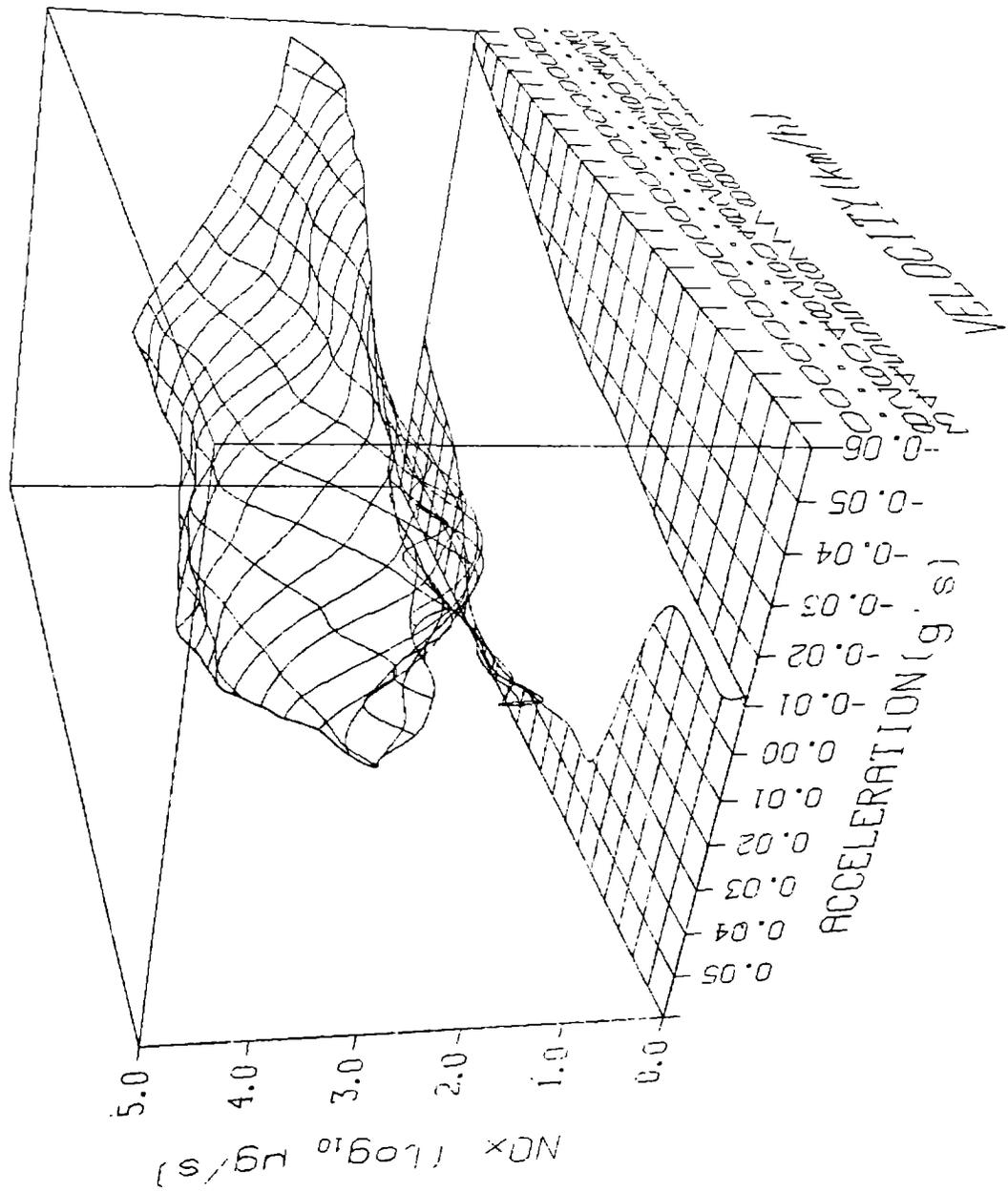
Figure 20. Oxides of nitrogen emissions — Chevrolet Station Wagon, gear 4.

Table 4. Hydrocarbon emissions table for Chevrolet Station Wagon.

HC EMISSIONS RATE (MG/S)   FOR 8-CYL CHEVY CAPRICE SW

BRAKE, GEARSHIFT AND MAX ACCEL BOUNDARIES INDICATED
B = BRAKE APPLIED   A = ACCELERATION OR SPEED EXCEEDS MAXIMUM

SPEED (FT/S)	-5.	-4.	-3.	-2.	-1.	0.	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	CRUISE G/MI	GEAR DISTRIBUTION
0.	.058	.058	.058	.058	.058	.058	.057	.056	.060	.061	.062	.061	.058	.058	.058	.058	.058	.080	99.99	BBBBB3111111111AAA
1.	.062	.062	.062	.062	.062	.062	.061	.065	.072	.075	.079	.081	.081	.081	.081	.080	.080	.080	0.33	BBBBB3111111111AAA
2.	.066	.066	.066	.066	.066	.066	.065	.074	.083	.091	.100	.105	.112	.113	.115	.116	.118	.118	0.17	BBBBB3111111111AAA
3.	.070	.070	.070	.070	.070	.070	.069	.083	.095	.111	.125	.135	.146	.154	.159	.164	.162	.160	0.12	BBBBB3111111111AAA
4.	.073	.073	.073	.073	.073	.073	.075	.093	.106	.132	.153	.173	.185	.205	.213	.226	.232	.226	0.10	BBBBB3111111111AAA
5.	.076	.076	.076	.076	.076	.076	.082	.102	.121	.160	.185	.216	.230	.264	.280	.307	.326	.318	0.08	BBBBB3111111111AAA
6.	.079	.079	.079	.079	.079	.079	.090	.113	.143	.195	.224	.259	.285	.326	.369	.418	.449	.432	0.07	BBBBB3111111111AAA
7.	.080	.080	.080	.080	.080	.079	.098	.126	.174	.238	.270	.301	.349	.385	.488	.57	.60	.58	0.06	BBBBB3111111111AAA
8.	.081	.081	.081	.081	.081	.081	.109	.142	.210	.287	.319	.344	.418	.449	.63	.76	.79	.77	0.05	BBBBB3111111111AAA
9.	.081	.081	.081	.081	CA1	CA1	.121	.163	.243	.338	.362	.396	.483	.53	.79	.97	1.02	.99	0.04	BBBBB3111111111AAA
10.	.082	.082	.082	.082	CA1	CA1	.135	.187	.269	.382	.397	.457	.53	.62	.97	1.20	1.27	1.24	0.04	BBBBB3111111111AAA
11.	.083	.083	.083	.083	.083	.082	.151	.211	.291	.416	.432	.52	.57	.72	1.16	1.86	1.89	1.55	0.04	BBBBB3111111111AAA
12.	.085	.085	.085	.085	.085	.085	.169	.233	.311	.435	.473	.57	.59	.83	1.38	1.77	1.89	1.89	0.04	BBBBB3111111111AAA
13.	.088	.088	.088	.088	.088	.087	.199	.252	.331	.446	.51	.59	.61	.98	1.62	2.10	2.19	2.19	0.04	BBBBB3111111111AAA
14.	.090	.090	.090	.090	.090	.093	.211	.254	.350	.460	.51	.57	.64	1.05	1.86	2.44	2.50	2.50	0.03	BBBBB3211111111AAA
15.	.093	.093	.093	.093	.093	.098	.235	.254	.380	.460	.485	.53	.70	1.14	2.10	2.76	2.76	2.76	0.03	BBBBB3211111111AAA
16.	.095	.095	.095	.095	.095	.097	.180	.326	.412	.50	.450	.51	.79	1.36	2.37	2.95	2.95	2.95	0.03	BBBBB3211111111AAA
17.	.097	.097	.097	.097	.097	.097	.159	.271	.450	.50	.51	.58	.99	1.58	2.73	3.15	3.15	3.15	0.03	BBBBB3221111111AAA
18.	.099	.099	.099	.099	.099	.099	.181	.309	.49	.50	.461	.63	1.00	1.85	3.18	3.42	3.42	3.42	0.03	BBBBB3221111111AAA
19.	.100	.100	.100	.100	.100	.108	.193	.329	.49	.50	.50	.75	1.14	2.19	3.65	3.69	3.69	3.69	0.03	BBBBB3221111111AAA
20.	.101	.101	.101	.101	.101	.105	.215	.350	.52	.51	.56	.88	1.30	2.62	3.86	3.86	3.86	3.86	0.03	BBBBB3221111111AAA
21.	.101	.101	.101	.101	.101	.105	.227	.369	.55	.51	.72	.99	1.59	3.11	4.07	4.07	4.07	4.07	0.03	BBBBB3221111111AAA
22.	.101	.100	.100	.100	.100	.105	.239	.385	.58	.53	.78	1.10	1.90	3.89	4.41	4.41	4.41	4.41	0.02	BBBBB3222111111AAA
23.	.100	.099	.099	.099	.099	.104	.251	.402	.55	.83	.88	1.24	2.26	4.73	4.73	4.73	4.73	4.73	0.02	BBBBB3222111111AAA
24.	.099	.098	.098	.098	.098	.104	.263	.418	.61	.95	1.56	1.38	2.70	5.04	5.04	5.04	5.04	5.04	0.02	BBBBB3222111111AAA
25.	.098	.097	.097	.097	.097	.105	.276	.432	.61	.78	1.75	1.56	3.17	5.38	5.38	5.38	5.34	5.34	0.02	BBBBB3222111111AAA
26.	.097	.097	.097	.097	.097	.106	.290	.445	.62	.88	1.95	1.75	3.70	5.58	5.58	5.58	5.58	5.58	0.02	BBBBB3222111111AAA
27.	.097	.097	.097	.097	.097	.106	.276	.432	.62	.70	1.03	1.95	4.22	5.77	5.77	5.87	5.87	5.77	0.02	BBBBB3222111111AAA
28.	.097	.097	.097	.097	.097	.108	.290	.445	.62	.88	1.11	2.15	4.65	5.87	5.87	5.87	5.87	5.87	0.02	BBBBB3222111111AAA
29.	.097	.097	.097	.097	.097	.111	.305	.460	.62	1.00	1.19	2.33	4.99	6.02	6.02	6.02	6.02	6.02	0.02	BBBBB3222111111AAA
30.	.098	.098	.098	.098	.099	.115	.322	.479	.62	1.16	1.26	2.52	5.32	6.22	6.22	6.22	6.22	6.22	0.02	AAAA3222111111AAA
31.	.000	.000	.000	.001	.000	.121	.341	.50	.63	1.33	1.33	2.74	5.71	6.48	6.48	6.48	6.48	6.48	0.02	BBBBB3222111111AAA
32.	.121	.121	.121	.121	.128	.128	.352	.52	.64	.79	1.40	2.98	6.09	6.76	6.76	6.76	6.76	6.76	0.02	BBBBB3222111111AAA
33.	.122	.122	.122	.122	.122	.137	.367	.54	.65	.85	1.89	3.23	6.67	7.06	7.06	7.06	7.06	7.06	0.02	BBBBB3332221111AAA
34.	.123	.123	.123	.123	.123	.147	.367	.55	.66	.89	1.63	3.47	6.79	7.34	7.34	7.38	7.38	7.38	0.02	BBBBB3332221111AAA
35.	.123	.123	.123	.123	.123	.160	.388	.57	.67	.93	1.81	3.72	7.11	7.63	7.63	7.63	7.63	7.63	0.02	BBBBB3332221111AAA
36.	.124	.124	.124	.124	.124	.173	.401	.58	.68	.98	2.04	4.01	7.50	7.99	7.99	7.99	7.99	7.99	0.03	BBBBB3332221111AAA
37.	.125	.125	.125	.125	.125	.187	.419	.59	.69	1.05	2.33	4.34	7.98	8.38	8.38	8.38	8.38	8.38	0.03	BBBBB3332221111AAA
38.	.127	.127	.127	.127	.127	.201	.435	.59	.71	1.16	2.68	4.71	8.50	8.78	8.78	8.78	8.78	8.78	0.03	BBBBB3332221111AAA
39.	.128	.128	.128	.128	.128	.213	.447	.59	.73	1.29	3.09	5.10	9.01	9.12	9.12	9.12	9.12	9.12	0.03	BBBBB3332221111AAA
40.	.128	.128	.128	.128	.128	.225	.457	.59	.75	1.46	3.61	5.68	9.42	9.42	9.42	9.42	9.42	9.42	0.03	BBBBB3332221111AAA
41.	.128	.128	.128	.128	.128	.235	.465	.60	.76	1.65	4.23	6.27	9.8	9.8	9.8	9.8	9.8	9.8	0.03	BBBBB3332221111AAA
42.	.128	.128	.128	.128	.128	.244	.70	.61	.79	1.86	4.97	7.09	10.4	10.4	10.4	10.4	10.4	10.4	0.03	BBBBB3332221111AAA
43.	.127	.127	.127	.127	.127	.253	.75	.68	.81	2.11	5.89	8.11	11.2	11.2	11.2	11.2	11.2	11.2	0.03	BBBBB3332221111AAA
44.	.126	.126	.126	.126	.126	.263	.79	.88	.85	2.40	7.00	9.35	12.2	12.2	12.2	12.2	12.2	12.2	0.03	BBBBB3332221111AAA
45.	.126	.126	.126	.126	.126	.273	.88	.67	.89	2.74	8.37	10.8	13.4	13.4	13.4	13.4	13.4	13.4	0.03	BBBBB3332221111AAA
46.	.127	.127	.127	.127	.127	.288	.90	.67	.98	3.11	9.7	12.2	14.8	14.8	14.8	14.8	14.8	14.8	0.03	BBBBB3332221111AAA
47.	.129	.129	.129	.129	.129	.295	.50	.66	.99	3.51	10.8	13.1	14.7	14.7	14.7	14.7	14.7	14.7	0.03	BBBBB3332221111AAA

