REPORT

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WYLE RESEARCH REPORT

WR 79-23

LIGHT VEHICLE NOISE: VOLUME V – AN URBAN DRIVING STUDY TO DETERMINE THE OPERATING AND ACOUSTIC EMISSION CHARACTERISTICS OF LIGHT VEHICLES

For

U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Noise Abatement and Control
Arlington, Virginia 22202

Contract No. 68-01-3948

By

Eric Stusnick
Peter K. Kasper

WYLE RESEARCH
Arlington, Virginia 22202

August 1979

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1.0 INTRODUCTORY SUMMARY

1.1 Background

There are several existing methods for measuring the noise emissions of automobiles and light trucks, collectively termed light vehicles. In general these methods involve operations that are not representative of the way in which vehicles are typically driven, and hence, are considered unsatisfactory as they do not rank vehicles in accordance with their contribution to community noise. The method currently in general use in the United States is the Society of Automotive Engineers (SAE) J986b procedure[1] that specifies the measurement of sound for full-throttle vehicle operation at speeds in excess of 30 mph. From existing vehicle driving studies, it is known that full-throttle acceleration is not a typical mode of operation for most light vehicles, and hence, is responsible for only a small part of urban community noise. Further, vehicles exhibiting similar sound levels as measured by the SAE J986b procedure do not necessarily contribute equally to community noise. It has also been observed that the noise reductions achieved by many engineering treatments as measured under full-throttle conditions are not as great in other less severe but more typical operating conditions.[2] The standard method of measurement used in Europe — namely, the International Standards Organization (ISO) R362 procedure[3] — is very similar to the SAE J986b procedure in terms of vehicle operation and hence, is equally unsatisfactory in representing typical operating conditions.

The failure of the existing full-throttle test procedures to reproduce the sound levels typically generated in the community has led to the development of alternative test procedures based on studies of urban driving characteristics. The U.S. Environmental Protection Agency has proposed a light vehicle noise test procedure that simulates the noise emissions from light vehicles accelerating in urban areas.[4] The test involves a partial-throttle acceleration of the vehicle to achieve a given operating condition determined from an analysis of available driving data and the results of a limited series of driving experiments. The General Motors Corporation has also developed a noise test procedure based on acceleration data obtained from driving studies conducted in two U.S. cities.[5] Note that both these test procedures address the acceleration mode only.

An alternative test procedure to determine vehicle noise emissions under the more typical partial-throttle operation has been proposed by the Comite des Constructeurs

D'Automobile du Marche Commun (Committee of Common Market Automobile Constructors — CCMC).[6] This method takes advantage of the relative simplicity and repeatability of the full-throttle test procedure, and involves the interpolation ofsound levels measured during full-throttle and cruise operations according to a formula developed from urban driving studies. These studies were conducted in several cities and provide a fairly comprehensive data base of European driving characteristics. However, it is not known whether these characteristics are typical of those exhibited by drivers in the United States.

The fundamental concern underlying the selection of noise test methodology is the reduction of vehicle noise in communities. In order to achieve such a reduction, it is necessary to identify the specific automobile operations that produce the impact and then reduce the sound levels associated with these operations. The sound levels before and after abatement measures are applied must be measured by subjecting the automobile to a standard test procedure. The levels measured under this procedure should be representative of those to which the community is exposed, which means that the test procedure should include the operations that produce most of the vehicle noise emission.

The development of a measurement procedure to satisfy this requirement can be subdivided into three stages, namely:

- Determination of typical vehicle operating modes;
- Determination of the noise produced by automobiles in each of these typical modes;
- Determination of the contribution of each mode to the total noise emission.

Once the contribution of each operating mode is known, a test procedure can be constructed which represents, or is directly relatable to, those modes which are most significant to the total noise emission.

There are five sources of information which provide some indication of typical light vehicle operation in urban traffic conditions. These sources include:

- CAPE-10 Vehicle Operation Survey[7]
- EPA Urban Driving Cycle[8]
- General Motors Chase-Car Study[9]

- Wyle Traffic Motion Measurements[4]
- General Motors Urban Acceleration Rate Study[10]

Although many of these studies are quite extensive, each has sufficient limitations that none can be used to determine which vehicle operating conditions are the major contributors to the noise emission.

Of the five sources of information, the results of the General Motors Chase-Car Study of 1974 have been most often cited as an appropriate data base from which vehicle operation can be defined for noise exposure calculations. The "chase car" technique utilizes an instrumented vehicle in an attempt to follow and simulate visually and thereby monitor the behavior of individual vehicles in a flow of traffic. This technique has several limitations. The first is the ability of the chase-car to simulate accurately the acceleration of the vehicle being chased. The instantaneous value of acceleration is considerably more difficult to duplicate visually than steady or slowly varying speed because of the added derivative of time. The duplication of acceleration is also inexact because the manner in which a vehicle accelerates depends on both the characteristics of the vehicle and the driver. Thus, chase-car acceleration is strongly biased by the chase-car and the operator of the chase-car. In addition to the difficulty of duplicating the acceleration of another vehicle, the acceleration was not measured directly in the GM study, but was derived from the vehicle speed which was sampled at one-second intervals. From these data, it is difficult to define the detailed vehicle acceleration characteristics.

Another limitation of the chase-car technique is that it is not suited for either high or low density traffic situations. In high density traffic, contact with the chased vehicle can be lost easily due to lane changes or by vehicles coming in between the two vehicles. In low density traffic, it is difficult for the chase-car to remain undetected so that it does not influence the operator of the chased vehicle. A final limitation is that engine speed, the vehicle parameter most directly related to noise production, cannot be monitored with this method; thus, there is no accurate way of relating the measured operating conditions to vehicle noise emission.

In a similar manner, the CAPE-10 Study has several limitations which make it unacceptable as an information source of vehicle noise emission as a function of operating mode. It employed the chase-car data collection method and hence, suffers from the limitations described above. Further, it was conducted for purposes of determining exhaust emissions and hence, contains no information relating to the occurrence of operating mode with local environment, road type, population density, or traffic congestion, all of which may be important for purposes of determining noise exposure. Further, it was conducted in 1971 prior to the increased public awareness of fuel economy.

Several aspects of the EPA Urban Driving Cycle prohibit its use as a sole source of typical vehicle operation information for purposes of noise impact. Unlike the CAPE-10 and GM studies, the EPA Cycle utilized an instrumented vehicle directly for data collection. The Cycle consists of a velocity profile obtained from an instrumented vehicle as it was driven over a prescribed route in Los Angeles, CA. This route was developed to represent the morning home-to-work trip which is believed to be the type of urban trip which most significantly contributes to the air pollution problem in the Los Angeles area. The relationship of this type of trip to vehicular noise emission is not known, and indeed, the driving cycle for quantifying air pollution may be less sensitive to certain vehicle operating modes than that for noise exposure.

There are several aspects of the EPA Urban Driving Cycle that influence details of the velocity profile which are important for determining typical noise emission. Since only one vehicle was used in developing the Cycle, the derivative of the velocity profile (acceleration) is biased by that particular vehicle. Also, the Cycle has been modified so that accelerations greater than 4.84 ft/sec^2 (0.15g) do not occur. This is required so that the trip may be duplicated on a dynamometer.

Unlike the other three studies, the Wyle study was not designed to establish general vehicular operational patterns. The intent of the study was to demonstrate a specific data collection technique and to obtain very limited data for purposes of comparison to the other studies. The study was performed by making a high-speed movie at a road intersection for a given period of time, and subsequently replaying the movie, frame by frame, to measure the distance traveled by each vehicle. In this way, vehicle velocity (sampled 24 times per second) and hence, acceleration could be determined. It was not possible to measure engine RPM by this remote technique. Because of the very limited nature of the study, it cannot be used to determine vehicle operations for noise emission purposes.

A recent addition to the existing data base of urban vehicle operation is the General Motors Urban Acceleration Rate Study of 1978. This experiment measured vehicle speed and acceleration, engine RPM, and throttle setting for a series of trips for each of five vehicles. Each vehicle was driven by ten drivers over two different routes — one in the Phoenix, Arizona area, the other in the San Fernando Valley near Los Angeles, California. The data for each operating parameter was recorded on strip-charts and later manually abstracted for analysis.

Since the purpose of the experiment was to characterize typical accelerations from intersections, only acceleration events which began at or below 8 mph and continued through 30 mph were included in the analysis. The results of the analysis are presented as sets of 50th percentile and 90th percentile bands showing typical and extreme relations between vehicle acceleration and vehicle speed and between vehicle speed and distance traveled.

Although this G.M. study is one of the most complete to date, it cannot effectively be used to determine these vehicle operating conditions which are the major contributors to noise emission in urban traffic. Only the speeds and accelerations for a specific single operating condition have been analyzed. To manually abstract from the strip charts of speed, acceleration, and RPM data for all types of urban vehicle operation would be a monumental undertaking. It would be much more cost effective to gather data anew, in a format that allows computerized processing and analysis.

Other limitations to this G.M. study are that no manual transmission vehicles were included in the data base, no assurance was made that the routes used were in any sense typical of urban roadways, and no attempt was made to tailor the test driving population to the characteristics of the national driving population.

The purpose of the study described in this report is to experimentally determine the vehicle modes contributing most to community noise, and to use this data to define a suitable noise test procedure applicable to light vehicles operating in urban areas. Previous studies[4,11] have provided a data base of noise emission levels from 66 vehicles for various conditions of vehicle speed (V), acceleration (A), and engine RPM (R). In this program, investigations were carried out on a subset of this group of vehicles to determine combinations of values of these operating parameters that are typical of urban driving. The operating data was collected in a form that would allow easy computer processing. Both automatic and manual transmission vehicles representing a wide range of engine types were included in the study. The vehicles were driven over a test route that contains a distribution of roadway types that is representative of the national average urban roadway system. A large population of drivers was employed, the characteristics of which are generally typical of those of the national driving population.

The results of this driving study were combined with the existing noise level data base to provide a joint distribution of emitted acoustic energy as a function of vehicle speed, acceleration, and engine RPM for a typical urban trip for each vehicles. From these distributions, three candidate measurement methodologies have been developed.

1.2 Overview of Program

To determine vehicle operating conditions that are representative of urban areas, nine automobiles were driven over a fixed route in the metropolitan Washington, D.C. area by a selection of non-professional drivers. Trips were made by each driver in both rush-hour and non-rush-hour traffic conditions. The vehicles were instrumented to measure and digitally record the vehicle speed and acceleration and the engine RPM.

The vehicles selected for this study represent a wide range of body styles and weights, engine sizes and displacements, and transmission types.

The route selected for this study was a 24.6-mile closed loop that went from the suburban community of Alexandria, VA, to the city of Washington, D.C., and back. It was designed in such a manner that the percentages of expressway, arterial, collector, and local road segments were similar to the corresponding averages for the urban road system in the United States. The average trip time on this route was 60 minutes.

The driving population employed in this study consisted of 157 subjects stratified over age, sex, and marital status in such a way as to be representative of the licensed driving population in the United States.

The instrumentation in each vehicle consisted of an electrical ignition pickup for measuring engine speed, an optical encoder coupled to the speedometer cable to measure vehicle speed, and a strain-gauge accelerometer to measure vehicle acceleration. Power supplies and signal conditioners coupled these transducers to a digital data logger which sampled each of the three parameters once every 104 msec, and recorded the result on magnetic tape. Every second sample of each parameter on these tapes was transferred in the laboratory onto floppy disks, resulting in an effective sampling rate of 208 msec. The resultant data was then analyzed using a minicomputer.

Computer software was developed to transform the time history of vehicle speed, acceleration, and engine RPM for each vehicle into joint statistical distribution functions of these three variables. In performing this binning procedure, increments of 5.0 mph, 0.025g, and 250 RPM were used for speed, acceleration, and RPM, respectively. The set of distributions for the trips for a given vehicle were combined to produce an average distribution for that vehicle.

Next, multiple linear regressions were performed on the acoustic data base available for each vehicle to establish the relationship between sound level and vehicle operating conditions. Tire noise contributions were removed from the data base before performing the regressions. Using these relationship, a sound level value was obtained for each speed-acceleration-RPM combination in the vehicle operation distribution.

These sound levels were combined with the vehicle operation distribution function to produce an acoustic energy distribution function for each vehicle. Each cell of this energy distribution function gives the fraction of the total acoustic energy emitted during the trip that corresponds to the particular speed-acceleration-RPM combination. By locating the maxima of this distribution function and by performing averages over combinations of each of the three independent operating parameters, the vehicle operating modes corresponding to the maximum acoustic energy emission were identified for each vehicle. The operating modes so identified for each vehicle were then compared between vehicles to identify commonality among the different vehicles.

1.3 Major Findings

Based on the analysis of the acoustic energy distributions described above, three candidate test methodologies were developed. The first methodology, a bi-modal test corresponding to a cruise and an acceleration region that account for most of the acoustic energy emission, consists of the following test conditions:

- Cruise: 41 mph, 0.00g, 51 percent rated RPM
- Acceleration: 29 mph, 0.09g, 47 percent rated RPM.

The second candidate methodology is a bi-modal test corresponding to an intermediate and a high speed range, which together account for most of the vehicle noise emission. It consists of the following test conditions:

- Intermediate Speed: 30 mph, 0.04g, 44 percent rated RPM
- High Speed: 53 mph, 0.00g, 60 percent rated RPM.

The third candidate methodology is a tri-modal test corresponding to intermediate speed cruise, intermediate speed acceleration, and high speed cruise ranges. The test conditions for this methodology are:

- Intermediate Speed Cruise: 33 mph, 0.00g, 43 percent rated RPM
- Intermediate Speed Acceleration: 27 mph, 0.10g, 46 percent rated RPM
- High Speed Cruise: 54 mph, 0:00g, 61 percent rated RPM.

It should be noted that, for automatic transmission vehicles, the intermediate speed acceleration condition is essentially the same as Test Condition 2 in the EPA Urban Acceleration Noise Test Procedure for light vehicles,[4] which specifies an acceleration of 0.12g at 25 mph, corresponding in practice to 0.12g at 47 percent of the maximum rated engine speed.

Further field studies remain to be carried out to validate these proposed vehicle operating conditions on a large number of light vehicles and to determine how the effects, on the test of tire noise can be minimized. Experiments also should be conducted to investigate the feasibility of replacing some of these moving tests with stationary test procedures.

2.0 EXPERIMENTAL METHODOLOGY

2.1 Introduction

The purpose of the experimental program was to establish a data base of vehicle operating parameters which is representative of the way light vehicles are typically operated in urban areas of the United States. Since the intended application of this data base is to develop a vehicle noise test methodology, the operating parameters monitored were those which correlate most strongly with noise emission. The method chosen for obtaining this data was to instrument a selected number of test vehicles and record operating parameters as they were driven by non-professional drivers along a preplanned route. The program was conducted within the metropolitan area surrounding Washington, D.C. The route itself was chosen to provide a relative representation of the major road types found in urban areas within the United States. The experimental methodology is discussed below in terms of the following:

- Test vehicle selection
- Route selection
- Driver selection
- Instrumentation
- Experimental procedures.

2.2 Test Vehicle Selection

A major consideration in selecting vehicles for the experimental program was the requirement that acoustical data be available to characterize the noise emission under various operating conditions. In view of the extensive vehicle noise data base acquired under the EPA Light Vehicle Testing Program[4,10] previously carried out by Wyle Laboratories during 1977 in Marana, Arizona, vehicles for the current program were chosen to be representative of those in the Marana study.

In addition to the availability of an acoustic emission data base, other factors considered in the selection of test vehicles were the requirements that they be representative of:

- major vehicle body types,
- major vehicle manufacturers,

- common engine and transmission types, and
- common vehicle performance characteristics, such as engine displacement and rated engine power.

Finally, as a practical matter, an important factor was the short term availability of the vehicles within the Washington, D.C. metropolitan area.

Applying these criteria, nine vehicles were obtained for use in the program. A listing of these vehicles and their specifications is shown in Table 2.1(a), while a listing of the corresponding Marana vehicles is shown in Table 2.1(b). As can be seen in these tables, many of the vehicles obtained for this study are later models than the 1977 versions used in the Marana program. In these cases, it was not expected that the year-to-year model change would have an appreciable effect on vehicle noise emission since in all cases the power train and curb weight of each vehicle driven in this study was the same as that in the Marana study. A further change from the vehicles in the Marana program was the substitution of the Chevrolet Camaro and Oldsmobile Omega which again, have identical power trains and similar curb weights as the corresponding Marana vehicles.

2.3 Route Selection

Selection of the test route was made on the basis of the following crtieria:

- The route must, in some sense, be representative of a "national average";
- The route must be sufficiently straightforward that an untrained driver can traverse it without getting lost after only one or two practice runs;
- To facilitate the experimental logistics, the route should be located in the Washington, D.C. metropolitan area; and
- Because the recording time available on the digital data logger is 90 minutes, the length of the route must be such that it can reasonably be traversed in less than this time during rush hour.