43

Table 4. Hydrocarbon emissions table for Chevrolet Station Wagon. (Continued)

SPEED (FT/S)	ACCELERATION (FT/S/S)																		CRUISE G/MI	GEAR DISTRIBUTION
	-5.	-4.	-3.	-2.	-1.	0.	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.		
48.	.130	.130	.130	.130	.130	.205	.50	(.66)1.05	(.66)1.05	(3.91)3.91	10.8	13.4	14.2	14.2	14.2	14.2	14.2	14.2	0.03	BBBBBJ33227AAAAAA
49.	.130	.130	.130	.130	.130	.175	.51	(.66)1.11	(4.30)	11.0	13.2	13.1	13.1	13.1	13.1	13.1	13.1	13.1	0.02	BBBBBJ332211AAAAA
50.	.129	.129	.129	.129	.129	.195	.52	(.67)1.18	(4.67)	11.3	12.7	11.9	11.9	11.9	11.9	11.9	11.9	11.9	0.02	BBBBBJ33221TAAAAA
51.	.127	.127	.127	.127	.127	.200	.53	(.68)1.26	(5.05)	11.9	12.1	11.3	11.3	11.3	11.3	11.3	11.3	11.3	0.02	BBBBBJ33221TAAAAA!
52.	.124	.124	.124	.124	.124	.209	.50	(.70)1.36	(5.47)	12.1	11.6	11.2	11.2	11.2	11.2	11.2	11.2	11.2	0.02	BBBBBJ33221TAAAAA!
53.	.122	.122	.122	.122	.122	.220	.58	(.72)1.47	(5.93)	11.5	11.3	11.4	11.4	11.4	11.4	11.4	11.4	11.4	0.02	BBBBBJ4322TAAAAAPA
54.	.120	.120	.120	.120	.120	.218	.77	(.74)1.61	(6.41)	10.7	11.3	11.3	11.3	11.3	11.3	11.3	11.3	11.3	0.02	BBBBBJ4322TAAAAAPA
55.	.119	.119	.119	.119	.119	.203	.88	(.76)1.78	(6.89)	10.3	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1	0.02	BBBBBJ4322TAAAAAA
56.	.117	.117	.117	.117	.117	.193	.93	(.78)1.97	(7.39)	10.3	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	0.02	BBBBBJ4322TAAAAAA
57.	.115	.115	.115	.115	.115	.188	.53	(.80)2.18	(7.80)	10.5	11.0	11.1	11.1	11.1	11.1	11.1	11.0	11.0	0.02	BBBBBJ4322TAAAAAA
58.	.113	.113	.113	.113	.113	.191	.05	(.82)2.42	(8.32)	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1	0.02	BBBBBJ4322AAAAAAA
59.	.112	.112	.112	.112	.112	.198	.36	(.85)2.70	(8.63)	10.4	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1	0.02	BBBBBJ4322AAAAAAAA
60.	.110	.110	.110	.110	.110	.206	.28	(.87)2.99	(8.85)	9.45	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4	0.02	BBBBBJ4322AAAAAAAA
61.	.108	.108	.108	.108	.108	.213	.26	(.90).31	(9.45)	8.88	9.45	9.45	9.45	9.45	9.45	9.45	9.45	9.45	0.02	BBBBBJ4322AAAAAAAA!
62.	.105	.105	.105	.105	.105	.218	.32	(.90)3.64	(9.09)	9.18	8.88	8.88	8.88	8.88	8.88	8.88	8.88	8.88	0.02	BBBBBJ4322AAAAAAAA
63.	.103	.103	.103	.103	.103	.220	.48	(.93)3.97	(9.16)	9.18	9.18	9.18	9.18	9.18	9.18	9.18	9.18	9.18	0.02	BBBBBJ4322AAAAAAAA
64.	.100	.100	.100	.100	.100	.221	.75	(.97)4.32	(2.31)	9.7	9.7	9.7	9.7	9.7	9.7	9.7	9.7	9.7	0.02	BBBBBJ4322AAAAAAAA
65.	.099	.099	.099	.099	.099	.220	.06	(.75)4.68	9.09	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	0.02	BBBBBJ4322AAAAAAAA
66.	.099	.099	.099	.099	.099	.220	.56	(1.11)5.06	9.09	9.09	9.09	9.09	9.09	9.09	9.09	9.09	9.09	9.09	0.02	BBBBBJ4322AAAAAAAA
67.	.101	.101	.101	.101	.101	.223	.60	(1.17)5.46	8.55	8.76	8.76	8.76	8.76	8.76	8.76	8.76	8.76	8.76	0.02	BBBBBJ432AAAAAAAA
68.	.102	.102	.102	.102	.102	.223	.63	(1.24)5.90	8.47	8.55	8.55	8.55	8.55	8.55	8.55	8.55	8.55	8.55	0.02	BBBBBJ432AAAAAAAA
69.	.104	.104	.104	.104	.104	.249	.63	(1.32)6.37	8.51	8.47	8.47	8.47	8.47	8.47	8.47	8.47	8.47	8.47	0.02	BBBBBJ432AAAAAAAA
70.	.105	.105	.105	.105	.105	.266	.31	(1.42)6.90	8.64	8.51	8.51	8.51	8.51	8.51	8.51	8.51	8.51	8.51	0.02	BBBBBJ432AAAAAAAA
71.	.108	.108	.108	.108	.108	.288	.21	(1.54)7.48	8.05	8.64	8.64	8.64	8.64	8.64	8.64	8.64	8.64	8.64	0.02	BBBBBJ432AAAAAAAA
72.	.110	.110	.110	.110	.110	.299	.69	(1.68)8.11	8.85	8.05	8.05	8.05	8.05	8.05	8.05	8.05	8.05	8.05	0.02	BBBBBJ432AAAAAAAA
73.	.112	.112	.112	.112	.112	.310	.61	(1.85)8.00	9.17	9.17	9.17	9.17	9.17	9.17	9.17	9.17	9.17	9.17	0.02	BBBBBJ432AAAAAAAA
74.	.113	.113	.113	.113	.113	.320	.69	(2.05)9.5	10.3	9.6	9.6	9.6	9.6	9.6	9.6	9.6	9.6	9.6	0.02	BBBBBJ432AAAAAAAA
75.	.114	.114	.114	.114	.114	.330	.73	(2.28)10.2	11.0	10.3	10.3	10.3	10.3	10.3	10.3	10.3	10.3	10.3	0.02	BBBBBJ432AAAAAAAA
76.	.114	.114	.114	.114	.114	.340	.75	(2.55)10.9	11.7	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	0.02	BBBBBJ432AAAAAAAA
77.	.114	.114	.114	.114	.114	.352	.78	(2.85)11.4	12.3	11.7	11.7	11.7	11.7	11.7	11.7	11.7	11.7	11.7	0.02	BBBBBJ432AAAAAAAA
78.	.114	.114	.114	.114	.114	.366	.80	(3.19)11.6	12.3	12.3	12.3	12.3	12.3	12.3	12.3	12.3	12.3	12.3	0.02	BBBBBJ432AAAAAAAA
79.	.114	.114	.114	.114	.114	.382	.83	(3.57)12.2	12.6	12.6	12.6	12.6	12.6	12.6	12.6	12.6	12.6	12.6	0.02	BBBBBJ432AAAAAAAA
80.	.113	.113	.113	.113	.113	.402	.85	(3.98)12.3	12.9	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	0.02	BBBBBJ432AAAAAAAA
81.	.111	.111	.111	.111	.111	.426	.89	(4.43)12.4	12.9	12.9	12.9	12.9	12.9	12.9	12.9	12.9	12.9	12.9	0.02	BBBBBJ432AAAAAAAA
82.	.110	.110	.110	.110	.110	.455	.98	(4.90)12.4	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	0.02	BBBBBJ432AAAAAAAA
83.	.107	.107	.107	.107	.107	.489	1.01	(5.39)12.8	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	0.03	BBBBBJ432AAAAAAAA
84.	.105	.105	.105	.105	.105	.52	1.10	(5.89)12.1	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	0.02	BBBBBJ432AAAAAAAA
85.	.105	.105	.105	.105	.105	.54	1.20	(6.37)11.9	12.6	12.6	12.6	12.6	12.6	12.6	12.6	12.6	12.6	12.6	0.02	BBBBBJ432AAAAAAAA
86.	.104	.104	.104	.104	.104	.51	1.30	(6.85)11.7	12.3	12.3	12.3	12.3	12.3	12.3	12.3	12.3	12.3	12.3	0.02	BBBBBJ432AAAAAAAA
87.	.104	.104	.104	.104	.104	.478	1.37	(7.29)11.5	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	0.02	BBBBBJ432AAAAAAAA
88.	.105	.105	.105	.105	.105	.047	1.42	(7.69)11.4	11.9	11.9	11.9	11.9	11.9	11.9	11.9	11.9	11.9	11.9	0.02	BBBBBJ422AAAAAAAA
89.	.105	.105	.105	.105	.105	.028	1.42	(8.01)11.3	11.8	11.8	11.8	11.8	11.8	11.8	11.8	11.8	11.8	11.8	0.03	BBBBBJ422AAAAAAAA
90.	.104	.104	.104	.104	.104	.020	1.38	(8.24)11.2	11.8	11.8	11.8	11.8	11.8	11.8	11.8	11.8	11.8	11.8	0.03	BBBBBJ422AAAAAAAA
91.	.102	.102	.102	.102	.102	.018	1.31	(9.39)11.2	11.7	11.7	11.7	11.7	11.7	11.7	11.7	11.7	11.7	11.7	0.02	BBBBBJ422AAAAAAAA
92.	.102	.102	.102	.102	.102	.018	1.23	(.98)11.2	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	0.02	BBBBBJ422AAAAAAAA
93.	.098	.098	.098	.098	.098	.015	1.17	10.7	11.3	11.3	11.3	11.3	11.3	11.3	11.3	11.3	11.3	11.3	0.02	BBBBBJ422AAAAAAAA
94.	.094	.094	.094	.094	.094	.009	1.12	10.4	11.2	11.2	11.2	11.2	11.2	11.2	11.2	11.2	11.2	11.2	0.02	BBBBBJ422AAAAAAAA
95.	.092	.092	.092	.092	.092	.008	1.10	10.3	11.2	11.2	11.2	11.2	11.2	11.2	11.2	11.2	11.2	11.2	0.02	BBBBBJ422AAAAAAAA
96.	.093	.093	.093	.093	.093	.005	1.08	10.3	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1	0.02	BBBBBJ42AAAAAAAA
97.	.098	.098	.098	.098	.098	.018	1.05	10.5	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1	0.02	BBBBBJ42AAAAAAAA
98.	.103	.103	.103	.103	.103	.045	1.03	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1	0.02	BBBBBJ42AAAAAAAA
99.	.106	.106	.106	.106	.106	.481	1.18	8.03	8.03	8.03	8.03	8.03	8.03	8.03	8.03	8.03	8.03	8.03	0.03	BBBBBJ4AAAAAAAA
100.	.107	.107	.107	.107	.107	.52	1.67	8.28	8.28	8.28	8.28	8.28	8.28	8.28	8.28	8.28	8.28	8.28	0.03	BBBBBJ3AAAAAAAA
101.	.109	.109	.109	.109	.109	.56	3.62	8.63	8.63	8.63	8.63	8.63	8.63	8.63	8.63	8.63	8.63	8.63	0.03	BBBBBJ3AAAAAAAA

Table 4. Hydrocarbon emissions table for Chevrolet Station Wagon. (Continued)

SPEED (FT/S)	ACCELERATION (FT/S/S)																		CRUISE G/MI	GEAR DISTRIBUTION
	-5.	-4.	-3.	-2.	-1.	0.	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.		
102.	.113	.113	.113	.113	.285	.60)3.59)	9.03	9.03	9.03	9.03	9.03	9.03	9.03	9.03	9.03	9.03	9.03	9.03	0.03	BBBB443AAAAAAAAAF
103.	.118	.118	.118	.118	.287	.68)3.58)9.42	9.42	9.42	9.42	9.42	9.42	9.42	9.42	9.42	9.42	9.42	9.42	9.42	0.03	BBBB443AAAAAAAAAA
104.	.121	.121	.121	.121	.290	.69)3.66)9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	0.04	BBBB443AAAAAAAAAA
105.	.124	.124	.124	.124	.294	.78)3.79)10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	0.04	BBBB443AAAAAAAAAA
106.	.126	.126	.126	.126	.297	.79)3.92)10.3	10.3	10.3	10.3	10.3	10.3	10.3	10.3	10.3	10.3	10.3	10.3	10.3	0.04	BBBB443AAAAAAAAAA
107.	.129	.129	.129	.129	.300	.83)4.05)10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	0.04	BBBB443AAAAAAAAAA
108.	.134	.134	.134	.134	.304	.88)4.17)10.7	10.7	10.7	10.7	10.7	10.7	10.7	10.7	10.7	10.7	10.7	10.7	10.7	0.04	BBBB443AAAAAAAAAA
109.	.140	.140	.140	.140	.307	.83)4.31)10.9	10.9	10.9	10.9	10.9	10.9	10.9	10.9	10.9	10.9	10.9	10.9	10.9	0.04	BBBB443AAAAAAAAAA
110.	.150	.150	.150	.150	.311	.91)4.47)11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	0.04	BBBB443AAAAAAAAAA

3.1.3 Other Deliverable Results

In addition to the results required on fuel consumption and emissions as just discussed above, tasks were required on tradeoffs in fuel consumption and emissions between idling and stopping and restarting the engine. These tasks were listed as objectives 2 and 4 in Section 1.1. A separate technical memorandum outlining methodologies and results for each of those objectives was required; and those technical memoranda are included in this report as Appendices C and D, with Appendix C dealing with fuel consumption tradeoffs and Appendix D dealing with emissions.

3.2 OTHER RESULTS AND OBSERVATIONS

In this section some comparisons and observations are offered which attest to the validity and accuracy of the methods employed in and the results issuing from this project.

One of the best measures of the quality of the data is to compare results from the simulated fuel consumption with those from a gross measure of fuel consumption such as highway mileage. Recall that in the Procedures section it was pointed out that very careful measures of highway fuel consumption were taken on the trips to and from Tullahoma; this represents about 320 miles of real highway driving. The highway driving is typified by a 60 mph cruise; thus, the results from the gross measure of fuel consumption by carefully filling the vehicle's tank before and after each trip can be compared to the simulator-table value for a 60 mph cruise condition. This comparison is made in Table 5. Also shown is a comparison of results from this project with the Environmental Protection Agency's (EPA) highway fuel economy estimate. The EPA estimate results from driving vehicles on the highway driving cycle which is a relatively mild cycle with gentle accelerations and decelerations and no stops. Average speed for the EPA highway cycle is about 50 mph. So, in Table 5 the simulator-table results for 50 mph cruise condition are compared to the EPA highway fuel economy estimate. When examining the results in Table 5 one should compare the numbers in the first two columns separately from the numbers in the last two columns. (Note that while a comparison of results for this work with the EPA city driving fuel economy estimate would be intriguing, such could not be done for two reasons: (1) the city driving cycle cannot be approximated accurately by a simple, single average speed; thus, the simulators would have to be exercised over the driving cycle, and resources did not permit such; (2) the EPA city cycle includes cold starting, while all data from this project are for "warmed-up" vehicles.)

The conclusion from examining Table 5 is that the simulator values of fuel consumption are very good — at least, judging by these two comparisons. There are just a few exceptions, but there are also feasible explanations for the exceptions as follows:

Table 5. Comparison of fuel economy estimates from ORNL simulators to other measures.

Vehicle number	Make and model	Fuel economy (mpg)			
		60 mph cruise (from table)	Actual highway mileage to/from Tullahoma	50 mph cruise (from table)	EPA highway estimate
1	'82 Ford Fairmont	25	Insufficient Data	30	30
2	'82 Chevrolet Citation	28	26	38	40
3	'82 Ford Futura	26	Insufficient Data	30	28
4	'83 Plymouth Reliant	26	24	30	30
5	'82 Toyota Corolla	29	29	31	32
6	'83 Ford Escort	32	31	40	38
7	'83 Pontiac Firebird	32	26	33	34
8	'83 Chevrolet Monte Carlo	28	27	30	29
9	'82 Chevrolet Chevette (Diesel)	34	33	44	43
10	'81 Chevrolet Caprice (Diesel)	30	27	35	33
11	'83 Chevrolet Silverado (Diesel)	23	25	24	31
12	'81 Datsun 210	23	25	39	39
13	'82 Chevrolet Caprice Station Wagon	23	20	27	28
14	'81 Buick Century	28	20	31	30
15	'84 Chevrolet S-10 Pickup	23	25	30	33

1. Vehicle number 7, the Pontiac Firebird, shows that the simulator for it would predict 32 mpg for the 60 mph cruise, whereas only 26 mpg was actually achieved on the highway trip. This car had an automatic overdrive transmission, and on the hilly terrain between Oak Ridge and Tullahoma spent much of the driving time in third gear rather than in overdrive. But, the simulator indicates that at a 60 mph cruise the transmission would be in overdrive. Thus, the discrepancy between the actual driving conditions (hilly) and the ideal conditions of the simulator (level terrain) probably account for the 6 mpg difference.

2. Vehicle number 11, the Silverado Pickup with diesel engine, shows that its simulator would predict 24 mpg for the 50 mph cruise, whereas the EPA highway estimate is 31 mpg. This results even though there is good agreement in the first two columns at 60 mph. The data seems to be validated by the good agreement at 60 mph, thus the issue is why the difference at the 50 mph condition? This probably results from the fact that there was substantial difference between this test vehicle and the nominal one certified by EPA. The test vehicle weighed approximately 25% more than the EPA-certified vehicle. It had virtually all optional accessories, two fuel tanks, extra trim, and a cap on the cargo area. It is suspected that the extra weight decremented the mileage since this vehicle was not representative of those certified by EPA with the same engine and drivetrain.

3. Vehicle number 14, the Buick Century, shows a significant difference between the simulator's 60 mph prediction of 28 mpg and the actual road experience of only 20 mpg, although there is good correlation between the other two columns. Here, it is suspected that the simulator values are correct while there was an error in the gross measure of the on-road fuel economy. Since it is difficult to make such a large error in a simple measurement such as filing the tank and calculating the mileage, it is suspected that this car's fuel system had a leak somewhere. A leak of only about 1/100 gallon for each mile of the trip would account for the discrepancy. But, a leak in the fuel system would not show up in the dynamometer tests since fuel flow actually going to the engine is measured.