In addition to the above requirements, it was felt that the route should be a closed loop, rather than a linear design that would be traversed in both directions, since a loop would allow more different road sections to be included. This requirement, coupled with

Table 2.1(a)

Specifications for Vehicles Driven in the Program

Vehicle No.	Year	Make	Model	Curb Weight (lb)	Engine Type	CID	Maximum Rated BHP @ RPM	Transmission Type
1	1978	Ford	Pinto SW	2425	L4	140	88 @ 4800	3A
2	1978	Chevrolet	Chevette	1991	L4	98	68 @ 5000	3A
3	1978	Ford	Pinto SW	2537	V6	171	90 @ 4200	3A
4	1977	Volkswagon	Rabbit	1860	L4	97	78 @ 5500	4M
5	1977	Ford	Granada	3410	L6	250	98 @ 3400	4M
6	1977	Datsun	280 Z	2765	L6	168	149 @ 5600	4M
7	1977	Dodge	Monaco	4265	V8	360	155 @ 3600	3A
8	1979	Chevrolet	Camaro	3522	V8	350	170 @ 3800	3A
9	1978	Oldsmobile	Omega	3250	V6	231	105 @ 3400	3A

Table 2.1(b)

Specifications for Selected Marana Vehicles

Vehicle No.	Marana Test No.[4,11]	Year	Make	Model	Curb Weight (lb)	Engine Type	CID	Maximum Rated BHP @ RPM	Transmission Type
1	38	1977	Ford	Pinto SW	2642	L4	140	89 @ 4800	3A
2	19	1977	Chevrolet	Chevette	1958	L4	97	63 @ 4800	3A
3	47	1977	Ford	Pinto	2477	V6	171	93 @ 4200	3A
4	6,20	1977	Volkswagon	Rabbit	1860	L4	97	78 @ 5500	4M
5	10	1977	Ford	Granada	3410	L6	250	98 @ 3400	4M
6	8	1977	Datsun	280Z	2765	L6	168	149 @ 5600	4M
7	2	1977	Dodge	Monaco	4265	V8	360	155 @ 3600	3A
8	1	1977	Oldsmobile	Cutlass	3696	V8	350	170 @ 3800	3A
9	17,18	1977	Buick	Skylark	3394	V6	231	105 @ 3200	3A

the length restriction, essentially required that the route lie well within the circumferential interstate highway (Beltway) which surrounds the metropolitan Washington, D.C. area.

In order to define a "national average" route, data on the distribution of daily vehicle miles traveled (DVMT) for various city population levels and road types was combined with data on the percentage of the total urban population living in cities of each population level[12] to produce weighted average DVMT's for each roadway type. Table 2.2 shows the resultant percentages. The column labeled "weighting factor" represents the fraction of the total urban population that resides in cities of each population class.

As can be seen in this Table, 29 percent of the route should be on expressways. Because of the scarcity of this road type in most areas within the Beltway, this requirement restricts the route to portions of northern Virginia. In addition, since a great many trips in urban areas are from the suburbs to a downtown business district and return, a requirement was added to extend the route into Washington, D.C.

Based on these results along with the other constraints expressed above, three candidate routes were developed. Each route has essentially the same D.C. segment; the routes differ only in the Virginia portion. In defining roadway types along these candidate routes, a certain amount of individual judgment is required. In general, the descriptions of highway classifications used by the U.S. Department of Transportation[13] were employed. The three candidate routes each match the "national average" route defined above quite closely. Table 2.3 shows the percentage of each roadway type for each of the routes. Although the agreement could probably have been made better by making the routes more convolved, the requirement to keep the routes relatively simple had to be met. In general, as few road changes — especially local road changes — as possible was the design goal. Where possible, the route changes occur only at the ends of road segments; thus, the necessity to look for specific intersections was minimized.

Table 2.2

Definition of "National Average" Route[12]

Population Class (Thousands)	Weighting Factor*	Daily Vehicle Miles Traveled (in Thousands) by Roadway Type				
		Expressway	Arterial	Collector	Local	Total
>1,000	0.150	428,105	476,630	84,664	137,544	1,126,943
1,000–500	0.103	94,568	116,836	27,034	31,897	270,335
500–250	0.083	101,362	161,796	30,103	48,873	342,134
250–100	0.114	45,946	97,523	18,782	23,816	186,067
100–50	0.133	23,202	68,197	13,226	18,888	123,513
50–25	0.142	16,774	77,943	14,477	21,109	130,303
25–5	0.274	29,710	137,703	25,551	37,338	230,302
	Weighted Sum	101,215	165,944	30,940	46,429	344,528
	Percentage	29	48	9	14	100

*Fraction of Total Urban Population Residing in Given Population Class.

Table 2.3

Percentages of Roadway Types for Candidate Routes

Roadway Type	National Average	Candidate Route		
		Southern	Western	Northern
Expressway	29	28	26	27
Arterial	48	51	47	46
Collector	9	9	8	11
Local	14	12	19	16

Since each of these candidate routes matched the national average criteria so closely, the final selection of a single route was based upon the availability of a suitable field facility near the route. The availability of a two-bay service station within two blocks of the original alignment of the southern route caused this to be the preferred choice of the three. A minor re-alignment of this route, which only slightly changed the road-type statistics, allowed the route to pass in front of the service station, which thus became the field facility from which the trip began.

Tables 2.4, 2.5, and 2.6 show the roadway type, speed limit, and traffic control statistics for the final alignment of the southern route. A series of strip maps showing each segment of the route is given in Appendix A, while the detailed characteristics of the various segments of this route are described in Appendix B.

2.4 Driver Selection

To meet the requirements of the program, driving tests subjects were recruited from the general population of the Washington, D.C. metropolitan area. The procedure used was to establish a pool of potential drivers recruited through newspaper advertising. Initial screening of the respondents was performed by personnel of the Virginia Employment Commission. So that candidate drivers would be thoroughly familiar with the road system and traffic conditions in the Washington area, only persons who had resided in Washington or its suburbs for more than two years were included in the driver pool.

Table 2.4. Roadway Type Summary for Selected Route

Road Type	Length (Miles)	Percentage	National Average
Expressway	6.8	28	29
Arterial	11.1	45	48
Collector	2.4	10	9
Local	4.3	17	14
TOTAL	24.6	100	100

Table 2.5. Speed Limit Summary for Selected Route

Speed Limit (mph)	Roadway Type (Miles)				Total
	Expy.	Art.	Coll.	Loc.	
55	4.9				4.9
50					
45	1.9				1.9
40		1.3			1.3
35		6.5	0.2		6.7
30					
25		3.3	2.2	4.3	9.8
TOTAL	6.8	11.1	2.4	4.3	24.6

Table 2.6. Traffic Control Devices for Selected Route

Type	Roadway Type				Total
	Expy.	Art.	Coll.	Loc.	
Traffic Lights	0	44	8	14	66
Stop Signs	0	0	0	8	8
Right Turns	0	4	2	4	10
Left Turns	0	5	3	6	14

In selecting drivers for participation in the investigation, a stratified sample that is representative of the national licensed driving population was constructed for each vehicle. In determining the strata to be used in such a sampling scheme, the parameters which most affect driving behavior were considered.

Based on the general criteria that insurance companies employ in pricing their automobile insurance policies, age, sex, and marital status are the predominant parameters that correlate with driving behavior. Thus these characteristics were used as the strata to define the sample driving population for the vehicle operating mode study.

In order that sufficient data be available for each category formed by using these three parameters, the number of age groups had to be kept to a minimum. Studies[14,15,16] have shown that male drivers under the age of 25 have significantly higher rates of traffic citation and of accidents than older drivers. Thus it would seem appropriate to consider, for the purposes of this study, only two age groups — those at or younger than 25 and those older than 25. Similarly, although marital status can be broken into at least four categories, the need to maximize the amount of data available for each category would suggest that only two groups be used — married and unmarried.

Combining the distribution of licensed drivers by sex and age[17] with the marital status of the total population by sex and age[18] results in Table 2.7, which gives the percentage distribution of licensed drivers by sex, age, and marital status. This target distribution was used as a guide in selecting test drivers for each vehicle from the overall driver pool.

Table 2.7

National Percentage Distribution of Licensed Drivers
By Sex, Age, and Marital Status

Age	MALE		FEMALE		Male Total	Female Total	Overall Total
	Married	Unmarried	Married	Unmarried			
≤ 25 Years	5	7	6	5	12	11	23
> 25 Years	35	7	27	8	42	35	77
Total	40	14	33	13	54	46	100

2.5 Instrumentation

On-board instrumentation in each test vehicle consisted of an electrical ignition pickup for measuring engine speed, an optical encoder coupled to the speedometer cable to measure vehicle speed and a frame-mounted accelerometer to measure vehicle acceleration. Power supplies and signal conditioners coupled these transducers to a digital data logger which sampled each of the three parameters once every 104 msec, and recorded the result on magnetic tape. Also recorded on tape was the output of a time base generator internal to each data logger. Electrical power for each on-board instrumentation system was supplied by the vehicle battery through use of an AC inverter.

A block diagram of instrumentation for vehicle speed, engine RPM, and vehicle acceleration is given in Figure 2.1. Five such instrumentation packages were developed for use in this program.

A signal averaging time constant of 100 msec was chosen for each of these instrumentation systems in order to maintain compatibility with the sound level measurements taken in the previous Marana program, which had a similar time constant.

Calibration of the vehicle speed circuit was accomplished by first measuring the total number of pulses emitted by the optical encoder when the vehicle was moved 100 feet. From this figure, a calibration frequency corresponding to a given vehicle speed was calculated. Before each trip, this calibration frequency was input into the frequency-to-voltage converter in the speed measuring circuit and the circuit was adjusted to provide the proper output speed. After each trip, the calibration frequency was again input into the circuit and the value of the output speed was recorded in the trip log.

Calibration of the engine RPM circuit was accomplished in a similar manner. A calibration frequency, which depended on the number of cylinders in the engine, was computed for a given engine RPM. Prior to each trip, the RPM circuit was adjusted to provide this output RPM when the calibration frequency was input into the circuits. After each trip, the value of the output RPM corresponding to the calibration frequency was recorded in the trip log.

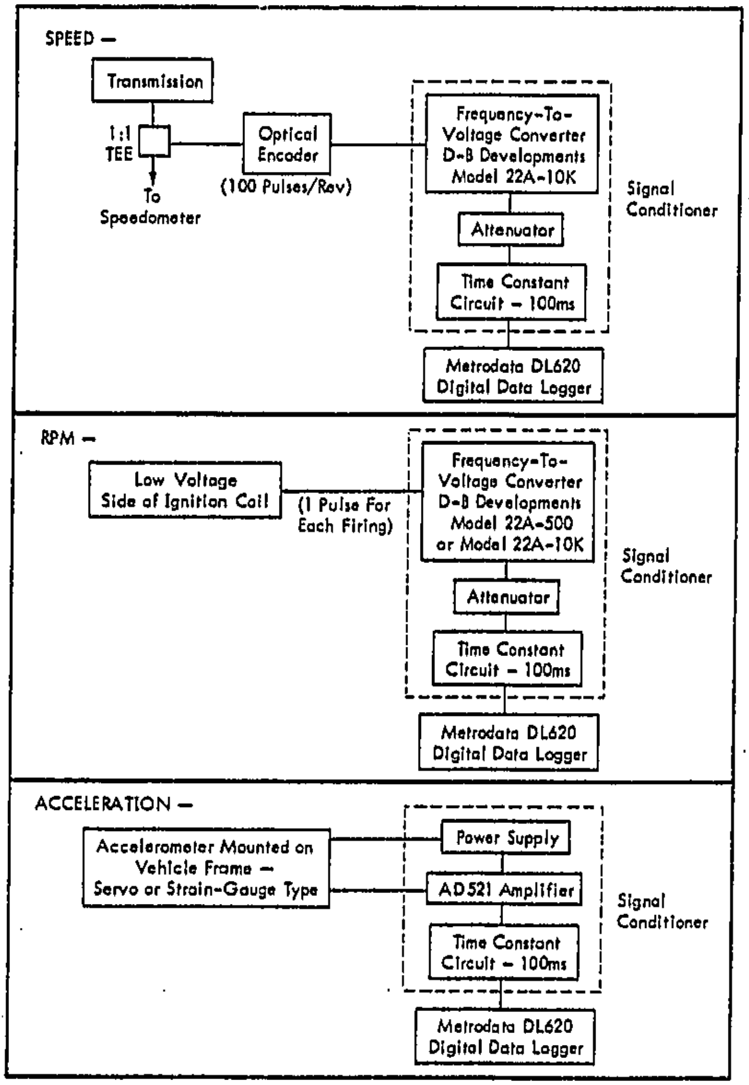

Figure 2.1. Instrumentation For Measuring Vehicle Speed, Engine RPM, and Vehicle Acceleration.

To calibrate the accelerometer circuit before each trip the vehicle was first placed on level ground with the driver (and passenger, if any) in position. The accelerometer itself was then leveled in the vehicle and the output voltage of the accelerometer circuit was adjusted to zero. The accelerometer was then tipped through a +90° angle and the output voltage was set at +1 volt; it was then tipped through a -90° angle and the output voltage was set at -1 volt. Following this, a recheck (and readjustment, if necessary) was made at all three accelerometer positions. The accelerometer was then returned to the level position. Following each trip, the value of the output voltage with the vehicle on level ground was recorded in the trip log.

2.6 Experimental Program

To maintain a degree of uniformity in traffic conditions, the driving tests were performed only on weekdays. Drivers from the main subject pool were selected according to the distribution criteria discussed in Section 2.4 and scheduled for particular days. To the extent possible, drivers were assigned to specific vehicle types or categories for which they had driving experience. Upon arrival at the field station, a brief orientation session was held followed by a photographic slide lecture describing the test route in detail. Each driver was given a step-by-step strip map (see Appendix A) to further assist in following the route.

During the orientation lecture, the drivers were told that the purpose of the program was to better understand how automobiles are driven in urban traffic and that, in order to determine this, they would drive an instrumented vehicle along a pre-selected route three times, the first trip being a practice run to acquaint them with the vehicle and the route, the other two trips being instrumented runs. They were instructed to drive as they normally would, neither hurrying to complete the trip or traveling abnormally slowly.

After the orientation period, the subjects drove their assigned vehicle on the practice run over the route. Vehicle instrumentation was not turned on for this trip. The drivers were thus given an opportunity to become accustomed to the route and to the vehicle before any data was acquired. After this uninstrumented practice run, the vehicle instrumentation was calibrated and the subjects were instructed to make official test runs.

The overall field program itself was undertaken in two phases. In the initial phase up to five people per day participated, each person driving a different vehicle. The drivers were asked to make two instrumented trips along the route. The schedule was designed so that the initial instrumented trip would occur in the early afternoon with an expected light volume of traffic. The second instrumented trip was scheduled to occur during the heavier commuter traffic period. In this manner, data was obtained allowing a comparison to be made between two traffic conditions. Vehicles used in this first phase were those numbered 1 through 5.

After each trip, the vehicle odometer was noted and the driver was debriefed to determine if any anomalies had occurred during the trip. Occasional instances, such as the driver getting badly lost or an unusual traffic event occurring (such as a minor accident), were noted and the trip was not included in the later data analysis since such abnormal behavior would bias the data base in an uncontrolled fashion.

The first data collecting phase lasted from October 30, 1978 to November 29, 1978. During the week of November 27, the instrumentation was transferred to the four remaining vehicles, numbers 6, 7, 8, and 9. With the exception of vehicle #3, all five Phase I test vehicles had been driven by between 16 and 20 drivers by November 29.

Due to various instrumentation problems, vehicle #3 had been driven by far fewer subjects; thus, it was decided to continue operating this vehicle during the Phase II test period. Not only would this procedure provide more data for this vehicle but, by analyzing separately the data for this vehicle from each of the two operational phases, statistical tests could be performed to determine if there were any differences in driving patterns due to the methodology changes in Phase II, which are discussed below. The results of such tests showed no measurable differences between the two phases.

It was decided to truncate the program in early December because it was feared that continuation into the Christmas shopping season would contaminate the data base with anomalous information due to the presence of holiday shopping traffic patterns. In order to have a sufficient number of drivers operate the Phase II vehicles during the limited test period available, it was necessary to make changes in the experimental procedure. Up to ten people per day were scheduled, two for each vehicle. This was judged to be feasible based on the experiences of the Phase I test period, and indeed the double schedule was easily carried out in most instances. To accommodate the increased number of drivers per vehicle per day, the orientation trip was taken by both participants of a given vehicle who then switched passenger and driver roles at a point along the route. Thus, both became familiar with the route and with the handling of the car.

Following the practice trip, four instrumented trips were carried out for each vehicle. The two drivers assigned to each car alternated on the trips, one driver doing the driving on trips 1 and 3 while the other driver acted as a passenger, and then reversing roles on trips 2 and 4.

In total, 318 trips were driven by 159 drivers. After data editing,* a total of 257 trips driven by 141 drivers remained. In view of the necessity of rejecting occasional trips to maintain the integrity of the data base, it was not possible to keep a totally uniform distribution of driver categories among the nine test vehicles. Table 2.8 shows the resulting distribution of drivers according to driver category and test vehicles. The overall distribution of drivers as indicated in this table agrees well with the desired percentages derived in Section 2.4.

*The data qualification procedure used to validate each trip is described in Section 3.3.

Table 2.8

Distribution of Drivers For Test Vehicles

Sex	Marital Status	Age (Yrs)	Percentage of Drivers in Each Category												
			Total Vehicles		Individual Vehicles (Actual)										
			Desired	Actual	1	2	3	4	5	6	7	8	9	Ave.	σ
Male	Married	≤ 25	5.0	5.0	6.2	0	4.7	6.2	6.7	0	6.2	5.6	7.1	4.8	2.8
Male	Married	> 25	35.0	29.1	31.3	44.4	33.3	31.3	33.3	25.0	12.5	27.8	28.6	29.7	8.4
Male	Unmarried	≤ 25	7.0	15.6	12.5	22.2	19.0	12.5	13.3	12.5	18.7	16.7	14.3	15.7	3.6
Male	Unmarried	> 25	7.0	5.0	6.2	0	0	6.2	6.7	6.2	12.5	5.6	0	4.8	4.2
Female	Married	≤ 25	6.0	5.0	6.2	0	0	6.2	6.7	12.5	6.2	0	7.1	5.0	4.2
Female	Married	> 25	27.0	22.6	25.0	22.2	23.8	25.0	13.3	18.7	31.3	22.2	21.4	22.5	4.9
Female	Unmarried	≤ 25	5.0	9.9	6.2	11.1	9.5	6.2	6.7	18.7	12.5	11.1	7.1	9.9	4.1
Female	Unmarried	> 25	8.0	7.8	6.2	0	9.5	6.2	13.3	6.2	0	11.1	14.3	7.4	5.2
Total Number of Drivers					16	9	21	16	15	16	16	18	14	15.6	3.2

Total Number of Qualified Drivers: 141

3.0 VEHICLE OPERATION DATA BASE

3.1 Introduction

The purpose of this section is to describe the computer processing that was carried out on the vehicle operation data gathered in the experimental program described in Section 2 and to present the resultant data base that was developed. The process of developing this data base involved the following distinct steps, each of which are described in the sections below:

- Data Processing
- Data Qualification
- Binning of Temporal Data
- Sensivitity Analysis
- Summary of Results

In addition to the results described below, more detailed listings of the vehicle operation data base are given in Appendices C to H.