An interesting note on Table 5 is that the data tend to support the EPA's highway fuel economy estimate even though it is well known that the public does not put much faith in these figures. The problem, as the authors see it, is that the public also does not drive at 50 mph. An examination of the differences between the 50 and 60 mph cruise estimates shows the decrement in fuel economy from the EPA estimate that the public is really experiencing. The essence of the problem, in the authors' opinion, is not that the EPA estimates are incorrect; rather that there is not a good perception in the public of just what the estimate is, i.e. what are the conditions for which the estimate is made.

Another interesting point is the comparison of 60 mph fuel economies versus those at 50 mph. At 50 mph, there is a spread of 20 mpg between the lowest and highest mpg estimates of the 15 vehicles; the average is 32.8 mpg. But, at 60 mph the spread drops to 14 mpg; the average at 60 mpg is 27.1 mpg. This means that as one moves higher in speed there is compression of fuel economies of the various vehicles. Those that were much more economical at 50 mph are not so much more economical at 60 mph. This appears to be a case of diminishing returns; that is, if one buys a car for its high fuel economy estimate for city driving but then he proceeds to drive at 70 mph on the highway, he may not be saving much after all.

4.0 SUMMARY

Data-based simulators (computer models) have been developed to describe the fuel consumption characteristics of fifteen modern vehicles; emissions models were developed for six of those vehicles. These data-based simulators have been developed using a unique method which combines chassis dynamometer testing with on-road testing in order to produce models which reflect real-world conditions. Thus, the real effects of aerodynamic drag and rolling resistance are automatically incorporated into the data reported for each vehicle. Engines ranged from small 4-cylinder gasoline engines to large V-8 diesel engines. Samples of the results have been presented in this report, and the validity of the fuel consumption results has been supported by comparison with other measures.

The emissions simulators developed in this project will be applicable to warmed-up vehicles but not for cold-start situations. Because the Federal Test Procedure for emissions includes a cold start, it is difficult to find points of comparison for the emissions results developed in this project. Additionally, these emissions simulators are for steady-state operating conditions (in terms of engine speed and manifold vacuum), whereas in reality, considerable portions of the emissions of a vehicle occur during transient engine operating conditions. Nevertheless, the authors believe that the emissions simulators can be valuable in network analyses, at a minimum for comparative purposes.

As a result of this project, a new data base on post-1980 vehicles now exists for use by transportation engineers in assessing the energy and environmental impacts of highway design factors. When one studies the fuel consumption results, one should realize that the data now exist for studying some intriguing questions such as the benefits of providing climbing lanes for trucks on steep grades, optimizing signal timing for an urban area, and investigations of fuel-efficient driving strategies. Many other possibilities exist but need not be enumerated here. Thus, the value of this project should go well beyond the obvious value to FHWA in addressing its needs for an updated data base in fleet fuel consumption.

5.0 REFERENCES

Hooker, J. N., 1984a. Computer Simulation of Automobile Fuel Consumption and Emissions: User's Manual, Operations Manual, Maintenance Manual. ORNL.

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Hooker, J. N., 1984c. Time and Space Comparison of Three Automobile Simulation Methods. ORNL.

Hooker, J. N., A. B. Rose, and G. F. Roberts, 1983. Optimal Control of Automobiles for Fuel Economy. Transportation Science 17, 146—167.

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Rose, A. B., J. N. Hooker, G. F. Roberts, and J. Hodgson, 1982. A Data-Based Simulator for Predicting Vehicle Fuel Consumption. SAE Technical Paper #820302.

Santiago, A. J., 1983. Vehicular Fuel Consumption Maps and Passenger Vehicle Fleet Projections. Presented at Transportation Research Board, Washington, D.C., January, 1983.

Appendix A. List of Other Reports and Documentation
Submitted Previously During the Project

1. "Time and Space Comparison of Three Automobile Simulation Methods,"
   J. N. Hooker, Technical Memorandum to FHWA (unpublished), 1984.

2. "Computer Simulation of Automobile Fuel Consumption and Emissions:
   User's Manual, Operations Manual, Maintenance Manual," J. N. Hooker,
   Technical Memorandum to FHWA (unpublished), 1984.

3. "Computer Simulation of Fuel Consumption and Emissions for Groups of
   Automobiles: User's Manual, Operations Manual, Maintenance Manual,"
   J. N. Hooker, Technical Memorandum to FHWA (unpublished), 1984.

4. "Feasibility of Developing NO_x Maps," R. N. McGill, Letter
   Memorandum to A. Santiago, November 29, 1982.

5. "Effects of Ambient Temperature on Vehicle Fuel Economy — A
   Literature Review," J. W. Hodgson, Technical Memorandum to FHWA
   (unpublished), September 1982.

Appendix B. Equipment List and Instrumentation Installation

B.1 Equipment List

1. Datalogger
    Accurex Corporation "Autodata TEN/10"

2. Fifth Wheel
    Laboratory Equipment Corporation "Tracktest 620"

3. Tape Recorder
    Columbia Data Products, Inc. "Model 300 D"

4. Tachometer
    Validyne Engineering Corp. "Model FC236"

5. Inverter
    Nova Electric Manufacturing Co. "Model 2560-12"

6. Fuel Flowmeter Transducer
    Flow Technology, Inc. "Model FTM-N2-LB"

7. Fuel Flowmeter Pulse Rate Converter
    Flow Technology, Inc. "Model PRC-408AA1LZT"

8. Electric Dual Pump
    AC Division of General Motors Corp. "Model 4333"

9. Fuel Pressure Regulator
    CR Industries, Inc.

10. Engine Analyzer
    Sun Electric Corp. "Model 2001"

11. Chassis Dynamometer
    Sun Electric Corp. "Model RAM-937-1"

12. Computer Terminal
    Beehive International "Model B100"

13. Intake Manifold Vacuum Transducer
    Setra Systems, Inc. "Model 204"

14. Unburned Hydrocarbon Analyzer
    Beckman Instruments, Inc. "Model 400"

15. Carbon Monoxide Analyzer
    Horiba Instruments, Inc. "Model AIA-2"

16. NOX Analyzer
    Beckman Instruments, Inc. "Model 951"

17. Tedlar Bag
    Cal West Energy Services, Inc.

18. Air Flow Meter
    Scott and Fetzer Co. "Meriam Laminar Flow Element Model SOMC2-4F"

19. Air Flow Meter Differential Pressure Transducer
    Setra Systems, Inc. "Model 239"

20. Wet Test Meter
    Precision Scientific "Precision Wet Test Meter"

21. Data Cartridges
    3M Corp. "Scotch DC 300A"

22. Emission Pump
    Thomas Industries "Model 107CA18 TFE"

23. Engine Oil Cooler
    Young Radiator Company "Model F-602-HY-1P"

24. Fuel Pressure Gage
    Sun Electric Corp. "Model FPT-4"

25. Calibration Gas Mixtures
    Several sources including:
        Air Products
        Linde (Union Carbide)
        Burdette

26. Throttle Position Potentiometer
    H. E. Sostman and Co. "Model 1120-4E-1(3)"

27. Stopwatch
    Fisher Scientific "Heuer"

28. Thermocouples (Type K)
    Ari Industries, Inc. "Aer-O-Pak"

B.2 Instrumentation Installation

    Not all the instrumentation was required for every test, but it should be clear as to what instruments would be required for each of the tests run. The following breakdown is offered:

    Fuel Consumption Tests: Datalogger
                               Tape Recorder
                               Engine Analyzer
                               External Fuel Pump
                               Fuel Meter(s)
                               Intake Manifold Vacuum Transducer

Throttle Position Potentiometer (Diesels)
Engine Speed Sensor
Thermocouples
Engine Oil Cooler
Fuel Cooler

Emission Tests: All of the above plus
                          Air Flowmeter
                          Tailpipe Probe
                          Sample Cooler and Pump
                          CO NDIR Analyzer
                          OHC FID Analyzer
                          NO Photochemiluminescent Analyzer

Restart Tests (Fuel):   Although these tests were conducted with all the
                          fuel instrumentation installed, only the
                          following were necessary:

                          Fuel Flow Meter(s)
                          Engine Speed Sensor
                          Datalogger
                          Tape Recorder
                          Fuel Thermocouples

Restart (Emissions):   Emission Testers (as listed above)
                          Exhaust Collection Bag
                          Wet Test Meter
                          Stop Watch

The datalogger was installed in the vehicle so that the driver
could manipulate it, if necessary. All the transducer outputs in analog
form were fed to the datalogger which converted the analog signals to
digital form for recording on the tape recorder. The operator would
place "tape marks" on the tape and make notations in the log book to
assist in interpreting the data when it was reviewed and processed
later. The datalogger was programmed to scan some channels con-
tinuously, but some variables (namely, temperatures) which changed rela-
tively slowly were scanned less frequently. Initiation and termination
of scanning was controlled by the operator.

Since the pulsations of the mechanical fuel pumps on most engines
would create significant errors in fuel flow measurements by the
turbine-type flowmeters used, the engine's fuel pump was by-passed and
an electric fuel pump used to deliver the necessary fuel. In order to
prevent possible vapor formation in the fuel lines (and particularly in
the fuel flow meters), the fuel was run through an ice bath before being
introduced into the fuel meter(s). On some vehicles tested the car-
buretor had a fuel return line back to the fuel tank (the diesel engines
also have a return line from the injection system) and on these vehicles
it was necessary to measure both the supply and the return fuel flow
rates to determine the net flow to the engine. On the largest gasoline

55

engine tested (305 CID) the fuel flow rate exceeded the capacity of a single flow meter and thus two meters were used in parallel with each other.

The intake manifold vacuum transducer was connected to a convenient source of manifold vacuum. Care was taken to insure that the vacuum source was directly connected to the manifold without intermediary check valves or orifices between the two.

In the case of the diesel engines (which, of course have no intake manifold vacuum), the accelerator (or throttle) position was sensed by attaching a linear potentiometer to the throttle mechanism. The potentiometer was then energized with a regulated voltage and the voltage of the wiper pick-off was measured. The voltage was then taken as an indicator of the throttle opening.

The normal engine speed sensor used was an inductive pickup placed over the high tension secondary cable between the ignition coil and the distributor. On some GM vehicles with the coil integral with the distributor a special adaptor had to be used to pick off the necessary signal. The signal was then fed to a frequency-voltage converter which produced a D.C. voltage proportional to the frequency of the signal fed to it. Clearly, this system had to be modified for the diesel engines (which have no ignition wires). For these engines a magnetic pickup was located near the engine's front vibration damper such that it was able to detect the presence of a hole or other nonuniformity in the damper surface. The output from the magnetic pickup was then amplified and fed to the frequency-voltage converter to generate a voltage proportional to engine speed. The dynamometer's engine analyzer used either its own engine speed transducer or was coupled to the output of the frequency-voltage converter (in the case of diesel engine testing) so that the operator would have a display of engine speed to aid during the testing.

The engine oil cooler was used to make sure that the engine oil did not overheat during the testing. The fan blowing air into the front of the vehicle was adequate to provide sufficient radiator air, but would not provide the air flow required to cool the engine oil. The cooler used was a conventional shell-and-tube water-cooled heat exchanger. The oil was drawn off from the engine by replacing the oil filter with a remote oil filter adaptor and plumbing the heat exchanger into this system.

Thermocouples were used to monitor and record various temperatures including fuel, engine oil, transmission fluid, engine coolant, carburetor air, and ambient air. The transmission fluid temperature was particularly important during dynamometer testing as the lack of cooling air flow and the severity of some of the operating modes would lead to excessive (greater than 250°F) transmission fluid temperatures.

The mass flow rate of the emissions calculation was based on knowing the mass flow rate of air and fuel into the engine. To determine the mass flow rates of air a laminar flow element flow meter was connected to the air cleaner snorkle. Since most vehicles have a modulated air temperature control system which utilizes hot air off the exhaust manifold mixed with cooler air from the environment, the hot air intake duct had to be sealed off. Extreme care had to be taken to seal off the many potential sources of air leaking into the carburetor. In some vehicles the air flow could not be adequately measured because part of it came from the air pump and the inlet to the air pump was not accessible for flow measurements to be made. The flow meter produces a pressure drop across the laminar flow element and this pressure drop is proportional to the volumetric flow through the element. To measure and record this pressure drop a differential pressure transducer powered by a regulated voltage source was used. The output from the transducer was fed to the datalogger.

The probe used to sample the tailpipe emissions was a standard commercially available unit that was inserted to approximately one foot up the tailpipe. This probe rested in a slot cut in the exhaust hose that was used to duct the exhaust fumes out of the laboratory. The sample hose was a teflon stainless steel braided hose specifically designed for exhaust emission testing and led to a copper coil immersed in an ice bath to condense out most of the water vapor in the sample. The sample then passed through a water separator/filter, through the sample pump, and into the emission measurement system.

The instruments used to measure the emission levels consisted of a non-dispersive infrared analyzer sensitized for carbon monoxide, a flame ionization detector for measuring unburned hydrocarbons, and a photochemiluminescent analyzer for measuring NO_x levels. The analyzers were operated in accordance with the manufacturers' instructions and were calibrated before and during the emission tests. The instruments were very stable and exhibited no unusual behavior during the testing program.

In order to collect the total exhaust volume emitted during the restart tests, a large Tedlar (tradename, E.I. DuPont Corp.) bag was fabricated with a nozzle attachment on it. The nozzle was connected to an exhaust hose which was, in turn, connected to the vehicle's tailpipe. The connections were gas tight and the bag was sized to avoid any pressure build-up as the exhaust gases were collected in it. The nozzle was equipped with a valved hose connection that allowed the contents of the bag to be drawn off for analysis and measurement. The measurement of the gas volume was accomplished using a standard wet test meter. A small gas pump was used to pump the contents of the bag into the wet test meter. A hand-held stopwatch was used to measure the total time during which the exhaust was directed into the bag.

57

Appendix C. Study of Fuel Economy Tradeoff for Stopping and
Restarting an Automobile Engine Rather than Letting It Idle

OBJECTIVE: Measure the difference in fuel consumed by stopping and
restarting each of the 15 vehicles' engines compared to letting
them idle. Based on these results, determine for how long the
vehicle would have to idle before it uses more fuel than it would
if the engine were shut off and restarted.

METHODOLOGY

The object of the analysis was first to determine how much excess
fuel F_s is required to start a car, beyond that required to idle during
the same period, and then to use F_s to compute break-even times and con-
fidence bounds. The excess fuel F_s in a given stop/restart sequence was
calculated,

$$F_s = F - tf_n$$

where F = total fuel consumed during the stop/restart sequence,

t = length of time the car is running during the stop/restart
sequence, as indicated by an engine speed that is within
100 rpm of the mean engine idle speed in neutral, and

f_n = mean idle fuel flow rate while in neutral.

The break-even time was computed two ways. One calculation
(resulting in break-even time t_n) assumed that the car would be in
neutral if allowed to idle during the waiting period. The other
(resulting in t_d) assumed the car would be in drive. The formulas are
simply,

$$t_n = \overline{F_s}/\overline{f_n}, \quad t_d = \overline{F_s}/\overline{f_d} ,$$

where f_d is the idle fuel flow rate in drive, as measured in the fuel
consumption tests, and where the overbars indicate sample means.

It is important to estimate confidence bounds for $\overline{f_n}$, $\overline{f_d}$, $\overline{F_s}$, t_n,

and t_d. Confidence bounds for $\overline{f_n}$ and $\overline{f_d}$ were calculated on the assump-
tion that

$$\frac{\overline{f_n}}{S_n(n-1)^{1/2}} \text{ and } \frac{\overline{f_d}}{S_d(n-1)^{1/2}}$$

have approximately a Fisher's t distribution with n-1 degrees of freedom, where

$$S_n^2 = \text{sample variance of } f_n,$$

$$S_d^2 = \text{sample variance of } f_d, \text{ and}$$

$$n = \text{number of independent observations of } f_n \text{ or } f_d.$$

Examination of the idle flow data reveals that much of the variation in the measured flow rate is a rather slow, semi-periodic fluctuation with a period of from one to five seconds. When a mechanical carburetor is used this presumably results from a slightly sticky needle valve at the bowl inlet. Given this sort of fluctuation, readings taken at the rate of two or three a second cannot realistically be regarded as independent. But readings taken at intervals that are of the same order of magnitude as the period, say two seconds, should be more nearly independent. For this reason the number n of independent observations was taken to be one-fifth the number of readings. This results in a conservatively wide confidence interval, since any measurement error due to periodic fluctuation, which varies inversely with the number of periods, is overestimated by the confidence interval whose width varies inversely with the square root of the number of periods.

Confidence bounds for $\overline{F}_s$ were estimated on the assumption that

$$\frac{\overline{F}_s}{S_F(N-1)^{1/2}}$$

has approximately a t distribution, where

$$S_F^2 = \text{sample variance of } F_s,$$

$$N = \text{sample size (number of restarts)}.$$

To calculate confidence bounds for t_n and t_d, the variance $\hat{S}_n^2$ of t_n was estimated by the formula,

$$\hat{S}_n^2 = (\overline{F}_s/\overline{f}_n)^2 \left[(s_F/\overline{F}_s) + \frac{S_n^2}{\overline{f}_n^2(n-1)} \right] ,$$

and similarly for the variance S_d of t_d. It was assumed that

$$\frac{t_n}{\hat{S}_n(N-1)^{1/2}} \text{ and } \frac{t_d}{\hat{S}_d(N-1)^{1/2}}$$

have approximately a t distribution.

RESULTS

Table 6 identifies the fifteen test cars and reports the mean idle fuel flow rates $\overline{f_n}$ and $\overline{f_d}$ measured in neutral and drive, respectively. It has already been noted that the ninety percent confidence bounds are conservatively wide. They are especially wide for engines with a return fuel line; since in these cases the flow rate through the two meters is an order of magnitude greater than the flow rate into the engine. Thus a one percent error at either meter results in a ten percent error in the estimate of idle flow rate.

Table 7 displays the mean excess fuel $\overline{F_s}$ required to start each test car and the resulting break-even times t_n and t_d. Ninety percent confidence intervals are again shown. The negative figures for the Chevette should be interpreted as figures that cannot be statistically distinguished from zero.

These results do not take into account the fuel cost (if any) of cranking the engine, except to the extent that the recharging load results in higher fuel flows while flow data are still being recorded during several seconds after startup. But the energy required to crank the engine should be on the same order of magnitude as that required to keep it idling. Thus since cranking time is generally quite short (a second or so for the test cars), little error results from regarding cranking time simply as idling time. Furthermore, it is conceivable that discharging the battery during startup consumes no extra fuel or even saves fuel. If the battery is recharged during engine idle the additional alternator load may slow the idle speed and reduce fuel consumption. Table 6 suggests that most idling engines consume less fuel under a heavier load (as when the transmission is in drive) than under a lighter one (when in neutral).

RECOMMENDATIONS

If one's automobile is in reasonably good mechanical shape, he can save fuel by cutting off his engine rather than letting it idle — even for a time much shorter than the one minute that is often mentioned. Specifically, for a Ford Escort, Chevrolet Citation, Chevrolet Caprice diesel, Chevrolet V8 diesel pickup and Pontiac Firebird, the break-even time is under 5 s. For a Ford Fairmont, Ford Futura, Toyota Corolla, Chevrolet Monte Carlo, Chevrolet Caprice station wagon, Chevrolet S-10 pickup and Buick Century, it is under 10 s. For a Plymouth Reliant it is under 15 s. For a Datsun 210 it is probably under 20 s.

A reasonable rule of thumb would be that the break-even time is under 20 s for four-cylinder cars and under 10 s for larger cars (although it is evident that a small car can have one of the shorter break-even times). This suggests that one can save fuel by shutting off

Table 6. Type of fuel metering and mean measured idle fuel flow rates for the fifteen test cars (ninety percent confidence intervals are indicated).

Automobile	Fuel metering	Return fuel line?	Idle fuel flow rate (mL/s)			
			While in neutral		In drive, brakes locked	
			No. readings	Mean	No. readings	Mean
1. 1982 4-cyl Ford Fairmont	Carburetor	No	135	0.80 ± 0.06	371	0.67 ± 0.03
2. 1982 4-cyl Chevrolet Citation	Throttle-body injection	Yes	140	0.83 ± 0.08	112	0.83 ± 0.09
3. 1982 6-cyl Ford Futura	Carburetor	No	182	0.65 ± 0.03	322	0.74 ± 0.03
4. 1983 4-cyl Plymouth Reliant	Carburetor	No	129	0.67 ± 0.10	271	0.52 ± 0.02
5. 1982 4-cyl Toyota Corolla	Carburetor	No	46	0.27 ± 0.04	52	0.25 ± 0.03
6. 1983 4-cyl Ford Escort	Carburetor	Yes	110	0.40 ± 0.15	194	0.37 ± 0.09
7. 1983 6-cyl Pontiac Firebird	Carburetor	No	161	0.79 ± 0.04	256	0.68 ± 0.04
8. 1983 6-cyl Chevrolet Monte Carlo	Carburetor	No	188	0.50 ± 0.04	313	0.74 ± 0.04
9. 1982 4-cyl Chevrolet Chevette diesel	Injector	Yes	170	0.16 ± 0.13	317	0.22 ± 0.13
10. 1981 8-cyl Chevrolet Caprice diesel	Inector	Yes	147	0.63 ± 0.16	326	0.59 ± 0.07
11. 1983 8-cyl Chevrolet diesel pickup	Injector	Yes	175	0.51 ± 0.16	338	0.64 ± 0.09
12. 1982 4-cyl Datsun 210	Carburetor	Yes	110	0.11 ± 0.46	142	0.11 ± 0.40
13. 1982 8-cyl Chevrolet Caprice SW	Carburetor	No	120	0.49 ± 0.07	198	0.49 ± 0.05
14. 1981 6-cyl Buick Century	Carburetor	No	159	0.55 ± 0.05	125	0.50 ± 0.05
15. 1984 4-cyl Chevrolet S-10 pickup	Carburetor	No	84	0.37 ± 0.06	161	0.36 ± 0.04

Table 7. Mean startup fuel costs and mean break-even times
for the fifteen test cars
(ninety percent confidence intervals are indicated).