3.2 Data Processing

As described in Section 2, digital samples of the instantaneous vehicle speed, engine RPM, and vehicle acceleration were recorded on magnetic tape at intervals of 104 msec. throughout each trip using a Metrodata DL620 Data Logger. Although normally these instruments provide a one-hour recording time on repeating (endless loop) tape cartridges, the units used in this experiment were modified to provide a recording time of about 90 minutes.

The format of the data on the tape cartridges is a sequence of 20 word records. Each word consists of 8 four-bit BCD complement characters, the first of which indicates the sign of the word. The first two words of each record indicate the time at the start of that record. The data was multiplexed in such a manner that words 3, 8, 13, and 18 were speed samples; words 4, 9, 14, and 19 were acceleration samples; and words 5, 10, 15, and 20 were engine RPM samples. In this manner, each of the three parameters were sampled at equal time intervals. The time interval between successive speed-acceleration and acceleration-RPM samples was 20.8 msec.

The tape cartridges collected in the field program were replayed in the laboratory using a Metrosonics 622 Tape Reader connected to a Digital Equipment Corporation PDP-11 V03 computer system via a Heath/Schlumberger WH-11-2 parallel interface. The PDP-11 V03 computer system consisted of the following subsystems:

- PDP-11/03 packaged LSI-11 computer system with 32K sixteen-bit word MOS memory,
- RX V11 dual floppy disk system, each disk capable of storing 128K sixteen-bit words,
- LA36 DECwriter II terminal,
- KEV11 Extended Instruction Set/Floating Point Instruction Set,
- RT-11 Operating System Software,
- RT-11 FORTRAN IV Software.

Since the tape cartridges from the data loggers were to be reused throughout the course of the experiment, the data from each trip was transferred onto a floppy disk using the PDP-11 V03 system. Because the experimental design allowed for trips up to 90 minutes in duration, approximately 52,000 samples of each of the three vehicle operating parameters could be collected. In addition, for every four samples of each parameter, a time code was recorded, resulting in up to 13,000 time samples. The net result is that the tape cartridge could contain up to 168,000 words of information.

Since the floppy disks in the PDP-11 V03 system could hold at most 128,128 words, the decision was made to delete every other sample of each parameter in the transfer of data onto floppy disk, resulting in an effective sampling time of 208 msec. It was felt that this procedure would have no effect on the ultimate distributions of operating parameter values since all types of vehicle operation would be represented. Indeed, later analysis of the decorrelation times for each of the three vehicle operating parameters (Section 3.4 below) showed them to be much longer than this effective sampling rate.

The computer software developed for the processing of the data collected in the field program provided the following functions:

- Transfer of temporal data from tape cartridge to floppy disk;
- Printout and plotting of temporal data from floppy disk;
- Autocorrelation of time series for each parameter;
- Binning of temporal data to produce joint speed-acceleration-RPM probability functions for each trip;
- Calculation of average distributions for rush and for non-rush hour trips for each vehicle;
- Combination of rush and non-rush hour distributions for each vehicle;
- Printout of speed-acceleration-RPM, speed-acceleration, speed-RPM, acceleration-RPM, speed, acceleration, and RPM probability distributions; and
- Computation of average acceleration for various speed ranges.

With the exception of some subroutines used in the software that accomplished the transfer of the raw temporal data onto floppy disk, all software was written in RT-11 FORTRAN IV, which conforms to the specifications for American National Standard FORTRAN X3.9-1966. Since the raw data now resides on floppy disk, the transfer software is no longer needed. All other software used in the program is easily transportable to most other computer systems.

3.3 Data Qualification

The temporal data from 307 of the 318 trips was successfully transferred from tape cassette to floppy disk; data from 11 trips could not be transferred because of instrument malfunctions or defective tape cartridges. In order to determine which of these trips should be used for further analysis, the data sets for each trip were subjected to the following four tests:

- "lost driver" test,
- speed test,
- acceleration test,
- RPM test.

Only trips which passed all four tests were included in the processing that developed the final probability distribution data base.

The "lost driver" test was a quantitative method of deleting from the data base all trips in which the driver was not able to follow the route. Although this question was asked of each driver in the debriefing following each trip, it was decided that the driver's judgment as to whether or not he had become lost during the trip was too qualitative for use here. For example, a driver who had missed a turn and gone one or two blocks too far before backtracking to the correct route might report himself lost. However, in terms of the distribution of vehicle operation parameters for the trip, the effect of such an occurrence would be negligible. On the other hand, a driver who did become lost might not report this fact.

An examination of the length of each trip, as determined from the written records of the vehicle's odometer reading before and after each trip, showed them to be generally quite closely clustered about the measured trip length of 24.6 miles. Most trip lengths were well within 5 percent of this figure (±1.2 mi). Thus the criterion for a badly lost driver was established as having a trip length outside this 5 percent tolerance. Eleven such trips were deleted from the data base.

In addition to the "lost driver" test, three other tests were performed to guarantee the integrity of the vehicle operating parameters. The vehicle speed was tested by comparing the average trip speed, as determined from the odometer readings and start and return times in the trip log, with the mean speed from the digitized samples for each trip. The average trip speed was plotted as a function of mean digitized trip speed and a linear least squares curve fit was made to the data. Any trip which varied more than ±3 standard deviations from the fitted curve was eliminated. In this manner, ten trips were deleted from the data base.

The accelerometer in the vehicle was calibrated before each trip by zeroing the output voltage of the system to within 0.05mv when the vehicle was stationary on a level surface. After the return of each vehicle the calibration was rechecked and the output voltage was recorded in the trip log. Any runs for which the post-trip output calibration voltage exceeded 0.05mv were deleted from the data base. A total of nine such trips were removed in this manner.

Measurement of engine RPM was accomplished by monitoring spark-plug firing and thus had no possibility of a calibration shift. However, intermittent malfunctions in the signal conditioner for the engine RPM in vehicle #2 during the first phase of testing did lead to invalid data for certain trips for that vehicle. In such trips, anomalously high RPM values were recorded. A phenomenological engine speed criterion was developed to identify those trips in which the instrumentation malfunctioned. This test was applied to the RPM data for all vehicles resulting in the rejection of 22 runs.

In addition to the above, three other trips were deleted for miscellaneous reasons, such as a minor accident. Between those trips whose data could not be transferred to floppy disk and those trips failing one or more of the above criteria, a total of 61 trips were deleted from the data base. This process resulted in 257 valid trips driven by 141 drivers. Table 3.1 shows the distribution of valid trips among the nine vehicles.

Table 3.1

Distribution of Valid Trips

Vehicle	Trips	Valid Trips	Percent Valid
1	32	31	97
2	40	14	35
3	51	36	71
4	32	31	97
5	33	25	76
6	32	30	94
7	34	29	85
8	36	34	94
9	28	27	96
Total	318	257	81

3.4 Binning of Temporal Data

Before binning the temporal data to provide histograms representing the various probability distribution functions for each desired combination of vehicle operating parameters, suitable bin widths had to be chosen. To accomplish this, a rough binning algorithm incorporating a wide bin width for each variable was implemented in the computer. The rough binning procedure, which was carried out at the same time as the temporal data was transferred from tape cartridges to floppy disks, resulted in a crude distribution for each operating parameter for each trip. By examining the extreme values of the parameters for each trip, the range of each variable for the entire data set was determined.

As a result of this examination, it was determined that the speed data lay predominantly between 0 and 65 mph, the acceleration data lay predominantly between -0.3g and +0.3g, and the engine RPM data lay predominantly between 0 and 4000 RPM. Based on these ranges and the available storage in the computer memory, the bin widths in Table 3.2 were chosen.

Table 3.2

Bin Widths of Operating Parameters

Variables	Bin Width
Vehicle Speed	5 mph
Vehicle Acceleration	0.025g
Engine RPM	250 RPM

Allowing extra bins for occasional data lying outside the above ranges resulted in the formation of a 14 x 27 x 17 element data array to represent the speed-acceleration-RPM probability distribution histogram for each trip. The size of this 6,426 element matrix is sufficiently small to fit easily in the core of the computer, allowing ample room for software and other data arrays, while at the same time permitting bin sizes for each variable that are fine enough to provide detailed information on the distribution of the variables.

Once the appropriate bin sizes had been determined, computer software was developed to perform the binning of the temporal data set for each trip. The resultant combined speed-acceleration-RPM probability distribution array for each trip was stored on the floppy disk containing the temporal data for that trip. Thus, the floppy disk corresponding to each trip contains both the temporal record of the operational variables and the probability distribution array of those variables for that trip.

Having computed the speed-acceleration-RPM probability distributions for each trip, appropriate averages over all drivers for non-rush hour and rush hour traffic conditions for each vehicle were desired. Before such averages could be computed, it was necessary to classify each trip as a rush hour or non-rush hour trip. To allow a quantitative decision to be made, the behavior of the average trip speed as a function of trip start time was examined. Figure 3.1 shows the result of the analysis.

The open circles in this figure represent average values of trip speed over all trips occurring in the half-hour period starting with the indicated start time. The standard deviation for each of these averages was typically 1.5 to 2.0 mph. Even considering this relatively large standard deviation, a t-test shows that the difference between the average trip speed at 1430 and that at 1445 is statistically significant at the 90 percent level of confidence.

Thus the criterion was established that, since the traffic conditions after 1445 led to lower speeds than those before that time, trips starting before 1445 were labelled "non-rush" while trips starting after that time were labelled "rush".

This decision is consistent with the traffic behavior in the Washington, D.C. metropolitan area. The workday for many government agencies ends at 1530 and thus, the homeward traffic flow from the District of Columbia begins at that time. An examination of the test route shows that if a driver left the field station after 1445, he would indeed reach the downtown area of the District after 1530 and thus, would become part of the homeward bound "rush hour" traffic flow.

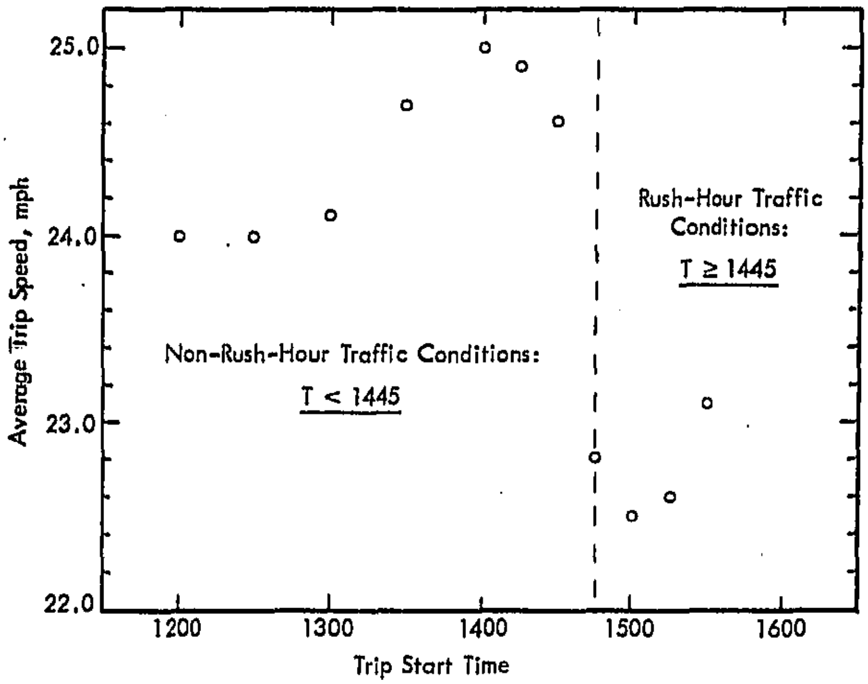

Figure 3.1. Average Trip Speed Versus Trip Start Time.

Table 3.3 shows the distribution of valid "non-rush" and "rush" trips that occurred when the above criterion was applied. Note that the change in procedure for vehicles 3b, 6, 7 8, and 9 (which was discussed in Section 2.6) resulted in a smaller ratio of rush to non-rush hour trips for these vehicles than for vehicles 1, 2, 3a, 4, and 5.

The mean trip time for the "non-rush" trips is 58.7 minutes with a standard deviation of 5.9 minutes; that for the "rush" trips is 63.6 minutes with a standard deviation of 6.8 minutes. A t-test, at the 95 percent confidence level, shows the difference between these two mean trip times to be statistically significant.

Having made the assignments indicated in Table 3.3, average speed-acceleration-RPM probability distributions were computed for the trips in each category. Averages for vehicle 3 were calculated separately for vehicle trips occurring during the Phase I experimental procedure (3a in Table 3.3) and for those occurring during the Phase II procedure (3b in Table 3.3).

Table 3.3

Distribution of Trips By Traffic Conditions

Vehicle	Traffic Conditions	
	Non-Rush	Rush
1	15	16
2	5	9
3a } *	4 } 23	7 } 13
3b	19	6
4	15	16
5	10	15
6	22	8
7	21	8
8	26	8
9	21	6
Total	158	99

* (3a indicates trips taken in vehicle #3 using Phase I procedure, 3b indicates trips taken using Phase II procedure. See Section 2.6 for description of procedural changes.)

3.5 Sensitivity Analysis

In order to assess the effect of the non-rush hour and rush hour traffic conditions on the speed-acceleration-RPM probability distributions as compared to the driver-to-driver variation in these distributions, a sensitivity analysis was performed which examined the statistical reliability of differences between the two averaged distributions for each vehicle. In addition, similar comparisons were made between the distributions for vehicle 3a and vehicle 3b to determine if the change in experimental procedure had effected these distributions in any measurable way.

Initially, the plan had been to determine whether or not any two speed-acceleration-RPM distribution arrays were statistically different by performing a chi-squared test on the arrays. One of the requirements of such a test is that the temporal samples incorporated into the distribution function be statistically independent.

In order to examine this point, autocorrelations were performed on the speed, acceleration, and RPM time series for twenty sample trips — one for each vehicle for each traffic condition. The sample trips were chosen randomly from the set of valid trips. A typical set of autocorrelation functions for speed, acceleration, and RPM for one of the twenty analyzed trips is shown in Figure 3.2. In Table 3.4 is shown the lag times for correlation coefficients of 0.75 and 0.50 for the speed, acceleration, and RPM time series for each sampled trip.

The behavior of these lag times is as expected with vehicle acceleration decorrelating most quickly, followed by engine RPM and then by vehicle speed. The relatively long decorrelation times for speed and RPM indicates that changes in the vehicle kinematics occurred slowly — there were not many sudden starts and stops. This is indicative of smoothly flowing traffic.

The length of these decorrelation times pose a technical problem in performing the intended chi-squared test on pairs of speed-acceleration-RPM distributions. If a correlation coefficient of 0.50 is taken as the criterion for statistical independence between samples, then the sampling time between pairs of any of the operational variables should

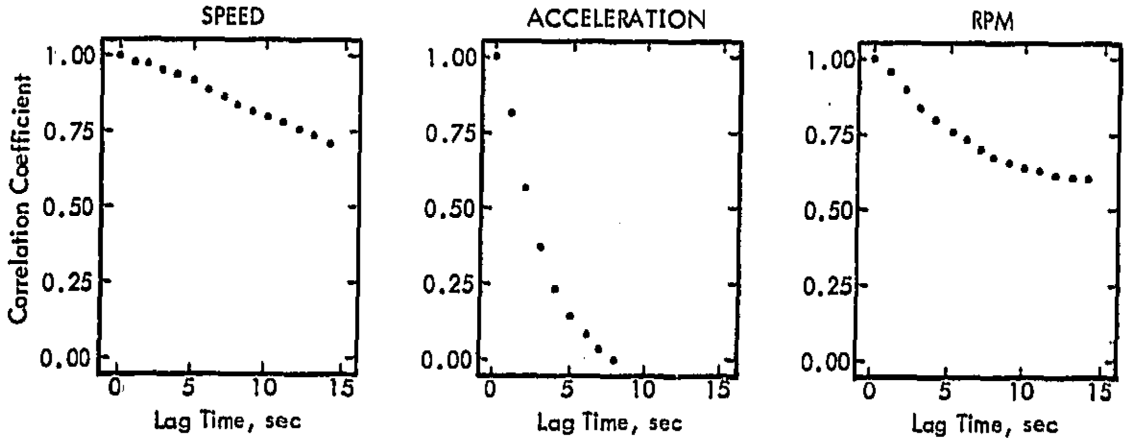

Figure 3.2. Autocorrelation Functions for Speed, Acceleration, and RPM Time Series for Trip 1/14/2. (Second Trip of 14th Driver of Vehicle 1.)

Table 3.4. Lag Times for 0.75 and 0.50 Correlations for Speed, Acceleration, and RPM for Sampled Trips

	Lag Time, sec.					
	0.75 Correlation			0.50 Correlation		
Trip*	Speed	Acc.	RPM	Speed	Acc.	RPM
1/12/1	10.4	1.5	5.2	19.8	2.7	13.5
1/14/2	12.5	1.2	5.2	23.9	2.5	21.8
2/05/1	14.6	0.8	7.3	29.1	1.9	26.0
2/05/2	12.5	0.6	12.5	29.1	1.9	28.1
3/04/1	8.3	0.4	7.3	29.1	1.0	23.9
3/13/1	10.4	0.4	7.3	22.1	1.0	23.9
3/03/2	14.6	0.6	7.3	30.2	1.7	27.0
3/26/2	11.4	0.6	5.2	25.0	1.5	17.7
4/08/1	11.4	1.2	4.2	25.0	2.3	15.6
4/11/2	12.5	1.2	5.2	22.9	2.5	12.5
5/04/1	11.4	0.8	3.7	19.8	1.7	8.7
5/02/2	14.6	1.7	2.7	28.1	2.9	6.2
6/05/1	10.4	1.2	4.2	21.8	2.3	7.9
6/14/2	11.4	1.5	4.2	23.9	2.7	12.5
7/09/1	14.6	0.6	5.8	28.1	2.5	22.9
7/15/2	13.5	0.6	4.6	28.1	1.7	18.7
8/13/2	11.4	0.8	6.2	23.9	2.5	23.9
8/14/2	11.4	1.0	6.2	21.8	2.7	21.8
9/06/1	14.6	1.5	4.2	26.0	2.7	15.6
9/12/2	11.4	1.5	3.7	22.9	2.5	10.4
Mean	12.2	1.0	5.6	25.1	2.2	17.9
St. Dev.	1.8	0.4	2.1	3.2	0.6	6.8

*Trip Code: Vehicle/Driver/Trip
(Example: 1/14/2 indicates the 2nd trip of the 14th driver of vehicle 1)

no less than 25.1 sec, the lag time at which the vehicle speed reached that correlation coefficient. Since the sampling time employed in this experiment was 0.208 sec, only every 121st data sample can be considered statistically independent. Deleting the intermediate 120 samples would mean removing 99 percent of the data.

Accepting such a procedure would mean that the bins corresponding to many of the rarely occurring operational conditions would be vacant. Since the chi-squared test requires that there be at least five samples in any one bin, an extremely complex algorithm would have to be developed to adjust bin sizes in each of the pair of arrays being compared so that none had less than five samples. (The bin sizes need not all be the same in order to perform the chi-squared test.)

In view of these complexities, and in order to use more of the data base, an alternate scheme was developed to study the statistical significance of differences between the mean non-rush and rush distributions for each vehicle. Examination of the distribution arrays for each of these cases showed them to be quite similar. For any of the arrays, only a small fraction of the 6426 bins corresponded to frequencies of occurance of greater than one percent. When these "peaks" in the distribution functions for the non-rush and rush cases were compared, it was seen that the operating conditions were generally the same. The only difference was the actual values of the two frequencies (non-rush and rush) for a given speed-acceleration-RPM combination.

It was thus decided to use a t-test to determine the statistical significance of the difference between values of the non-rush and rush hour distribution in all speed-acceleration-RPM bins for which either of the mean frequencies of occurence was greater than one percent. For those bins having a frequency of less than one percent, the size of the standard deviations about this frequency due to driver-to-driver variation is comparable to the frequency itself, so that differences between this portion of the non-rush and rush hour distributions are not statistically significant.

To implement such a procedure, not only were the mean values of the percentage for each bin required for non-rush and rush distributions, but also the standard deviations about those mean values. Computer software was developed to calculate the required standard deviations for each of the average distribution arrays corresponding to the vehicle categories in Table 3.3. A t-test was then performed on all bins corresponding to a probability greater than one percent. As an example, Table 3.5 shows the results for the five most common speed-acceleration-RPM conditions in the non-rush distribution for vehicle #1. Since in each case the calculated t value is less than the critical t value, there is no statistical difference between the non-rush and the rush frequencies of occurrence at the 95 percent confidence level.

Table 3.6 shows the number of bins for each vehicle that did have percentages which were statistically different at the 95 percent confidence level. Since there were no statistically significant differences between the great majority of bins, it was judged that for each vehicle there were essentially no differences between the non-rush and the rush speed-acceleration-RPM distributions. As a result, the non-rush and rush distributions for each vehicle were combined to produce a single average speed-acceleration-RPM distribution for each vehicle.

It should be noted that to a certain extent, the above result may have already been built into the experiment. As described in Section 2.3 the test route had been selected in such a manner that all trips would be completed in 90 minutes. This requirement necessitated the design of a route that would avoid the extremely heavy traffic conditions that exist during the evening rush-hour period on certain highways in the Washington, D.C. area. For example, had the direction of travel along the route been reversed, the trip times would have been much longer because of the extreme congestion in the outward-bound direction on the 14th Street Bridge and Shirley Highway during the evening rush-hour. It can be anticipated that, had such been the case, the non-rush and rush distributions would have been more different than indicated above, with the latter having a higher percentage of "stopped" and slow moving operating conditions than the former.

Finally, a similar sensitivity analysis of the average distributions for "vehicles" 3a and 3b showed only 3 bins out of 28 having statistically significant differences. This indicates that any changes incurred due to the change in experimental procedure between the Phase I and Phase II data gathering periods were smaller than driver-to-driver variations. As a result, these speed-acceleration-RPM distributions could be combined to produce a single average distribution for vehicle #3 and the same analysis procedure could be applied to the data from each of the experimental phases.

Table 3.5. Example of Sensitivity Test for Five Commonest Non-Rush Operating Condition for Vehicle 1.

Operating Condition			Rank		Frequency of Occurrence (Percent)				t - test		
					Non-rush (15 Trips)		Rush (16 Trips)		Degree of Freedom	Calc. t	Critical t*
Speed (mph)	Acc. (g)	RPM (rpm)	Non-Rush	Rush	Mean	St. Dev.	Mean	St. Dev.			
2.5	0.000	875	1	1	7.44	3.10	8.94	2.76	30	1.43	2.04
2.5	-0.025	875	2	2	3.85	1.86	4.51	1.78	31	1.01	2.04
2.5	0.025	875	3	3	3.47	2.29	3.80	2.47	31	0.39	2.04
32.5	0.000	1625	4	11	1.82	0.72	1.40	0.70	30	1.71	2.04
27.5	0.025	1625	5	8	1.82	0.99	1.53	0.91	30	0.84	2.04

*95 Percent Confidence Level

Table 3.6. Number of Bins for Which Non-Rush and Rush Percentages are Statistically Different

(95 Percent Confidence Level)

Vehicle	Total Number of Bins With p > 1%	Number of These Bins that are Statistically Different
1	19	2
2	16	1
3a	14	1
3b	13	2
4	14	0
5	11	0
6	10	1
7	9	3
8	12	0
9	16	1

3.6 Summary of Results

This section contains a summary of the average distributions that resulted for each of the nine vehicles tested. Also included is a brief analysis of the average acceleration as a function of speed range for all vehicles.

Figures 3.3(a) through 3.3(i) illustrate pictorially the structure of the peaks in the mean joint speed-acceleration-RPM probability distributions for each of the nine vehicles. For simplicity, only the highest fifteen bins have been shown for each vehicle.

Because of the difficulty of drawing a four dimensional percentage-speed-acceleration-RPM surface on a two dimensional page, a non-standard format has been developed for these figures. Each figure is a modification of a standard two dimensional projection of a three dimensional surface. Normally, in such a representation, the two independent variables (speed and RPM in this case) define a point in the projected horizontal plane and a single vertical bar represents the dependent variable (percent of time). Since a third independent variable (acceleration) must be represented in these figures, a series of bars is drawn at each defined speed-RPM point — each bar representing a different acceleration, as shown in the key to the figure. Thus, at each speed-RPM point in the horizontal plane, a projected vertical percentage-acceleration plane is drawn so that all four variables are indicated. Note that the speed-RPM point in the horizontal plane always defines the position of the zero acceleration bin.

By developing such a pictorial representation of the mean distribution function for each vehicle, comparisons can easily be made of similarities and differences in the major operating modes of the nine vehicles. Thus, for example, it is immediately apparent that for each vehicle the bin corresponding to 0 to 5 mph, -0.0125g to +0.0125g acceleration, and idle RPM is the most common. This fact is not surprising when one considers the large amount of time spent waiting at traffic control devices in urban areas.

A listing of the data presented in these figures is contained in Appendix C, which gives, in order of decreasing rank, the forty highest bins for the mean speed-acceleration-RPM distribution for each of the vehicles. For each bin is listed the mean value of the frequency of occurrence, in percent, over all valid trips for the vehicle, along with the corresponding standard deviation of the individual trip frequencies about that mean value.

The set of standard deviations corresponding to the mean frequencies for a given vehicle is a measure of the driver-to-driver variation in operating behavior. By examining these standard deviations, it can be determined that, in general, the differences between major peaks of a given mean distribution are statistically significant. However, the differences between the great majority of bins, each of which correspond to less than 1 percent of the total trip time, are not statistically significant. Thus, the peaks in these mean distributions, which are shown in the figures, can be considered as being superimposed upon a similar background for each vehicle.

Figures 3.4(a) through 3.4(i) show the individual probability distributions of speed, acceleration, and engine RPM. Each of these distributions is obtained by performing appropriate summations over two of the variables in the joint speed-acceleration-RPM probability distribution. Thus, for example, the speed distribution is obtained by summing the joint distribution over all accelerations and all RPM's.

As for the drawings of the joint probabilities, these figures allow easy identification of operating conditions common to all vehicles. For example, examination of the speed distributions shows the great majority of them to be tri-modal, with peaks in the 0-5 mph, 25-30 mph, and 50-55 mph bins. This result is consistent with the distribution of speed limits along the route as indicated in Table 2.5. Listings of the data in each of these Figures is given in Appendix D.

In Appendices E, F, and G are listed the joint probability distributions for the pairs of variables, speed-acceleration, speed-RPM, and RPM-acceleration, respectively. Each of these were calcuated from the joint speed-acceleration-RPM distribution by summing over the appropriate single variable (e.g., the joint speed-acceleration distribution is obtained by summing over RPM).

One functional relationship of general interest is the average acceleration of a vehicle as a function of vehicle speed. To investigate this relationship, bins for positive acceleration ($a \geq 0.0125g$) in the joint speed-acceleration distributions were used to compute the average acceleration over all possible speed ranges for each vehicle. The detailed results of this calculation are given in Appendix H. Averages were then formed over all vehicles of a subset of this data — namely, the average acceleration in 5 mph speed intervals from 5 mph to 60 mph. The resulting functional relationship is shown in Figure 3.5. The error bars on each point represent plus and minus one standard deviation.

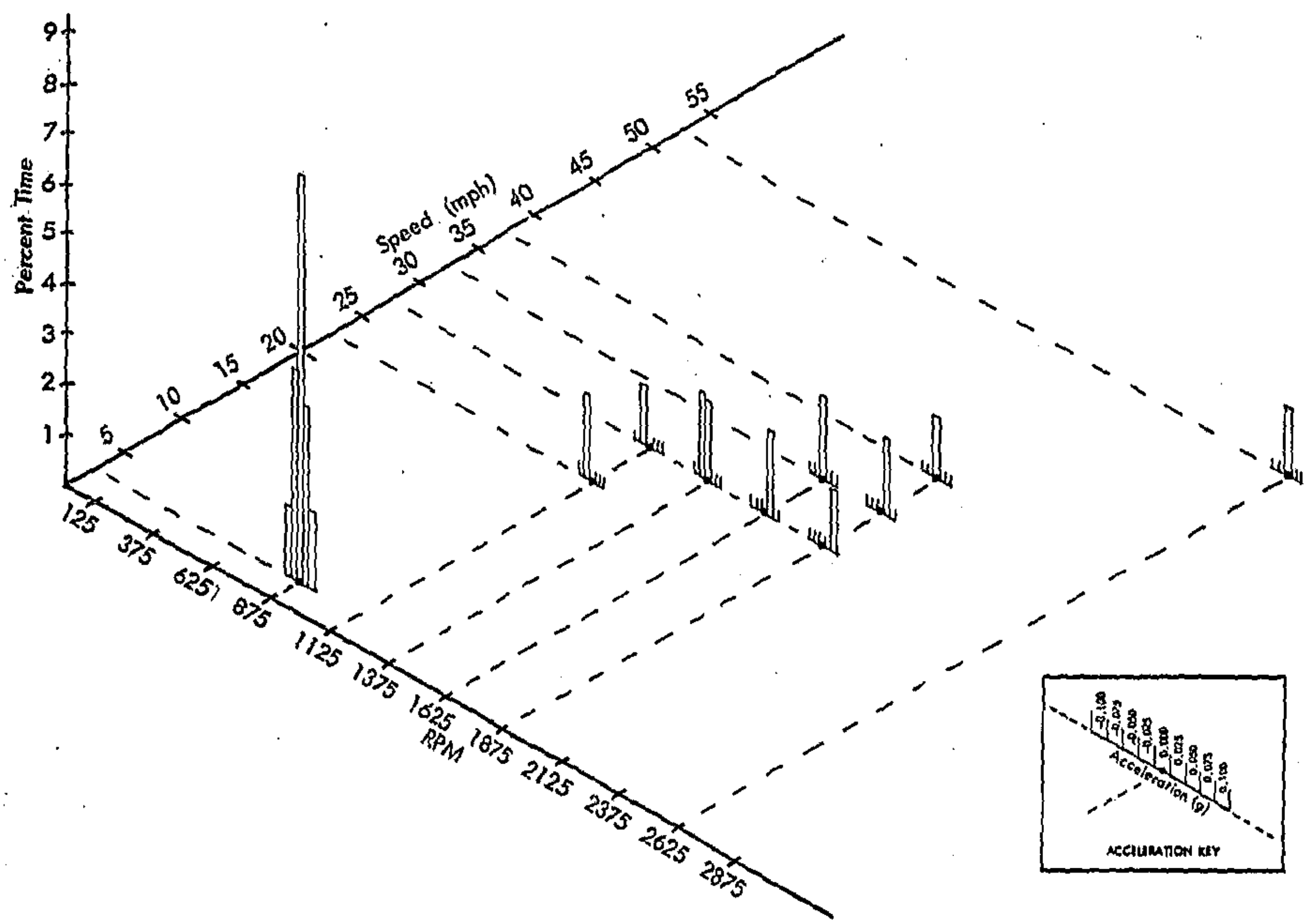

Figure 3.3(a). Percentage of Trip Time For Vehicle 1 – Ford Pinto (L4, 3A).

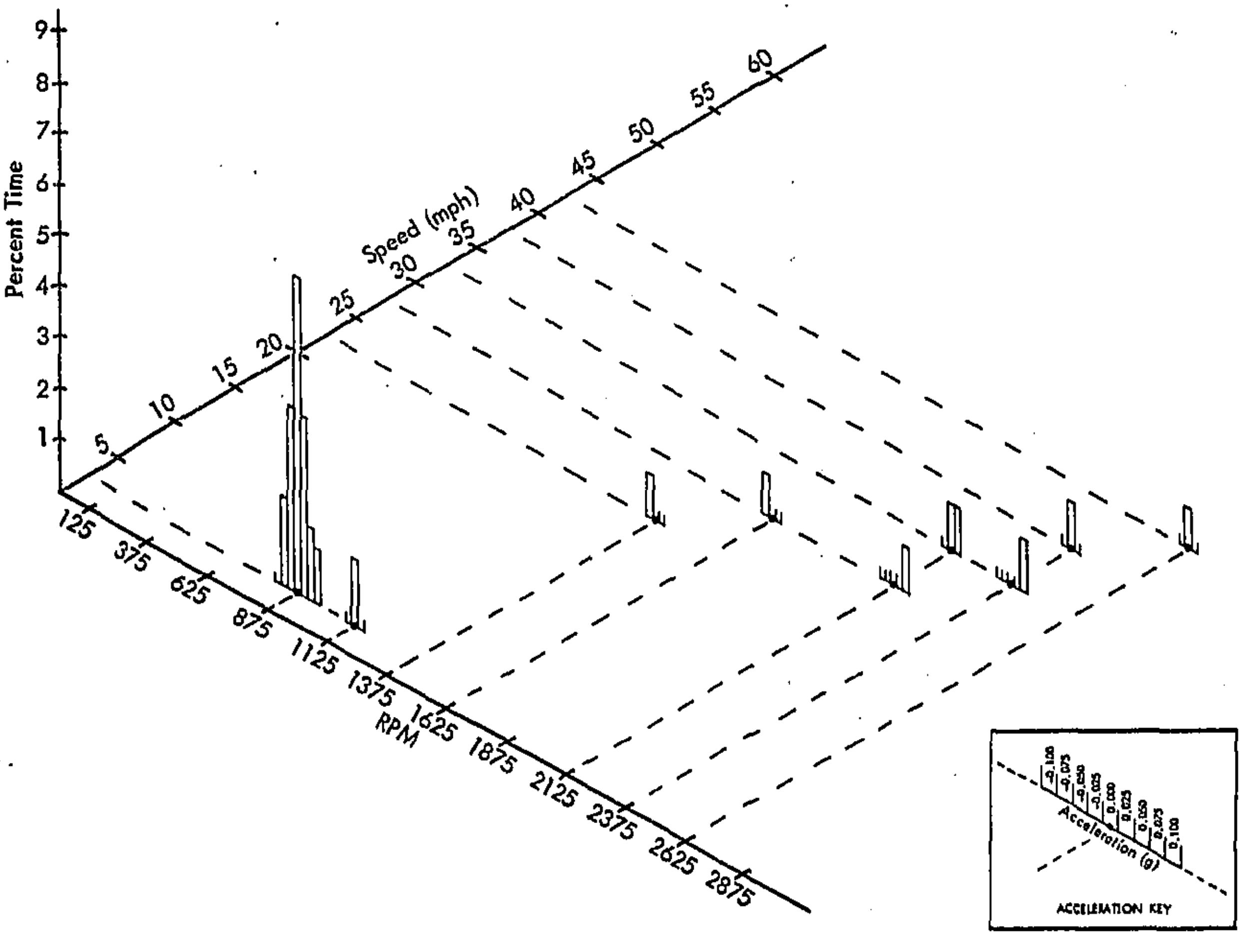

Figure 3.3(b). Percentage of Trip Time For Vehicle 2 – Chevrolet Chevette (L4, 3A).