Automobile	Startup cost (mℓ)		Break-even time(s)	
	No. trials	Mean	In neutral	In drive
1. Ford Fairmont	9	4.25 ± 0.23	5.3 ± 0.2	6.4 ± 0.2
2. Chevrolet Citation	8	1.13 ± 0.97	1.4 ± 0.8	1.4 ± 0.6
3. Ford Futura	9	5.54 ± 0.77	8.6 ± 0.7	7.5 ± 0.6
4. Plymouth Reliant	9	6.43 ± 1.35	9.6 ± 1.1	12.3 ± 1.4
5. Toyota Corolla	9	1.87 ± 0.21	7.0 ± 0.5	7.7 ± 0.5
6. Ford Escort	5	1.10 ± 0.72	2.8 ± 0.9	3.0 ± 0.9
7. Pontiac Firebird	10	1.37 ± 0.53	1.7 ± 0.5	2.0 ± 0.4
8. Chevrolet Monte Carlo	9	4.56 ± 0.62	9.2 ± 0.7	6.2 ± 0.5
9. Chevrolet Chevette diesel	9	−0.02 ± 1.28	−0.1 ± 4.4	−0.1 ± 3.1
10. Chevrolet Caprice diesel	10	2.65 ± 0.62	4.2 ± 0.6	4.5 ± 0.6
11. Chevrolet diesel pickup	9	0.41 ± 0.85	0.8 ± 0.9	0.6 ± 0.7
12. Datsun 210	9	2.05 ± 0.68	18.1 ± 15.6	19.0 ± 15.1
13. Chevrolet Caprice SW	8	2.72 ± 0.59	5.6 ± 0.7	5.6 ± 0.7
14. Buick Century	8	3.93 ± 0.38	7.2 ± 0.4	7.9 ± 0.4
15. Chevrolet S-10 pickup	10	1.79 ± 0.24	4.9 ± 0.4	5.0 ± 0.4

his engine even for a rather long red light or a short one if he drives one of certain, generally larger cars. It is clearly advantageous to shut off the engine when waiting at railroad crossings, etc.

The magnitude of the savings is generally small but highly variable from car to car, since it is proportional to the idle fuel flow rate. Since idle flow rates appear to range from about 0.1 to 0.8 mℓ/s (or gal/h*), the savings is between 6 and 48 mℓ for each minute of delay past the break-even point. One would accumulate a savings of one liter in delays totaling between a half hour and three hours (or one gallon in delays totaling between one and one-third and 10 hours), again depending on the idle flow rate. Assuming a fuel cost of $0.32 per liter ($1.20 per gallon), the money saved ranges from about one to nine cents per minute of delay.

It may be argued that even if the above recommendations are valid for a hot engine, they do not apply to a cold engine, which may be harder to start and thus may consume more fuel in restarting. But cold engines idle faster and therefore burn more fuel while idling, and this should at least partially offset the excessive fuel cost of restarting.

The recommendations do, however, assume that the driver starts his car according to the manufacturer's instructions.

Since the fuel savings are small, it is important to consider the other costs of shutting down an engine for a short period. One cost may be increased emissions.

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*One mℓ/s is approximately equal to one gal/h; more precisely, 1 mℓ/s = .95 gal/h.

Appendix D. Study of Emissions Tradeoffs for Stopping and
Restarting an Automobile Engine Rather than Letting It Idle

OBJECTIVE: Measure the difference in emissions resulting from stopping
and restarting each of the six vehicles compared to letting them
idle. Based on the results, determine for how long the vehicle
would have to idle before it emits more HC, CO, and NO_x than it
would if the engine were shut off and restarted.

METHODOLOGY

The emission restart test was conducted only once per vehicle. In
this test the exhaust from the vehicle tailpipe was collected for two
separate periods of time: the first time with the engine idling in
"drive" and the second with the engine idling in drive but with a shut-
down and immediate restart conducted during the time period. The bag
used to collect the emissions was initially evacuated and at time zero
the exhaust hose carrying the engine exhaust was directed into the bag.
At the end of the allotted time (usually about 60 seconds) the bag was
sealed off. A sample of the bag's contents was then directed through
the emission testers to determine the composition and then the volume of
the bag was determined by pumping the contents out through a wet test
meter. The results of the test consisted of the time, the con-
centrations of the emissions, and the bag volume. From these data, the
penalty (or benefit) from emissions considerations of stopping and
restarting versus continuous idling can be determined.

RESULTS AND ANALYSES

Before the results of these tests are discussed, it is appropriate
to enumerate the authors' concerns about possible misinterpretation of
the results. The concerns all stem from the same basis; that is, there
is not a unique answer to the idle versus stop/restart for any indivi-
dual car. Why? Very simply, the emissions from a vehicle are very much
a function of the immediate past driving duty of the car in addition to
being a function also of the present engine operating condition. For
example, with "cold" engines the issue of idling versus stop and restart
would be quite a different issue from that of the same engine when it is
"hot," because if the engine is "cold" the catalyst has not "lit off"
until after some driving time. As another example, some cars' catalysts
have a tendency to go into an "unlit" condition after some time at idle.
Clearly, on such a car, for the purposes of reducing emissions, one
would wish to shut off the engine rather than idle. But, how does the
driver know what the condition of the emissions control system is?

The reader should also be cautioned with regard to the statistical
significance of the results. Because of the time required to perform

these tests, each car was tested only once — i.e. one case of idling in drive and one case idling in drive with an engine shut-down and restart. Therefore, the results that will be presented do not represent averages or statistical means, but rather are simply the results of the single test for each car.

Table 8 presents the measured emissions concentration data along with the volume of exhaust collected and the duration of the simple idle-in-drive tests of the six cars.

Quite a wide variation in idle emissions concentrations can be seen in Table 8. Clearly, the Buick Century was emitting too much. The high CO level probably indicates that the idle fuel mixture was much too rich. The Datsun also had high idle emissions, but not quite so alarming. The data in Table 8 are, of course, only concentrations; of more use in this analysis are the emissions rates. Those can be calculated using the bag volume and test time as follows:

$$\text{Emission Rate} = \frac{\text{Pollutant Concentration x Bag Volume}}{\text{Test Duration}}$$

These data for the idle in drive case are presented in Table 9. The Total Emissions Rate cited in Table 9 is the sum of the three individual pollutant rates.

The data for the idle-plus-restart are presented in Tables 10 and 11 for emissions concentrations and emissions rates, respectively.

The penalty in emissions for restarting is simply the excess in pollutant(s) for the idle-plus-restart test over that for the idle-only case for the same length of test. Because there were some differences in test times between tests for the same car, the data must all be cast in the test duration for the idle-plus-restart test. Table 12 shows the volumetric total of the pollutants for the two types of tests. Those totals are obtained simply by multiplying the emissions rates by the test duration.

The break-even time is that time for which the vehicle would have to idle before it emits as much pollutant(s) as is caused by the stopping restarting of the engine. The penalty in emissions for the restart, as indicated above, is the excess in pollutant(s) over the idle-only case. Therefore, the break-even time can be computed as follows:

$$\text{Break-even time (s)} = \frac{\text{Emissions Penalty (m}\ell\text{)}}{\text{Idle Emissions Rate (m}\ell\text{/s)}}$$

In Table 94= above, the idle emissions rate was presented individually for HC, CO, and NO_x as well as for a total of the three. Therefore, a break-even time can be computed for each pollutant as well as for the total of the three. These results are presented in Table 13.

Table 8. Idle emissions concentration data.

Vehicle #	Vehicle	Concentrations (ppm)			Bag vol. (ℓ)	Test duration (s)
		HC	CO	NO$_x$		
1	'82 Ford Fairmont	300	197	31	336	45
7	'83 Pontiac Firebird	20	nil	41	135	30
12	'82 Datsun 210	640	3,160	42	117	60
13	'82 Chevrolet Wagon	42	200	49	237	60
14	'81 Buick Century	1,300	44,000	9	294	90
15	'84 Chevrolet S-10	45	nil	150	293	60

Table 9. Idle emissions rate data.

Vehicle #	Vehicle	Emissions rates (ml/s)			
		HC	CO	NO_x	Total Emissions Rate*
1	'82 Ford Fairmont	2.24	1.47	.23	3.94
7	'83 Pontiac Firebird	.09	nil	.18	.27
12	'82 Datsun 210	1.25	6.16	.08	7.49
13	'82 Chevrolet Wagon	.17	.79	.19	1.15
14	'81 Buick Century	6.37	216	.04	222.4
15	'84 Chevrolet S-10	.22	nil	.73	.95

*Total Emissions Rate = Sum of HC, CO, NO_x rates.

Table 10. Idle-plus-restart emissions concentration data.

Vehicle #	Vehicle	Concentrations (ppm)			Bag vol. ℓ	Test duration (s)
		HC	CO	NO$_x$		
1	'82 Ford Fairmont	230	1,381	53	222	30
7	'83 Pontiac Firebird	73	5,330	96	162	30
12	'82 Datsun 210	990	5,100	74	132	60
13	'82 Chevrolet Wagon	38	590	35	287	60
14	'81 Buick Century	960	16,700	12	203	60
15	'84 Chevrolet S-10	70	nil	130	151	30

Table 11. Idle-plus-restart emissions rate data.

Vehicle #	Vehicle	Emissions rates (mℓ/s)			
		HC	CO	NO_x	Total Emissions Rate
1	'82 Ford Fairmont	1.7	10.22	.39	12.31
7	'83 Pontiac Firebird	.39	28.8	.52	29.7
12	'82 Datsun 210	2.18	11.22	.16	13.56
13	'82 Chevrolet Wagon	.18	2.82	.17	3.17
14	'81 Buick Century	3.25	56.5	.04	59.8
15	'84 Chevrolet S-10	.35	nil	.65	1.0

Table 12. Emission volumes for the two different tests.

Vehicle #	Vehicle	Test duration (s)	IDLE-ONLY Emissions volume (mℓ)				IDLE + RESTART Emissions volumes (mℓ)			
			HC	CO	NO_x	Total	HC	CO	NO_x	Total
1	'82 Ford Fairmont	30	67.2	44.1	6.9	118.2	51	306.6	11.7	369.3
7	'83 Pontiac Firebird	30	2.7	nil	5.4	8.1	11.7	864	15.6	891
12	'82 Datsun 210	60	75	369.6	4.8	449.4	130.8	673.2	9.6	813.6
13	'82 Chevrolet Wagon	60	10.2	47.4	11.4	69	10.8	169.2	10.2	190.2
14	'81 Buick Century	60	382.2	12,960	2.4	13,344	195	3,390	2.4	3,588
15	'84 Chevrolet S-10	30	6.6	nil	21.9	28.5	10.5	nil	19.5	30

70

Table 13. Restart penalties and break-even times.