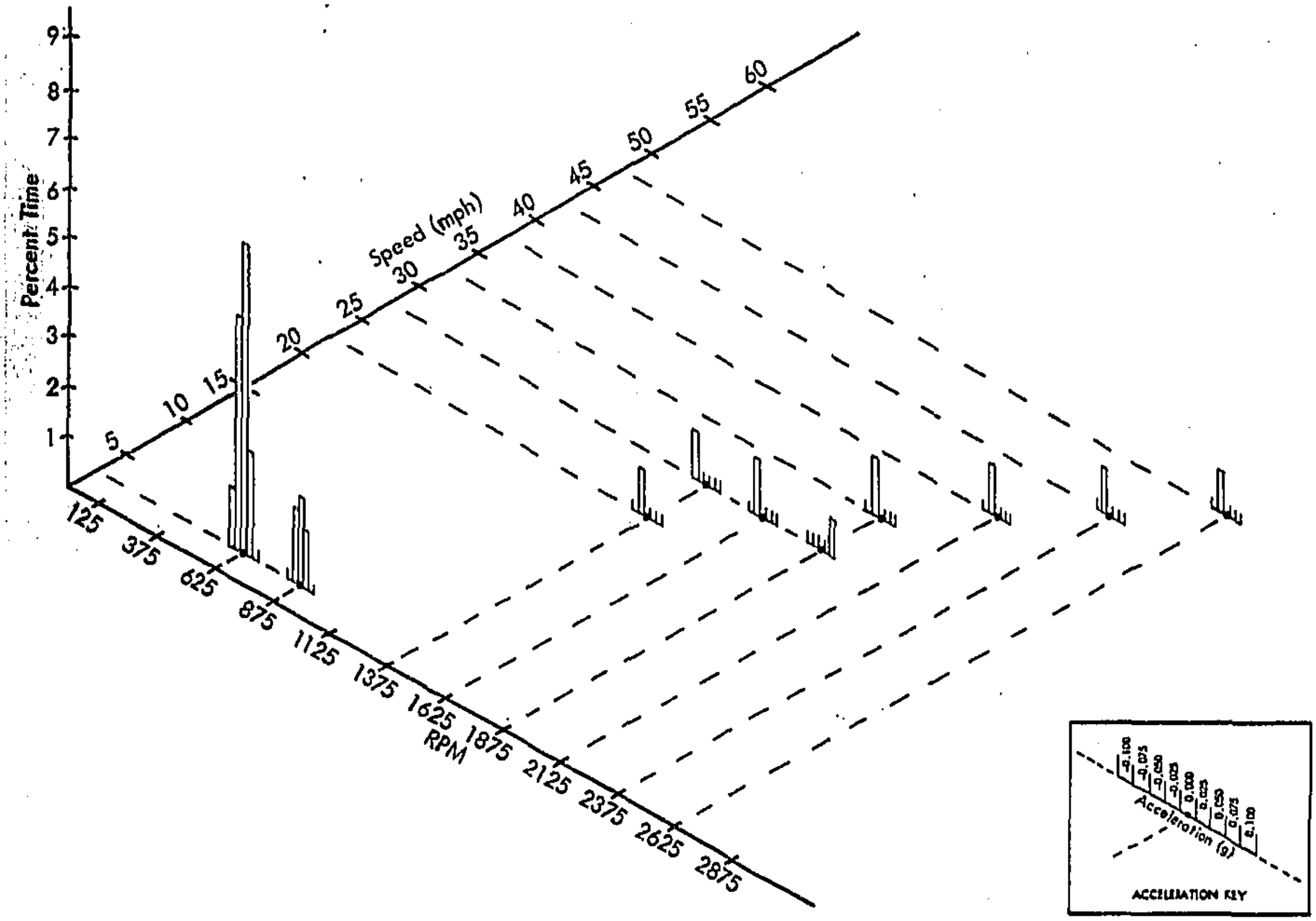

Figure 3.3(c). Percentage of Trip Time For Vehicle 3 – Ford Pinto (L6, 3A).

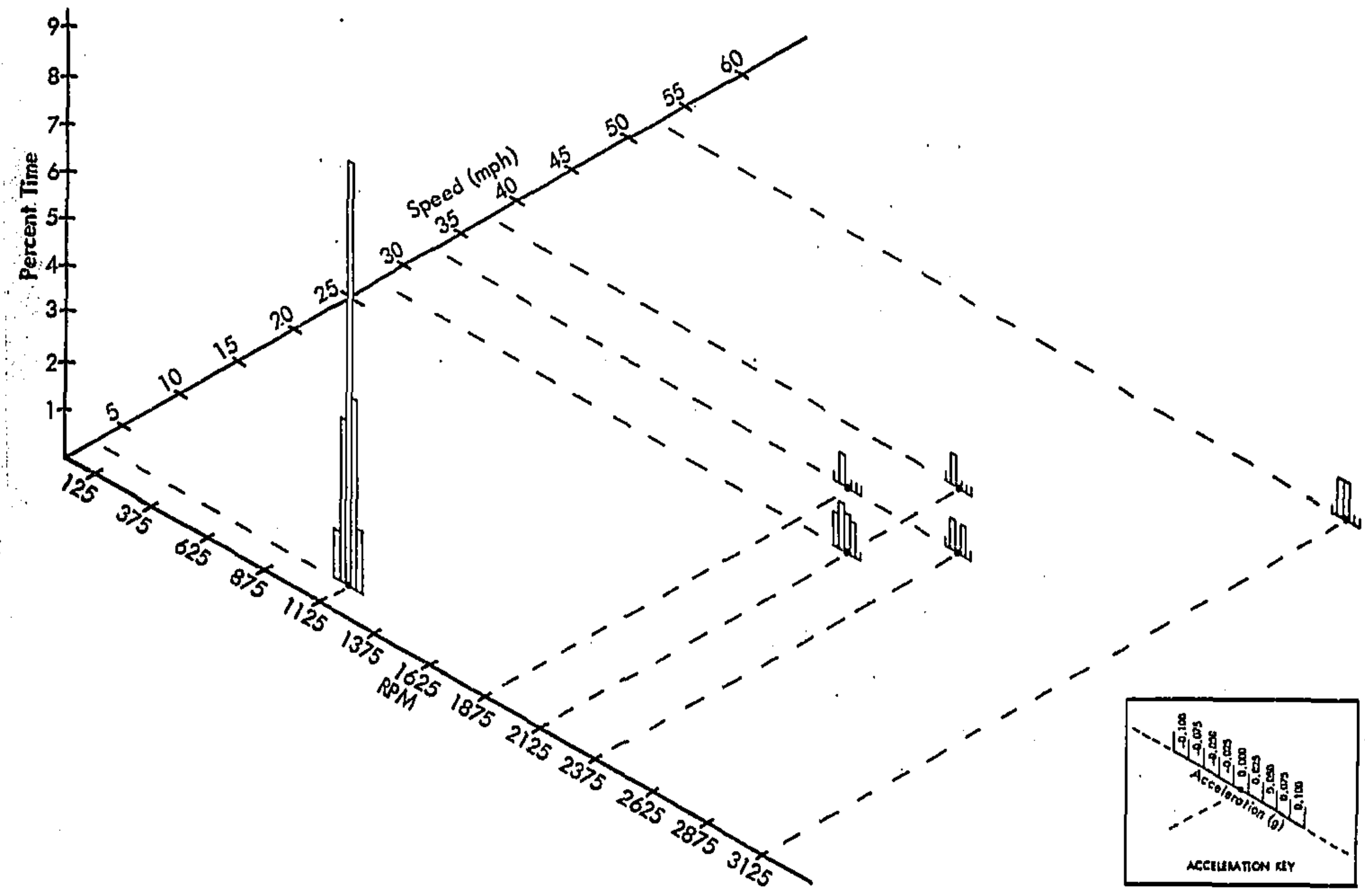

Figure 3.3(d). Percentage of Trip Time For Vehicle 4 — VW Rabbit (L4, 4M).

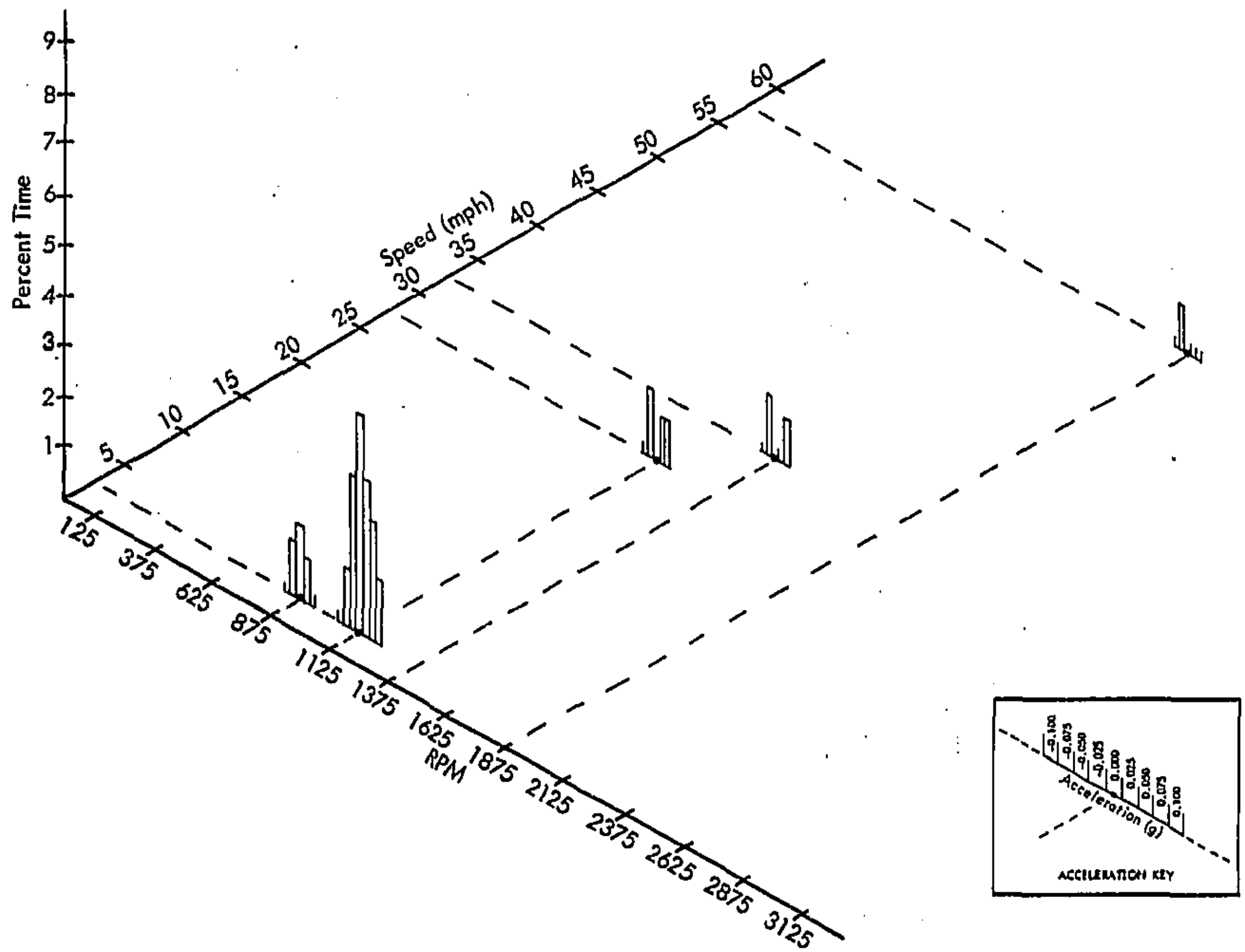

Figure 3.3(e). Percentage of Trip Time For Vehicle 5 – Ford Granada (L6, 4M).

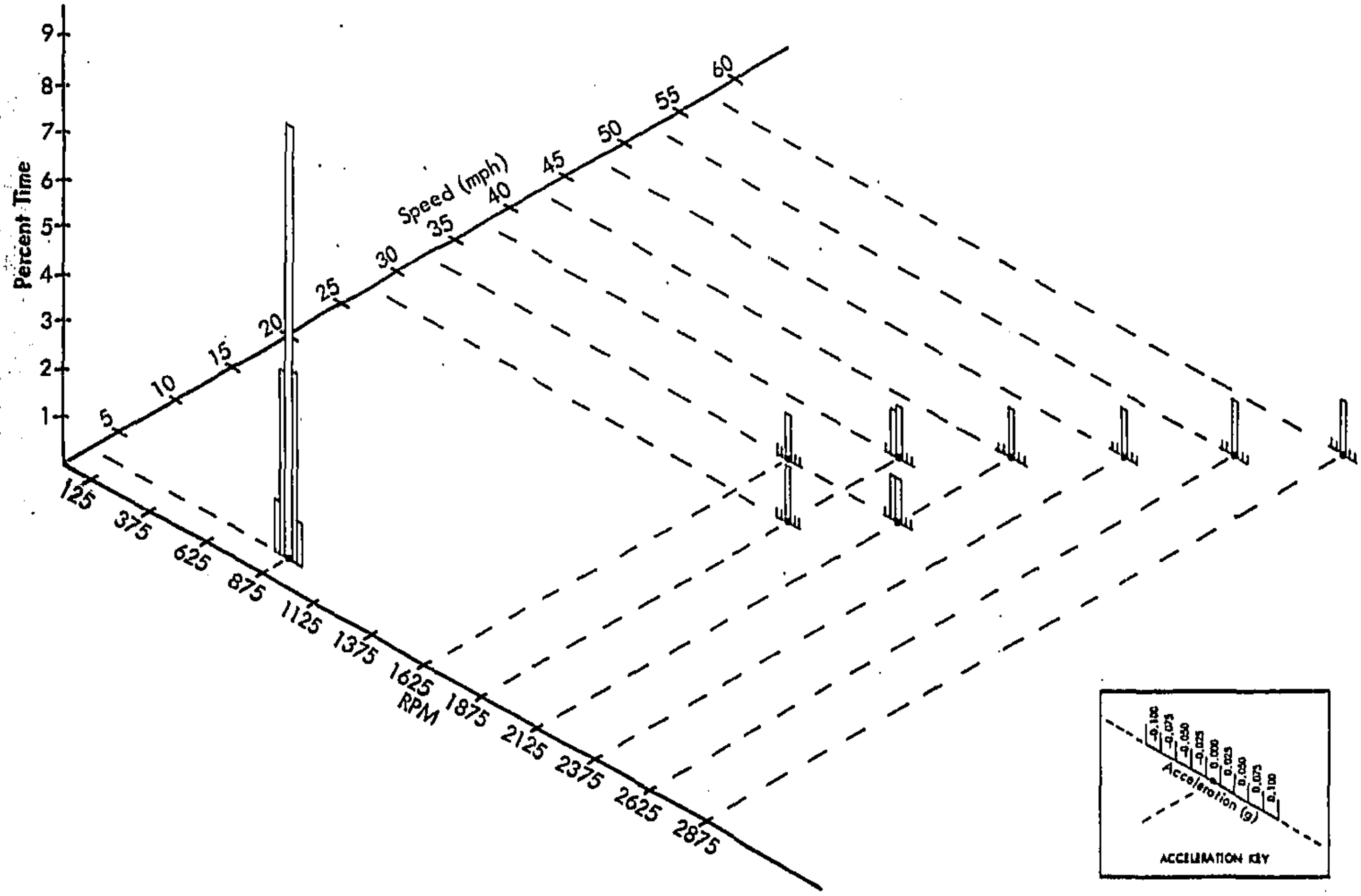

Figure 3.3(f). Percentage of Trip Time For Vehicle 6 – Datsun 280Z (L6, 4M).

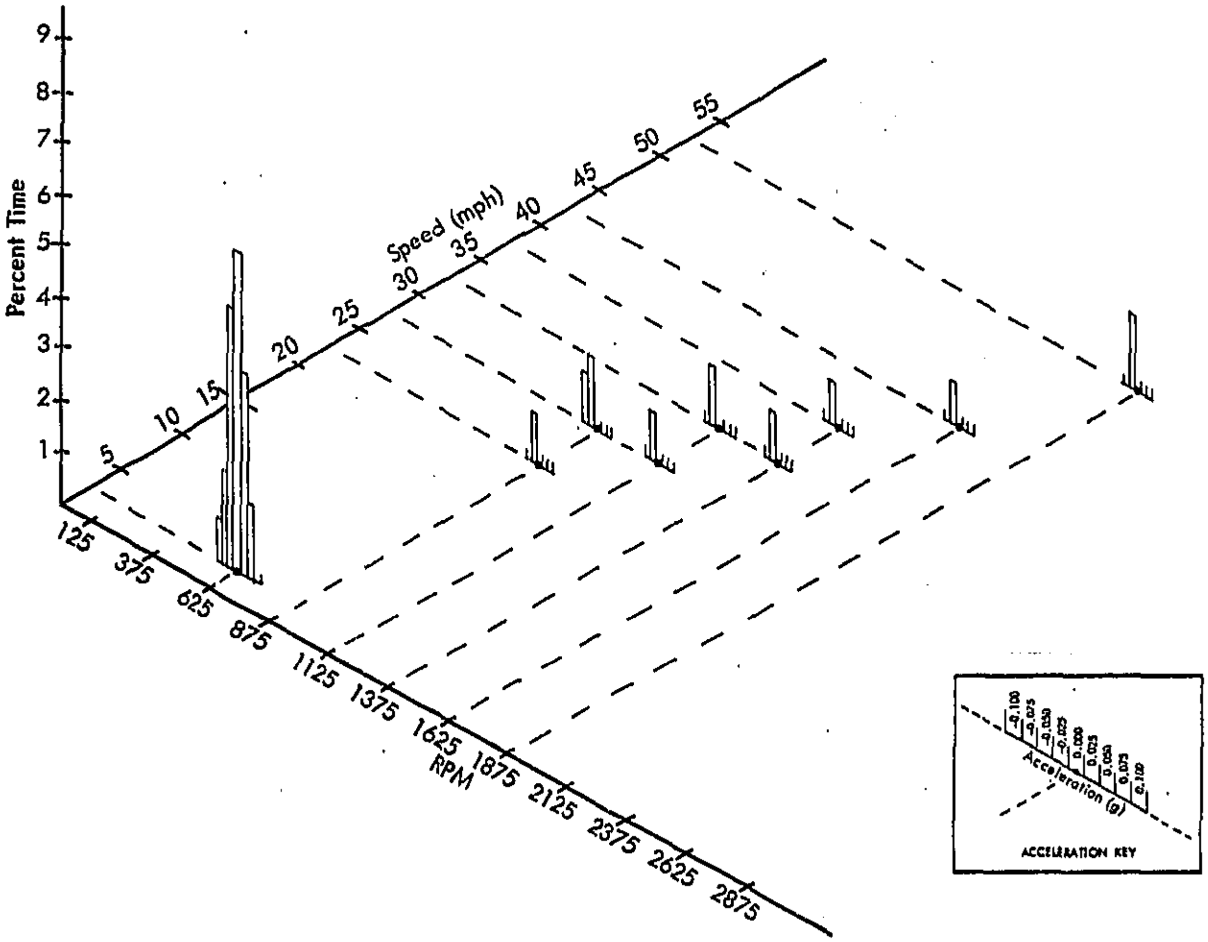

Figure 3.3(g). Percentage of Trip Time For Vehicle 7 – Dodge Monaco (V8, 3A).

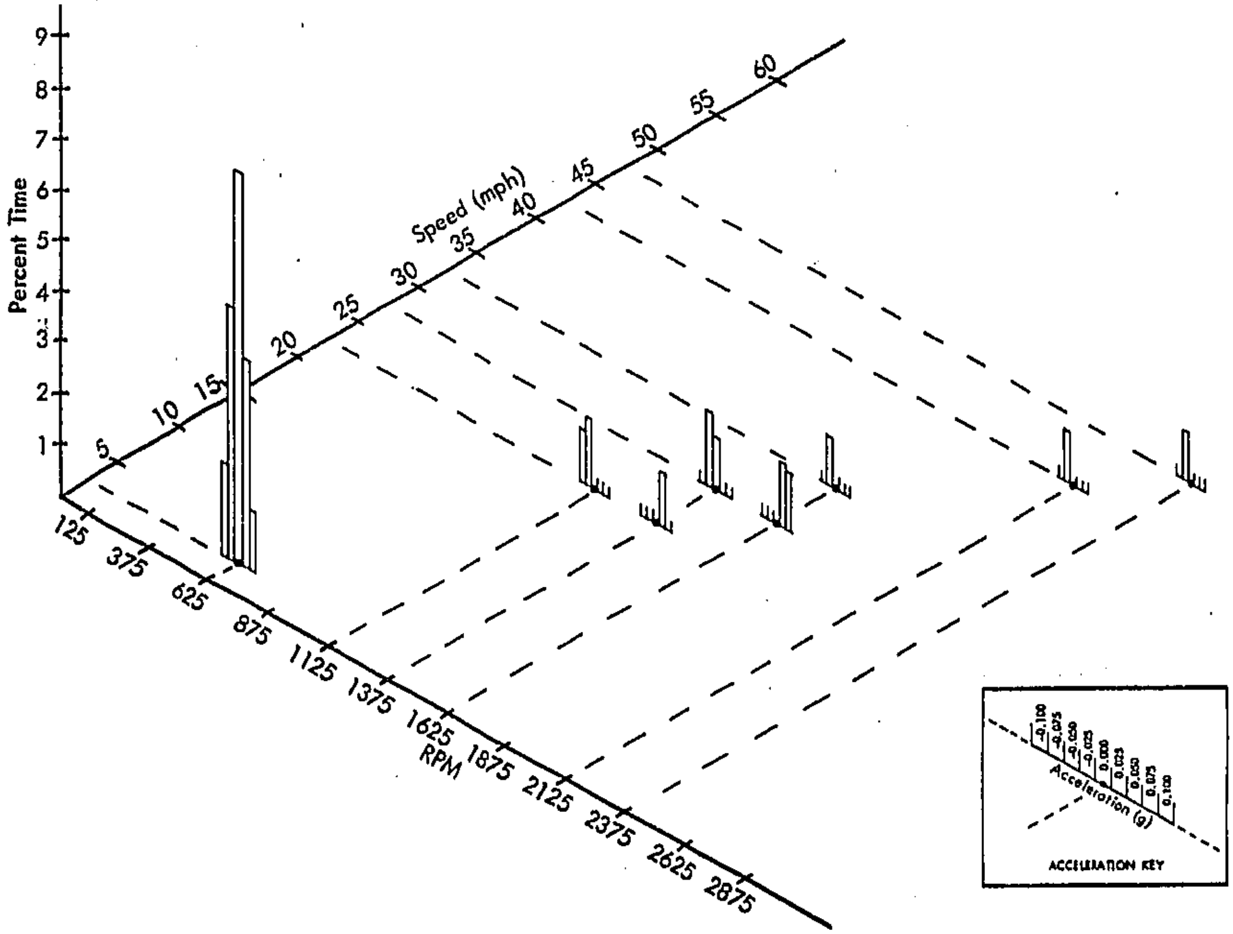

Figure 3.3(h). Percentage of Trip Time For Vehicle 8 – Oldsmobile Cutlass (V8, 3A).

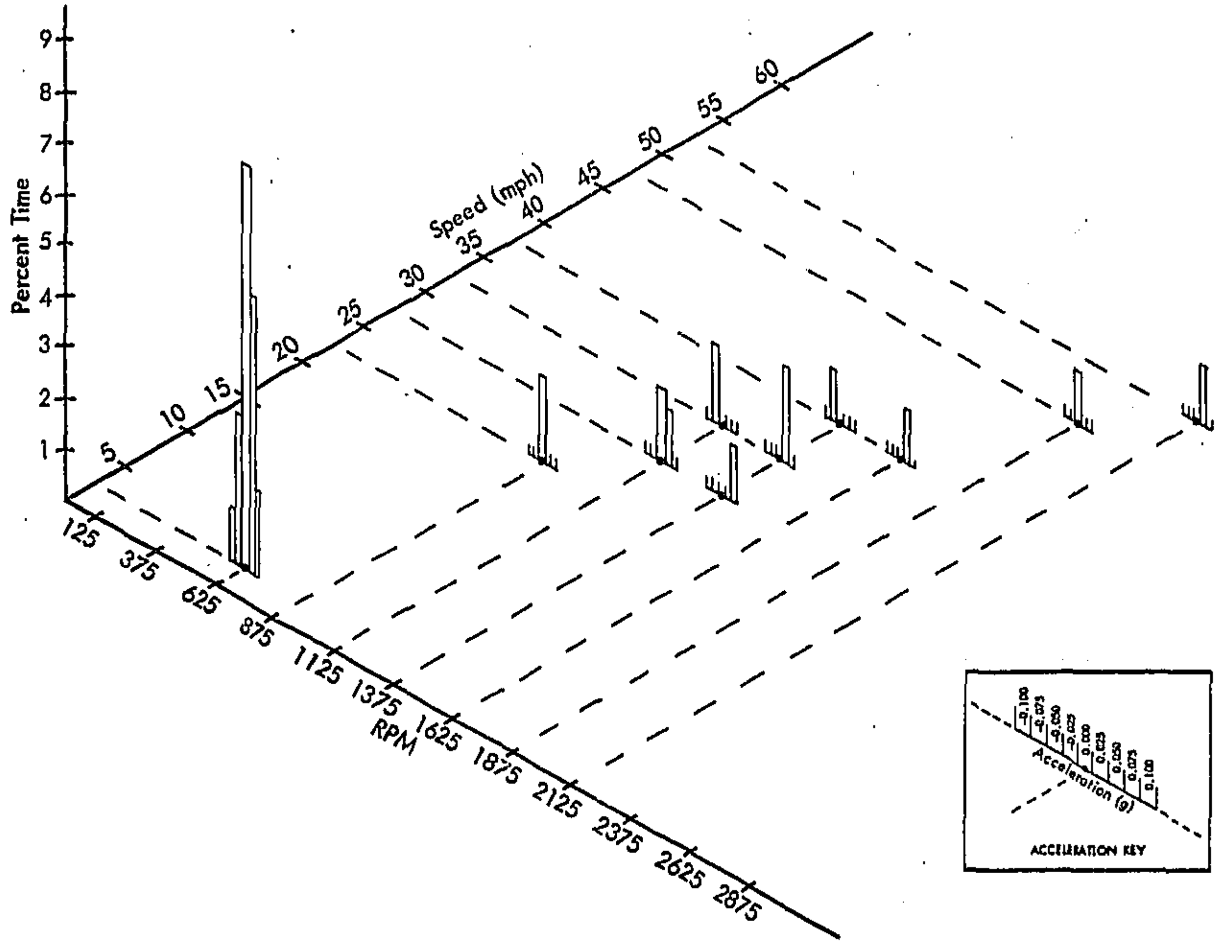

Figure 3.3(i). Percentage of Trip Time For Vehicle 9 – Buick Skylark (V6, 3A).

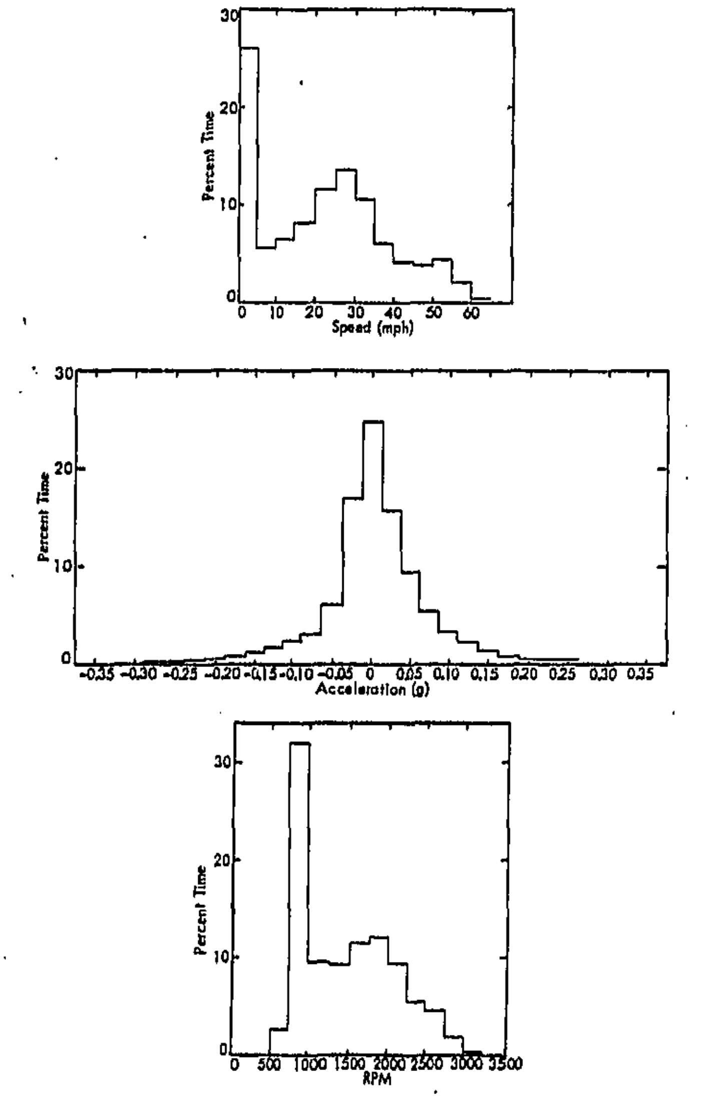

Figure 3.4(a). Percentage of Trip Time as Functions of Speed, Acceleration, and RPM For Vehicle 1 – Ford Pinto (L4, 3A). (Trip Time: 66.5 minutes)

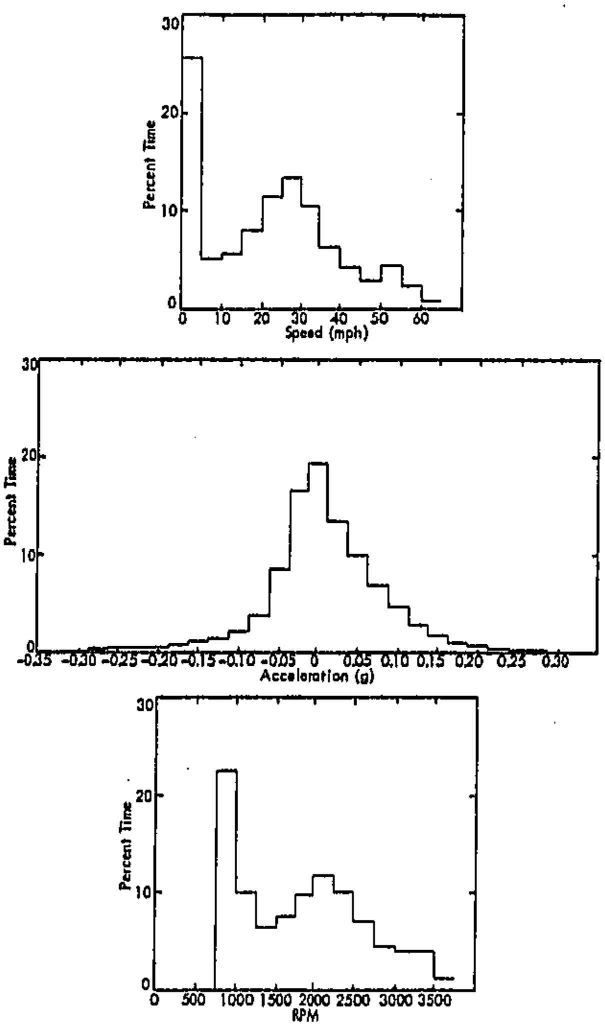

Figure 3.4(b). Percentage of Trip Time as Functions of Speed, Acceleration, and RPM For Vehicle 2 – Chevrolet Chevette (L4, 3A). (Trip Time: 65.3 Minutes)

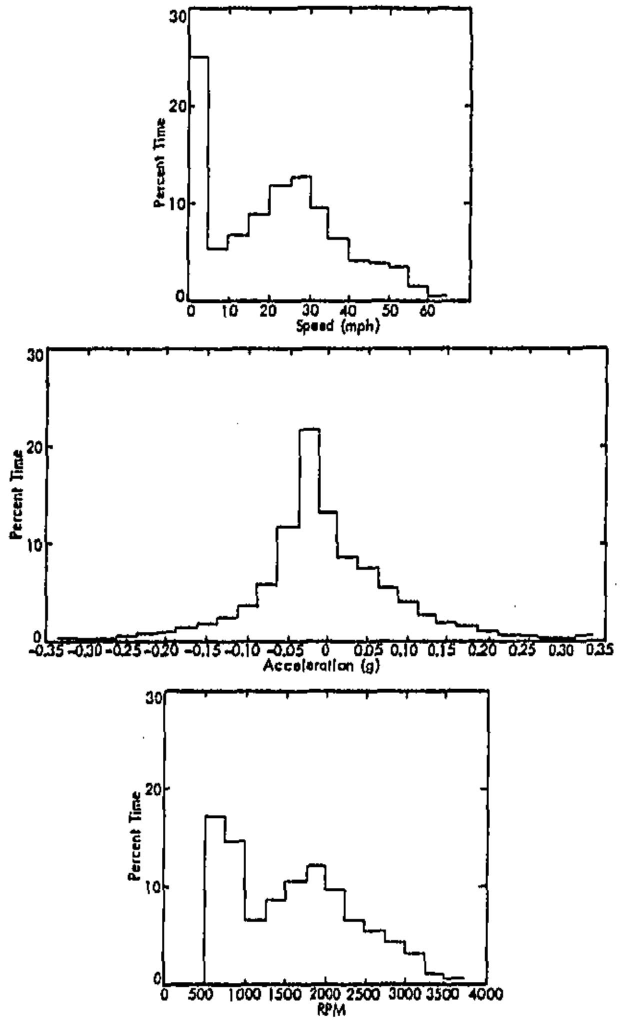

Figure 3.4(c). Percentage of Trip Time as Functions of Speed, Acceleration, and RPM For Vehicle 3 – Ford Pinto (L6, 3A). (Trip Time: 59.1 Minutes)