Vehicle #	Vehicle	Restart penalty (ml)				Break-even time (s)			
		HC	CO	NO_x	Total of the three	HC	CO	NO_x	Based on total
1	'82 Ford Fairmont	−16.2	262.5	4.8	251.1	Negative	179	21	64
7	'83 Pontiac Firebird	9	864	10.2	883.2	100	∞	57	3271
12	'82 Datsun 210	55.8	303.6	4.8	364.2	45	49	60	49
13	'82 Chevrolet Wagon	.6	121.8	−1.2	121.2	3.5	154	Negative	105
14	'81 Buick Century	−187.2	− 9750	0	− 9757	Negative	Negative	0	Negative
15	'84 Chevrolet S-10	3.9	0	−2.4	1.5	18	0	Negative	1.6

Obviously, the results presented in Table 13 are not very conclusive. For the Buick Century there is actually a benefit for restarting, and the authors do not believe that this is a generally true result. For one to try to glean from among the various break-even times for the individual pollutants some guideline to propose as a general rule appears to be frustrating. Therefore, the authors propose to confine attention only to the break-even time as calculated from the total emissions rate. In this case, the results for the Fairmont, the Datsun, and the Chevrolet Wagon actually look reasonable. One might intuitively expect that a warmed-up car idling for about one to two minutes would emit about the same as that caused by a shut-down and restart of the engine.

One other caution that should be added to those enumerated at the beginning of this section is the following: the stop and restart tests conducted for this investigation were carried out such that the restart occurred immediately after engine shut-down. In real world situations, there may be considerable time between engine shut-down and restart — so much time that the catalyst may become cold and ineffective at the beginning of the car's running again. This would tend to increase the penalty for the restart and would raise the break-even time considerably. Thus, there really is no simple answer from this study that should be applied to everyday driving situations.

Appendix E. Study of Ambient Temperature Effects on
Fuel Consumption Table Results

OBJECTIVE: Determine correction factors for ambient temperature effects
that can be applied to fuel consumption table values to account for
conditions at different ambient temperatures.

METHODOLOGY

Since ambient temperature has a nontrivial effect on fuel economy,
an effort was made to take account of this effect in the simulation of
fuel consumption and in the fuel consumption tables. A review of past
studies leads to the conclusion that temperature effects are very
vehicle-specific and probably significantly higher for smaller cars than
for large cars (see Hodgson [1982]). For this reason temperature effects
were investigated for each of the fifteen test cars, with the aim of
deriving a temperature adjustment factor for each one. In the end the
results were not good enough to derive factors for each car, but two
factors were estimated: one for cars with 4-cylinder engines, and one
for larger cars. It was most cost-effective to use the same data
collected for simulation purposes as a basis for inferring temperature
effects. The advantage of this approach is that it makes available a
very large data set for the study of temperature effects at very little
extra cost. The disadvantage is that the relatively small effect of tem-
perature must be distinguished from the much larger effects of vehicle
speed and acceleration.

EXPERIMENTAL PROCEDURE

To quantify temperature effects it is best to conduct tests over as
wide a temperature range as possible. But time and money constraints
dictated that road testing take place during a period of only two days
or so. To maximize temperature variation, the data gathering for the
vehicles was split into two identical series of tests. One series was
run in the cool of the early morning, shortly after dawn, and a second
series (when possible) was run in the heat of the afternoon. The tem-
perature ranges obtained, which appear in Table 14, are as narrow as
0.7°C and as wide as 17°C.

ANALYTICAL METHOD

One stage of simulation map construction was to overlay the speed/
acceleration plane with a rectangular grid and fit a quadratic polynomial

Table 14. Ambient temperature range and mean temperature during road testing of the 15 test vehicles

Automobile	Ambient temperature range (°C)	Mean temperature (°C)
1. 1982 4-cylinder Ford Fairmont	15 to 25	20.75
2. 1982 4-cylinder Chevrolet Citation	20 to 29	22.52
3. 1982 6-cylinder Ford Futura	17 to 24	22.09
4. 1983 4-cylinder Plymouth Reliant	8 to 15	9.81
5. 1982 4-cylinder Toyota Corolla	7 to 19	13.90
6. 1983 4-cylinder Ford Escort	20 to 22	21.24
7. 1983 6-cylinder Pontiac Firebird	−0.4 to 0.3	−0.16
8. 1983 6-cylinder Chevrolet Monte Carlo	16 to 24	19.94
9. 1982 4-cylinder Chevrolet Chevette diesel	23 to 34	29.82
10. 1981 8-cylinder Chevrolet Caprice diesel	19 to 33	25.90
11. 1983 8-cylinder Chevrolet diesel pickup	−4 to 5	1.16
12. 1982 4-cylinder Datsun 210	11 to 28	20.57
13. 1982 8-cylinder Chevrolet Caprice SW	24 to 34	28.84
14. 1981 6-cylinder Buick Century	24 to 32	28.57
15. 1984 4-cylinder Chevrolet S-10 pickup	20 to 30	25.62

to observations of fuel flow rate in the vicinity of each grid point. To correct for its effect, ambient temperature was made a third independent variable in the polynomial, resulting in the regression equation.

$$f = q(v, a, \Delta T) ,$$

where

$$q(v, a, \Delta T) = \beta_0 + \beta_1 v + \beta_2 v^2 + \beta_3 a + \beta_4 a^2 + \beta_5 va + \beta_6 \Delta T ,$$

and where $\beta_0, \ldots, \beta_6$ are the coefficients to be estimated. Here v is vehicle speed (km/h), a is acceleration (g's), and f is the fuel flow rate (based on measured engine speed and manifold vacuum) at the time v and a were measured. Also ΔT is the difference between the ambient temperature at the time v and a were measured and the mean ambient temperature during road testing of that car.

The magnitude of the temperature effect was not inferred from the coefficient β_6 because there is a different β_6 for each grid point, and no single β_6 is based on enough data to make its estimate reliable. Rather, the coefficients in the following regression formulas (among others) were estimated.

$$\Delta f = \beta_1 \Delta T , \qquad \text{(Model 1)}$$

$$\Delta f = \beta_1 \Delta T + \beta_2 a \Delta T , \qquad \text{(Model 2)}$$

$$\Delta f = \beta_1 \Delta T + \beta_2 \Delta a \Delta T + \beta_3 \Delta v \Delta T , \qquad \text{(Model 3)}$$

where $\Delta v = v - 60$ (km/h), and Δf is the percent deviation of actual fuel flow from that predicted for speed v and acceleration a at the mean ambient temperature. That is,

$$\Delta f = 100[f - q(v, a, 0)]/f .$$

Thus β_1 can be interpreted as the percent change in fuel flow rate per degree Celsius when the car is cruising at a steady 60 km/h. Any interaction between this temperature sensitivity and the car's speed and acceleration would presumably be reflected by β_2 and β_3.

In theory, Model 2 should be superior to Model 1, for the following reason. Note first that a large fraction of the ambient temperature effect can be explained by the change in air density that results from a change in temperature. A 1°C rise in air temperature causes a 0.37% decrease in air density, which effects a 0.37% decrease in air drag at a

75

given speed. If air drag accounts for about half of road load, we should expect roughly a 0.2% drop in fuel consumption per 1°C rise in temperature. This is on the order of magnitude of the 0.07 to 0.36% drop reported in the literature (Hodgson [1982]). But if changes in air drag account for so much of the temperature effect, a 1°C rise in temperature should cause a smaller percent reduction in fuel flow rate at high acceleration, when a larger fraction of fuel use is unrelated to air drag, than at low or negative acceleration. Thus Model 2, which takes into account the effect of acceleration on temperature sensitivity, should provide a better estimate of sensitivity than Model 1.

For similar reasons, Model 3 should be superior to Model 2, since it accounts for any effect of speed on temperature sensitivity. The effect of a change in air drag on fuel consumption should certainly increase with speed, and the other components of the temperature effect may not vary with speed in such a way as to offset this increase. Thus we should expect to see temperature sensitivity rise with speed.

INTERPRETATION OF RESULTS

Estimates of β_1, β_2 and β_3 in Models 1–3 for 14 of the 15 cars appear in Tables 15 and 16. No analysis was performed for the Pontiac Firebird, since the 0.7°C temperature range during testing would make any results ipso facto meaningless. Table 17 summarizes the temperature sensitivities in the three models.

At first glance the results may show no pattern, but on closer examination all but two of the counterintuitive results can apparently be explained, and a fair idea of the temperature effect for both small and large cars can be had.

Note first in Tables 15 and 16 that the interaction effect of acceleration is in most cases negative, as it should be. In those cases where it is positive or a negative number seriously out of line with the others, the temperature sensitivity is likewise unreasonable. Thus an explanation of the unreasonable sensitivities (below) should lead us to expect unreasonable interactions with acceleration. (The interaction figures are large because they represent percent change in fuel flow rate per one g change in acceleration, a very large acceleration unit.)

The interaction with speed (Table 16) is evidently very small and in many cases not significantly different from zero. The confidence bounds themselves are only estimates, based on the assumption that the regression equation is of the correct from to describe the underlying phenomena. These estimates should therefore be considered very rough, since the underlying temperature effects are unlikely to be linear, as the model assumes. It is best to conclude that the speed interaction is too small to measure with any statistical reliability.