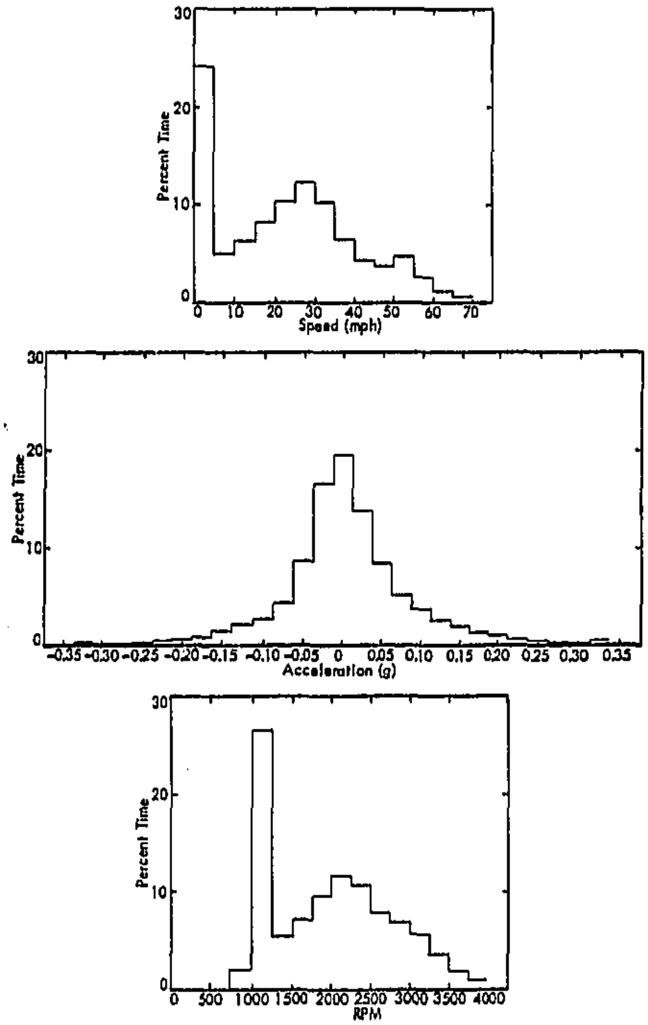

Figure 3.4(d). Percentage of Trip Time as Functions of Speed, Acceleration, and RPM For Vehicle 4 – VW Rabbit (L4, 4M). (Trip Time: 62.3 Minutes)

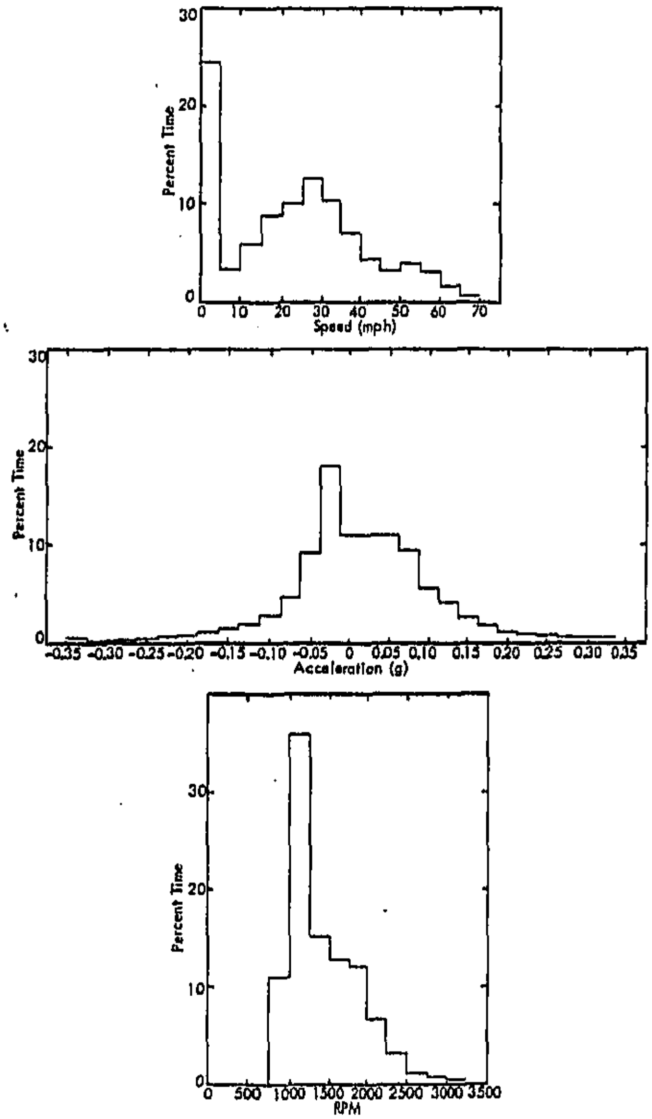

Figure 3.4(e). Percentage of Trip Time as Functions of Speed, Acceleration, and RPM For Vehicle 5 – Ford Granada (L6, 4M). (Trip Time: 58.5 Minutes)

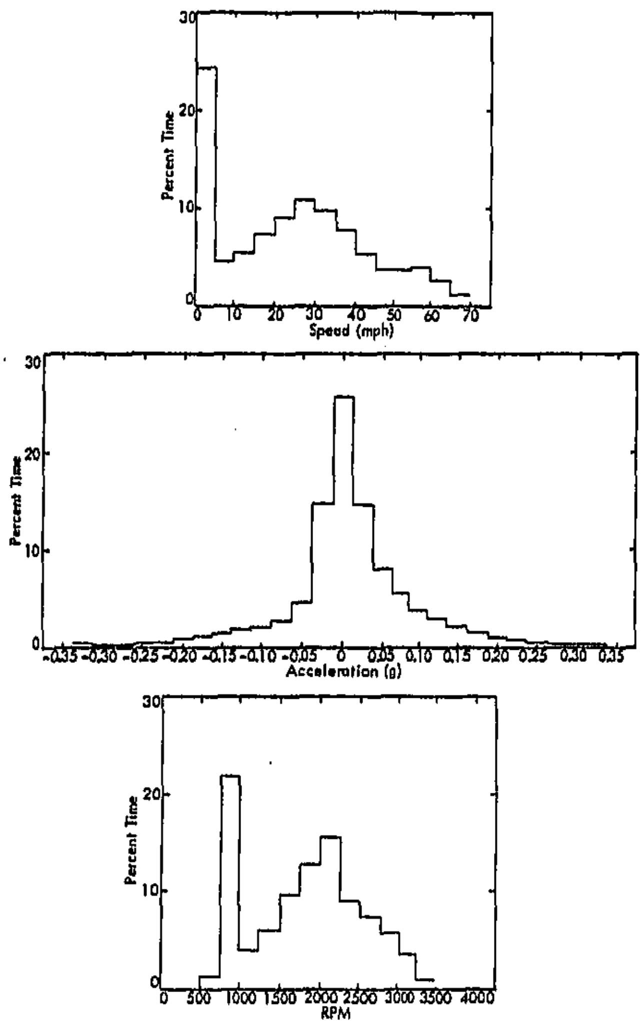

Figure 3.4(f). Percentage of Trip Time as Functions of Speed, Acceleration, and RPM For Vehicle 6 – Datsun 280Z (L6, 4M). (Trip Time: 58.9 Minutes)

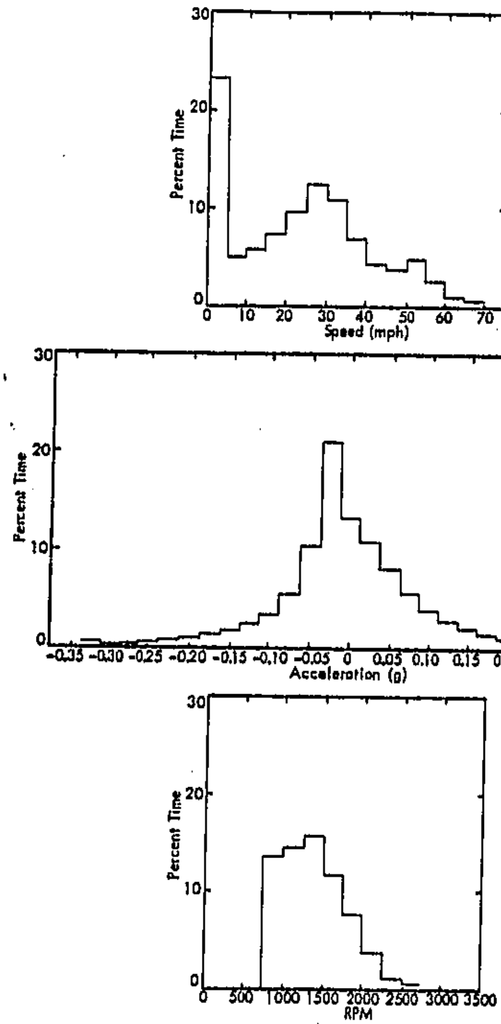

Figure 3.4(g). Percentage of Trip Time as Functions of Speed, Acceleration, and RPM For Vehicle 7 – Dodge Monaco (V8, 3A). (Trip Time: 58.9 Minutes)

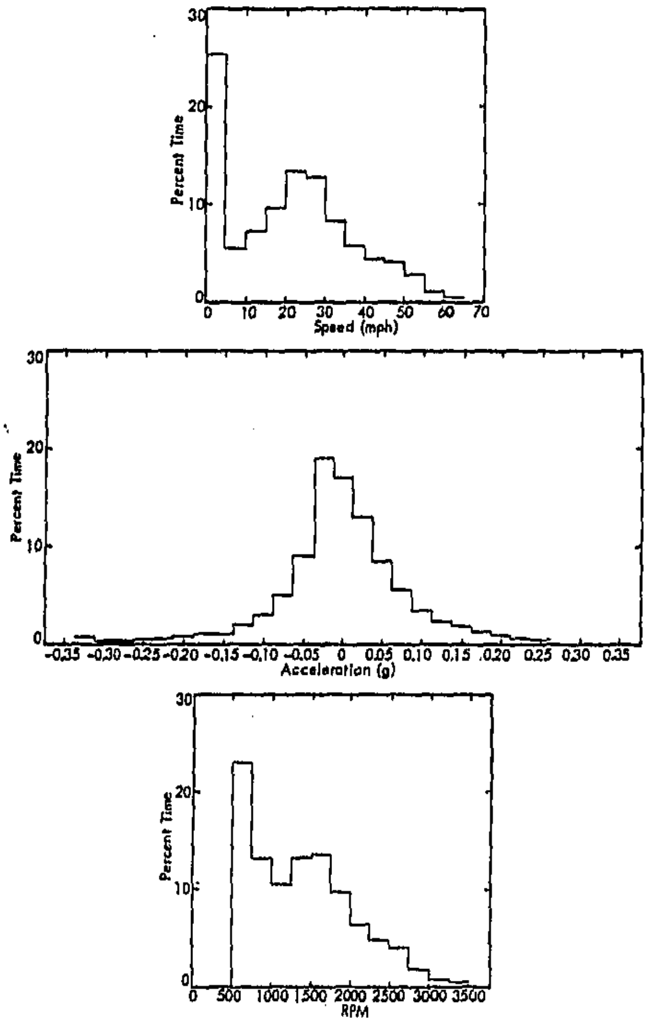

Figure 3.4(h). Percentage of Trip Time as Functions of Speed, Acceleration, and RPM For Vehicle 8 – Oldsmobile Cutlass (V8, 3A). (Trip Time: 59.6 Minutes)

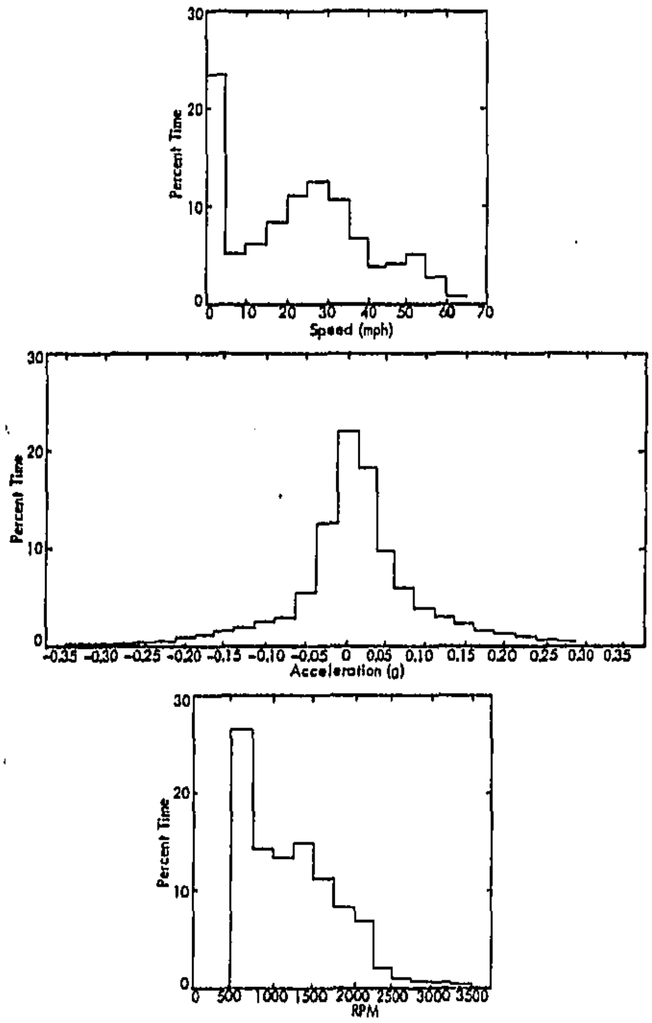

Figure 3.4(i). Percentage of Trip Time as Functions of Speed, Acceleration, and RPM For Vehicle 9 – Buick Skylark (V6, 3A). (Trip Time: 54.4 Minutes)

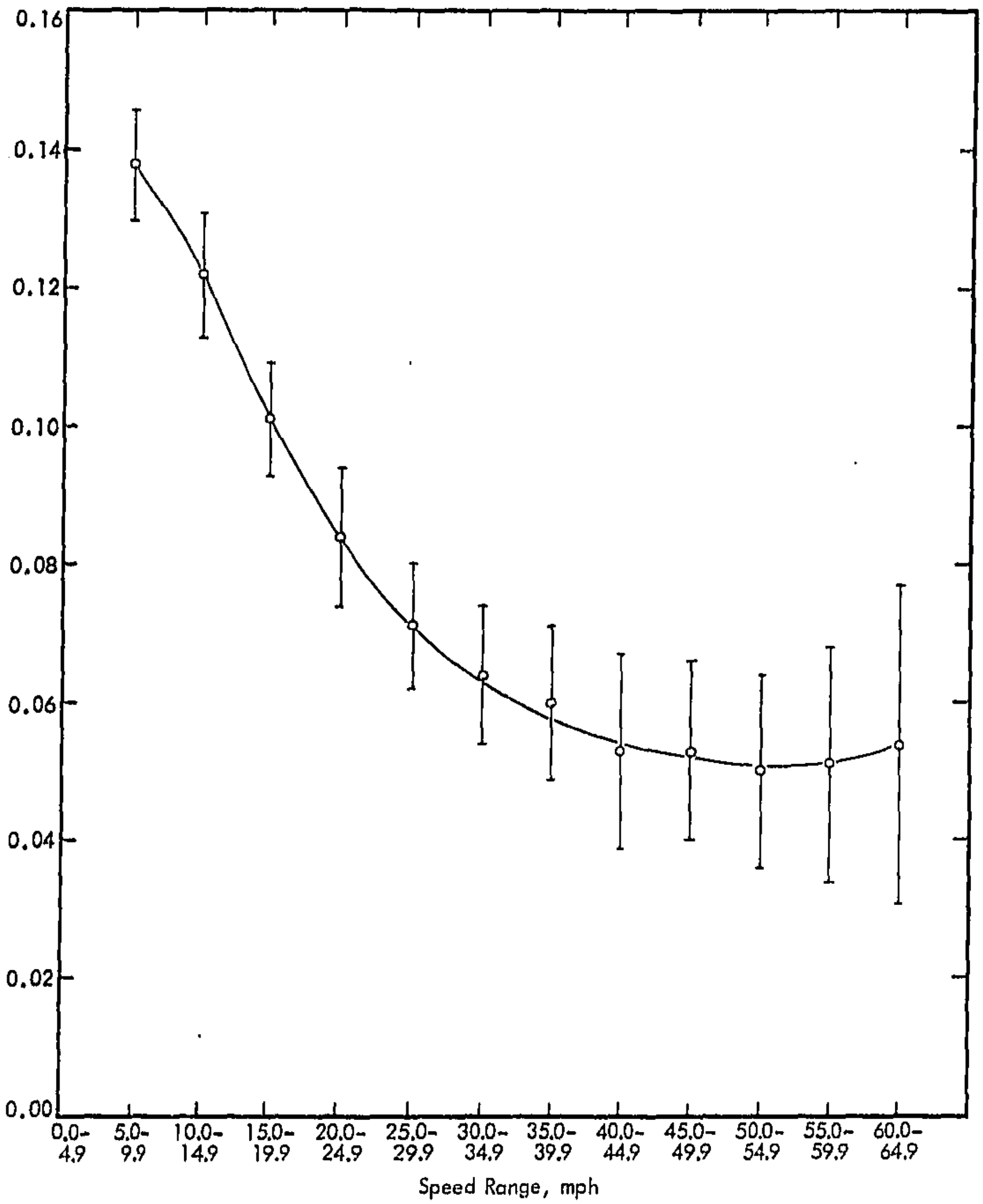

Figure 3.5. Average Acceleration as a Function of Speed Range For All Vehicles ($0.0125g \leq a < 0.3125g$).

3.7 Comparison with Previous Studies

Of considerable interest is a comparison of the operating parameter distributions resulting from the present study with the results of previous studies described in Section 1. The only study performed in sufficient detail to make accurate comparisons possible is that done by the Comite des Constructeurs D'Automobile du Marche Commun (Committee of Common Market Automobile Constructors — CCMC) in developing their proposed vehicle noise emission test.[6] A major objective of this program was to identify vehicle operating characteristics typical of drivers in Europe and develop a noise measurement procedure which more accurately reflected actual vehicle noise emission.

The experimental approach was similar to that in the current study — to instrument vehicles and record operating parameters as vehicles were driven over a designed route. Data was obtained for a total of 23 vehicles, five of which had automatic transmissions. A total of 6 different routes were used, each chosen to primarily represent central urban conditions. Both professional and non-professional drivers were utilized. Four vehicle parameters were recorded: vehicle speed, acceleration, engine RPM and under-bonnet noise level. The recorded data was processed by computer and statistically analyzed.