76

Table 15. Estimated coefficients in Models 1 and 2, with
90% confidence intervals

Automobile	Model 1	Model 2	
	β_1	β_1	β_2
1. 4-cylinder Ford Fairmont	−1.30 ± 0.14	−1.26 ± 0.13	38.4 ± 5.4
2. 4-cylinder Chevrolet Citation	−0.36 ± 0.16	−0.21 ± 0.18	−12.5 ± 6.5
3. 6-cylinder Ford Futura	−0.25 ± 0.20	−0.19 ± 0.20	−7.7 ± 4.9
4. 4-cylinder Plymouth Reliant	−0.57 ± 0.18	−0.47 ± 0.18	−14.3 ± 6.5
5. 4-cylinder Toyota Corolla	−0.19 ± 0.12	−0.18 ± 0.12	−3.8 ± 3.5
6. 4-cylinder Ford Escort	1.86 ± 1.39	2.34 ± 1.40	−113.8 ± 46.2
7. 6-cylinder Pontiac Firebird	no analysis performed		
8. 6-cylinder Chevrolet Monte Carlo	0.57 ± 0.13	0.93 ± 0.14	−26.6 ± 4.9
9. 4-cylinder Chevrolet Chevette diesel	0.94 ± 0.13	1.04 ± 0.13	30.6 ± 5.3
10. 8-cylinder Chevrolet Caprice diesel	−0.14 ± 0.11	−0.16 ± 0.11	8.7 ± 4.1
11. 8-cylinder Chevrolet diesel pickup	1.17 ± 0.08	1.29 ± 0.08	−18.6 ± 3.0
12. 4-cylinder Datsun 210	−0.06 ± 0.04	−0.06 ± 0.04	1.4 ± 2.1
13. 8-cylinder Chevrolet Caprice SW	10.59 ± 0.38	8.95 ± 0.35	−294.9 ± 16.6
14. 6-cylinder Buick Century	0.50 ± 0.09	0.54 ± 0.09	−31.0 ± 3.6
15. 4-cylinder Chevrolet S-10 pickup	−0.45 ± 0.08	−0.46 ± 0.08	−1.5 ± 4.2

Table 16. Estimated coefficients in Model 3, with 90% confidence intervals

Automobile	β_1	β_2	β_3
1. 4-cylinder Ford Fairmont	-1.47 ± 0.20	-0.007 ± 0.005	37.8 ± 5.4
2. 4-cylinder Chevrolet Citation	-0.29 ± 0.29	0.002 ± 0.007	-12.0 ± 6.7
3. 6-cylinder Ford Futura	-0.12 ± 0.28	-0.003 ± 0.006	-7.8 ± 4.9
4. 4-cylinder Plymouth Reliant	0.06 ± 0.25	-0.022 ± 0.007	-15.4 ± 6.4
5. 4-cylinder Toyota Corolla	-0.16 ± 0.13	-0.002 ± 0.004	-4.2 ± 3.6
6. 4-cylinder Ford Escort	5.82 ± 1.61	-0.208 ± 0.050	-140.5 ± 46.0
7. 6-cylinder Pontiac Firebird	no analysis performed		
8. 6-cylinder Chevrolet Monte Carlo	1.06 ± 0.16	-0.009 ± 0.004	-26.8 ± 4.9
9. 4-cylinder Chevrolet Chevette diesel	1.20 ± 0.14	0.003 ± 0.005	26.5 ± 5.5
10. 8-cylinder Chevrolet Caprice diesel	-0.23 ± 0.14	0.003 ± 0.004	9.3 ± 4.1
11. 8-cylinder Chevrolet diesel pickup	1.00 ± 0.10	0.016 ± 0.003	-18.9 ± 2.9
12. 4-cylinder Datsun 210	0.06 ± 0.06	-0.006 ± 0.002	-0.2 ± 2.1
13. 8-cylinder Chevrolet Caprice SW	13.02 ± 0.44	-0.181 ± 0.013	-347.6 ± 15.8
14. 6-cylinder Buick Century	0.86 ± 0.12	-0.012 ± 0.003	-35.4 ± 3.4
15. 4-cylinder Chevrolet S-10 pickup	-0.13 ± 0.12	-0.017 ± 0.004	-8.9 ± 4.6

Examination of Table 17 reveals that, for some cars, the speed interaction term of Model 3 absorbs a large part of the variation that the acceleration term explains in Model 2. This effect, common in regression studies, is probably spurious. It suggests that the Model 2 estimates of β_1 should be taken as more reliable than the Model 3 estimates. Since Model 2 captures the acceleration interaction, which is clearly large enough to measure, it should likewise be regarded as better than Model 1.

Past studies suggest that the temperature sensitivity should be on the order of 0.1 or 0.2% change in fuel flow rate per °C for larger cars, and greater for smaller cars. In view of this, five of the 14 Model 2 temperature sensitivities (Table 17) are reasonable. All but two of the others can apparently be explained by the wind conditions. Since the effect of air density change is on the same order as the temperature effect, one should expect any wind change between morning and afternoon to overpower the temperature effect. In particular, the presence of wind, even if it is parallel to the track, raises fuel consumption. This is because downwind test runs do not compensate for upwind runs (due to the nonlinear relation between air drag and fuel use), and because wind at (even a small) angle to the direction of travel sets up eddies that can substantially increase drag. Thus if it were calm in the cool morning and windy in the warm afternoon, fuel consumption may appear to rise with temperature.

Table 18 presents the wind conditions during testing of each car during four periods of the day (early and late morning, early and late afternoon). This permits an assessment of each sensitivity in light of the weather.

First, three 4-cylinder cars already have reasonable sensitivities for small cars: the Citation, Reliant, and S-10 pickup. Table 14 shows a wide temperature range for each, and Table 18 shows that winds were calm or very slight all through the testing of either car. (The Citation's Model 2 sensitivity is a little low, and the Model 1 and 3 sensitivities may be closer to the mark.) The Toyota and especially the Datsun sensitivities are low. In both cases winds were calm during the cool testing (early morning) and significant during warm testing (late morning or afternoon), which would tend to offset the temperature effect. The two remaining 4-cylinder cars, the Escort and Chevette, show sensitivities that are of the wrong sign and too large by an order of magnitude. The Escort was tested during stiff and variable winds, over a temperature range of only 2°C; one should not expect meaningful results. There is no apparent explanation, however, for the Chevette sensitivity.

Two of the larger cars have reasonable sensitivities: the Futura and Caprice diesel. Both were tested over a wide temperature range with no wind. The other four large cars — the Monte Carlo, Chevrolet diesel pickup, Caprice station wagon and Buick — have large positive sensitivities. In all cases but the Caprice, winds were absent in the morning and present in the afternoon. This could account for the

Table 17. Summary of estimates of ambient temperature sensitivity in percent change in fuel flow rate per degree Celsius

Automobile	Model 1	Model 2	Model 3
1. 4-cylinder Ford Fairmont	−1.30 ± 0.14	−1.26 ± 0.13	−1.47 ± 0.20
2. 4-cylinder Chevrolet Citation	−0.36 ± 0.16	−0.21 ± 0.18	−0.29 ± 0.29
3. 6-cylinder Ford Futura	−0.25 ± 0.20	−0.19 ± 0.20	−0.12 ± 0.28
4. 4-cylinder Plymouth Reliant	−0.57 ± 0.18	−0.48 ± 0.19	+0.06 ± 0.25
5. 4-cylinder Toyota Corolla	−0.19 ± 0.12	−0.18 ± 0.12	−0.16 ± 0.13
6. 4-cylinder Ford Escort	+1.86 ± 1.39	+2.34 ± 1.40	+5.82 ± 1.61
7. 6-cylinder Pontiac Firebird	no analysis performed		
8. 6-cylinder Chevrolet Monte Carlo	+0.57 ± 0.13	+0.93 ± 0.14	+1.06 ± 0.16
9. 4-cylinder Chevrolet Chevette diesel	+0.94 ± 0.13	+1.04 ± 0.13	+1.20 ± 0.14
10. 8-cylinder Chevrolet Caprice diesel	−0.14 ± 0.11	−0.16 ± 0.11	−0.23 ± 0.14
11. 8-cylinder Chevrolet diesel pickup	+1.17 ± 0.08	+1.29 ± 0.08	+1.00 ± 0.10
12. 4-cylinder Datsun 210	−0.06 ± 0.04	−0.06 ± 0.04	+0.06 ± 0.06
13. 8-cylinder Chevrolet Caprice SW	+10.59 ± 0.38	+8.95 ± 0.35	+13.02 ± 0.44
14. 6-cylinder Buick Century	+0.50 ± 0.09	+0.56 ± 0.09	+0.86 ± 0.12
15. 4-cylinder Chevrolet S-10 pickup	−0.45 ± 0.08	−0.45 ± 0.08	−0.13 ± 0.12

Note: Results for each of three models are shown, along with 90% confidence intervals.

Table 18. Wind conditions during road testing of the fifteen test automobiles

Automobile	Early morning	Late morning	Early afternoon	Late afternoon
1. 4-cylinder Ford Fairmont	5-6 km/h P	5-6 km/h P	No tests	No tests
2. 4-cylinder Chevrolet Citation	Calm	Calm	No tests	1-2 km/h P
3. 6-cylinder Ford Futura	Calm	Calm	Calm	No tests
4. 4-cylinder Plymouth Reliant	Calm	1-2 km/h P	No tests	No tests
5. 4-cylinder Toyota Corolla	Calm	9-11 km/h	No tests	No tests
6. 4-cylinder Ford Escort	Variable, gusts 13-16 km/h P	No tests	No tests	No tests
7. 6-cylinder Pontiac Firebird	11-16 km/h P	No tests	6-8 km/h P	8-10 km/h P
8. 6-cylinder Chevrolet Monte Carlo	Calm	Calm	Slight breeze, occasional gusts to 8 km/h	
9. 4-cylinder Chevrolet Chevette diesel	Calm	Calm	Calm	Calm
10. 8-cylinder Chevrolet Caprice diesel	Calm	Calm	Calm	Calm
11. 8-cylinder Chevrolet diesel pickup	Calm	3 km/h P	16 km/h, gusts to 30 km/h A	
12. 4-cylinder Datsun 210	Calm	11-13 km/h P	No tests	Slight breeze
13. cylinder Chevrolet Caprice SW	Calm	Calm	Calm	Calm
14. 6-cylinder Buick Century	Calm	6-8 km/h P	Slight breeze, gusts to 5-6 km/h	
15. 4-cylinder Chevrolet S-10 pickup	Calm	Calm	Calm	Calm

Note: "P" indicates wind parallel to the test track, "A" wind across the track.

apparent positive sensitivity. There is no apparent explanation for the highly anomalous Caprice results.

TEMPERATURE CORRECTION FACTORS

The fuel consumption simulators (i.e., computer models) were supplied with two temperature correction factors: one for 4-cylinder cars and one for larger cars. The small-car factor was estimated by averaging the three reasonable sensitivities mentioned above: —0.21% per °C for the Citation, —0.48% for the Reliant and —0.45% for the S-10 pickup. The large-car factor was obtained by averaging the two reasonable large-car sensitivities: —0.19% for the Futura and —0.16% for the Caprice diesel. The resulting sensitivites are,

—0.38% change in fuel flow rate per °C for 4-cylinder cars, and

—0.18% change in fuel flow rate per °C for larger cars.

The simulation polynomials, tables and plots delivered to FHWA contain fuel flow rates that are not adjusted for ambient temperatue. These should be interpreted as representing fuel consumption for the mean ambient temperature during testing. Table 14 lists these mean temperatures.

When the simulation routine is called, an ambient temperature must be passed to it, as well as the speed, acceleration, road grade and (optionally) gear. The routine automatically adjusts for ambient temperature, using the above factors. If an unadjusted fuel flow rate is desired, the ambient temperature should be set to the mean temperature during testing shown in Table 14.

Past studies suggest that the temperature effect is not linear over a wide temperature range. For this reason the temperature adjustments become rapidly less reliable as one moves away from the mean testing temperature. Fuel consumption simulation results should be used with this in mind.

REFERENCE

Hodgson, J. W., 1982. "Effects of Ambient Temperature on Vehicle Fuel Economy -- A Literature Review," prepared for FHWA. Mechanical and Aerospace Engineering Department, University of Tennessee, Knoxville.