Much of the data developed in the CCMC study was in the form of cumulative frequency distributions which make a detailed comparison to the current study somewhat difficult. It is instructive, however, to compare the overall statistical distributions of vehicle speed and acceleration and engine RPM between the two studies. In order to make this comparison, an adjustment in the data was required to account for the different bin size intervals used in the two studies. This was accomplished by dividing the time percentage in each bin by the size of the bin interval. Figures 3.6 to 3.8 show the comparison of the study results in terms of speed, acceleration, and RPM distributions averaged over all trips in each study.

As is apparent in these figures, there is considerable similarity between the two data sets. The speed distributions exhibit the same overall structure, having a primary peak at speeds below 5 mph and a secondary peak in the area of 30 mph. The Wyle data exhibits a tertiary peak near 50 mph which does not appear to be duplicated in the CCMC data. This may be due to the greater amount of urban expressways in this country as compared to the European cities studied by CCMC.

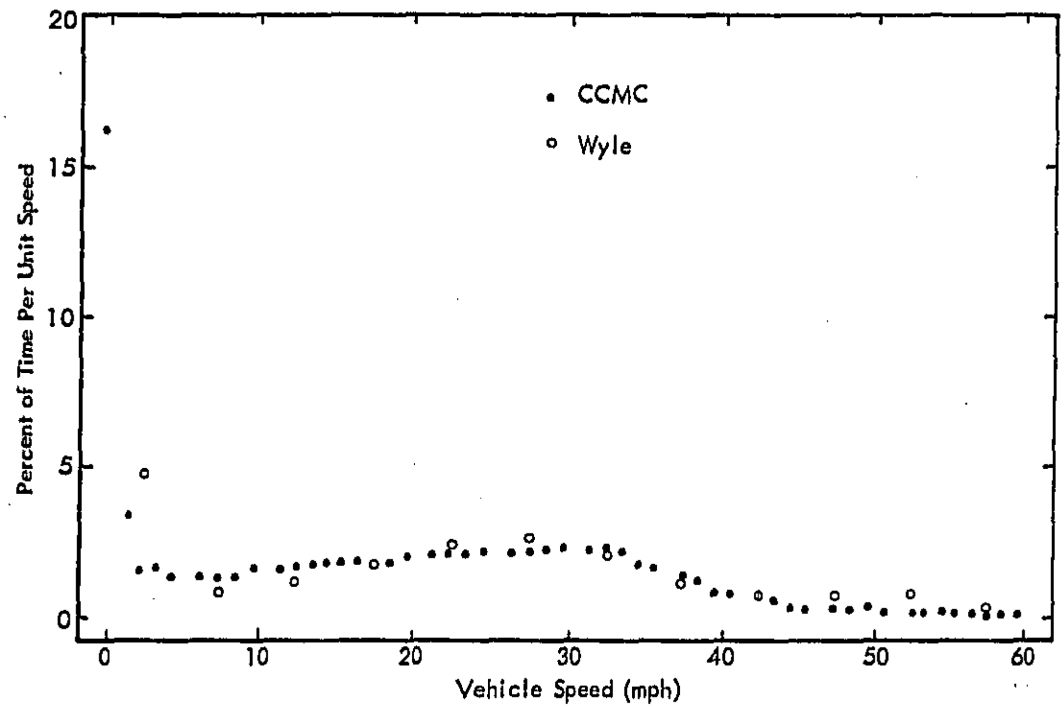

Figure 3.6. Average Distribution of Vehicle Speed For All Trips.

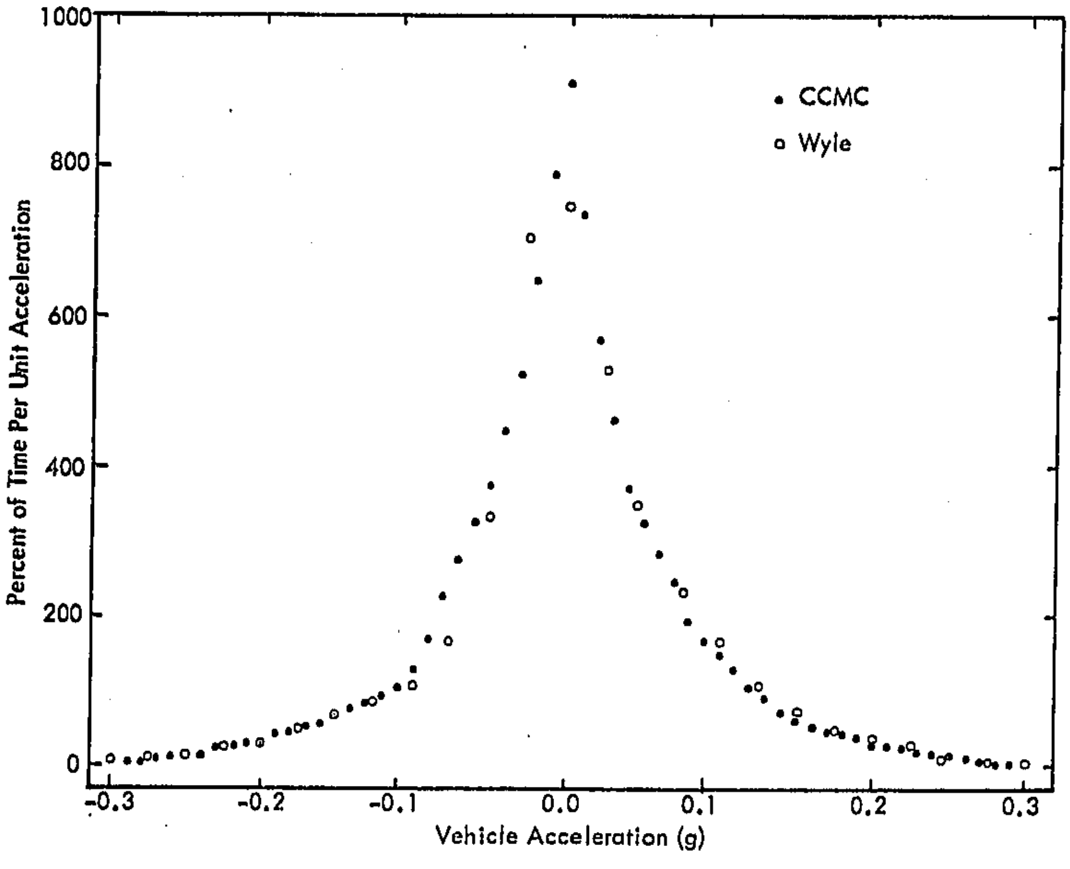

Figure 3.7. Average Distribution of Vehicle Acceleration for All Vehicles.

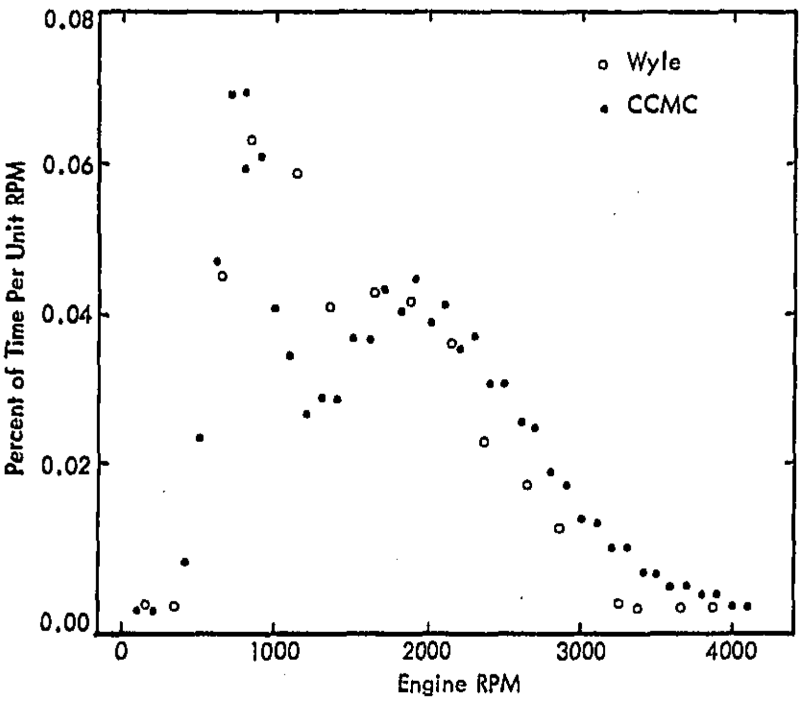

Figure 3.8. Average Distribution of Engine RPM For All Trips.

The acceleration data in the two studies is striking in its similarity. With the possible hint that decelerations may be more extreme in European driving, the acceleration distributions are almost identical.

Although the RPM distributions are somewhat similar, there are important differences evident between them. Both exhibit two peaks — one in the neighborhood of 800 to 1000 RPM, the other between 1500 and 2000 RPM. However, the CCMC distribution exhibits a larger percentage of time at high RPM than does the Wyle distribution. This is almost certainly indicative of the fact that more high RPM vehicles are included in the CCMC data than are included in the Wyle data.

In comparing these results, it must be remembered that detailed structure in each distribution has been removed by averaging over all vehicles in each study. Thus, although it appears that on a macroscopic scale there are few significant difference between European and United States vehicle operating characteristics, there may be considerable microscopic differences in the distributions for specific vehicles and routes.

4.0 VEHICLE ACOUSTICAL DATA BASE

4.1 Introduction

Although the joint probability distributions developed in Section 3 define the most common operating conditions of each of the nine vehicles tested, they do not, in themselves, define the operating conditions for which the acoustic emission from the vehicle is a maximum. For this, the distributions must be combined with the acoustic energy emission for each possible speed-acceleration-RPM combination and the percentage of the total trip acoustic energy for each combination of operating variables must be computed. The structure of the resulting acoustic energy emission distribution function can then be used to determine which operating conditions are most appropriate for an acoustic test procedure.

The purpose of this section is to describe the procedure that was carried out to develop such a joint acoustic energy emission distribution function for each of the test vehicles. The following steps in the process are each described in the sections below:

- Development of a Vehicle Noise Data Base
- Construction of an Acoustic Model
- Calculation of Acoustic Energy Emission Distribution Function
- Summary of Results.

4.2 Vehicle Noise Data Base

As discussed in Section 2.2, one of the criteria used to select vehicles for this study was the existence of an acoustical emission data base. Such a data base had been developed in an earlier EPA program[4,10] which had been conducted by Wyle Laboratories at a test track in Marana, Arizona.

In the series of tests carried out in the Marana program, vehicles were driven at various acceleration, cruise, and coast conditions past fixed arrays of up to eight microphones. Simultaneous measurements of vehicle speed and acceleration, engine RPM, and A-weighted, fast-response sound level were made at times corresponding to 0.7 foot increments of distance along the vehicle path. A total of 66 vehicles were tested in this manner.

Although the specific number and type of test performed varied from vehicle to vehicle, in general the following operating conditions were studied:

Automatic Transmission Vehicles

- Acceleration of 0.15g from standing start;
- Acceleration of 0.15g from moving starts of 10 mph and 15 mph;
- Full-throttle acceleration from standing start;
- Coast at 15, 20, 25, and 30 mph;
- SAE J986a procedure;
- Constant-throttle acceleration from standing start to achieve 100 feet in 5 seconds, 0.15g at the shift from first to second gear, and 0.15g at 25 mph.

Manual Transmission Vehicles

- Acceleration of 0.15g from standing start;
- Acceleration of 0.15g from moving starts of 10 mph and 15 mph;
- Full-throttle acceleration from standing start and from moving start of 15 mph;
- Cruise at 60 and 80 percent rated RPM in first gear and at 25 mph in second gear;
- Coast at 15, 20, 25, and 30 mph;
- SAE J986a procedure;
- Constant-throttle acceleration from 25 percent rated RPM to achieve 0.15g at 75 percent rated RPM.

In most cases, the above conditions were maintained only over a portion of the total path for which acoustic data is available. Once the vehicle had passed through the so-called "end zone" part of the path, the driver deviated in some random manner from the specified operating condition for the run — generally by starting to slow down to a stop. Since, in most cases, one or more microphones were located beyond the "end zone", some acoustic data is also available for vehicle operating conditions other than those corresponding to the operational scenarios described above.

From the total data set gathered for each of the vehicles in Table 2.1(a), the speed, acceleration, RPM, and sound level data at a 50-foot distance from the vehicle were abstracted. This was accomplished by selecting only those sets of measurements that were made when the vehicle was at its closest point of approach to one of the microphones located 50 feet from the vehicle and perpendicular to its path.

Since it was desired to obtain information on the engine acoustic emission, the data base formed in this manner consisted only of powered runs; coast conditions were omitted. The total number of speed-acceleration-RPM sound level samples gathered in this manner for each vehicle are listed in Table 4.1.

Table 4.1

Number of Speed-Acceleration-RPM
Sound Level Samples For Each Vehicle

Vehicle No.	Marana Test No.	Marana Vehicle	Engine	Trans-mission	Total No. of Samples	No. of Valid Samples
1	38	Ford Pinto	L4	3A	76	75
2	19	Chevrolet Chevette	L4	3A	48	47
3	47	Ford Pinto	V6	3A	44	43
4	6	VW Rabbit	L4	4M	335	335
5	10	Ford Granada	L6	4M	263	260
6	8	Datsun 280Z	L6	4M	240	239
7	2	Dodge Monaco	V8	3A	258	258
8*	1	Oldsmobile Cutlass	V8	3A	405	398
9*	17,18	Buick Skylark	V6	3A	500	500

* Equivalent Vehicles Tested in This Program Are: #8 – Chevrolet Camaro (V8, 3A),
#9 – Oldsmobile Omega (V6, 3A).

In order to detect erroneous data points in each set of data, the sound levels were plotted as a function of engine RPM. Any points lying far outside the envelope formed by the great majority of data was deleted. In this manner the valid samples enumerated in the last column of Table 4.1 were obtained.

The sound levels in the data base described above correspond to total vehicle noise. Since the intent of this program is to develop a test methodology that measures only engine, exhaust, and driveline noise, any tire noise contribution must be removed from the data base.

To accomplish this, estimates of tire noise contribution for each vehicle were subtracted from the total vehicle sound levels. These estimates were obtained as a function of vehicle speed by performing logarithmic regressions on the coast data for each vehicle. The regression coefficients for each vehicle are shown in Table 4.2.

Table 4.2

Regression Equations For Tire Noise Contribution

$$L_{Tire}(V) = K_1 + K_2 \log_{10}(V/35)$$

L_{Tire} = A-weighted, fast response sound level in dB,

V = Vehicle speed in mph.

Vehicle No.	Regression Coefficients	
	K_1	K_2
1	63.4	37.2
2	63.7	30.1
3	60.1	34.6
4	61.4	29.6
5	62.6	25.0
6	62.5	36.0
7	62.5	36.0
8	64.4	34.1
9	61.7	32.6

The estimates of tire sound level obtained from these regression equations were subtracted on an energy basis from the measured total sound levels to produce the sound levels due to non-tire sources using the relationship:

$$L_{engine} = 10 \log_{10} \left[10^{L_{Total}/10} - 10^{L_{Tire}/10}\right]$$

Throughout the remainder of this report, this sound level shall be referred to as the "engine sound level", L_{engine}, even though it corresponds to engine, driveline, and exhaust noise sources.

4.3 Model of Engine Sound Levels

To develop a model relating engine sound level to vehicle operating parameters, multiple linear regressions were performed. In order to determine which such operating parameters are most important in determining engine sound level, correlation coefficients between the sound levels in the data base and corresponding vehicle operating parameters were computed. The operating parameters studied were the measured vehicle speed (V), vehicle acceleration (A), engine RPM (R), and the derived power-like quantity VA, and the torque-like quantity VA/R. The resulting correlation coefficients are shown in Table 4.3.

The power-like parameter VA was included because recent experiments carried out by Wyle in another EPA sponsored program[19] indicated that engine sound level was closely correlated to engine RPM and to fuel flow (as determined by throttle setting). Although fuel flow was not measured directly in this program, the engine power is proportional to it. The derived quantity VA is not exactly proportional to engine power since air and frictional resistance terms have not been included; however, it should be a sufficiently good approximation for modeling purposes. The derived torque-like parameter VA/R is also related to fuel flow, and as a result, may correlate with engine sound levels.

Examination of Table 4.3 shows engine sound levels to be most closely correlated with engine RPM, as would be expected from most previous work in this area. Secondary correlates are engine "power" and vehicle speed, while tertiary correlates are vehicle acceleration and engine "torque".

Correlations between engine sound level and the logarithms of engine RPM, acceleration, "power", and "torque" were also computed for vehicle #1, which had an automatic transmission, and for vehicle #4, which had a manual transmission. No improvements, as compared to the values in Table 4.3, were observed so that this line of investigation was not continued for the remaining vehicles.

Simple linear regressions were performed between the engine sound level data for each vehicle and each of the operating parameters in Table 4.3. In addition, multiple linear regressions were performed between these sound levels and various combinations of these operating parameters. The standard errors of estimate for each of those regressions are shown in Table 4.4.

This table shows that the last four models — which relate engine sound level to RPM and acceleration, to RPM and "power", to RPM and "torque", and to RPM, acceleration, and speed — are essentially equally accurate. In order to choose among these models, a comparison was made of the correlation between pairs of the operating parameters RPM, acceleration, "power", and "torque" to determine which were most independent of each other. The results of this study are shown in Table 4.5.

Table 4.3. Correlation Coefficients Between Engine Sound Levels and Vehicle Operating Parameters

Vehicle Number	Operating Parameter				
	V	A	R	VA	VA/R
1	0.88	0.87	0.99	0.98	0.87
2	-0.14	0.83	0.86	0.82	0.76
3	0.94	0.82	0.98	0.93	0.63
4	0.51	0.17	0.96	0.38	0.13
5	0.38	0.24	0.87	0.39	0.23
6	0.64	0.36	0.91	0.54	0.34
7	0.83	0.38	0.92	0.78	0.41
8	0.76	0.33	0.93	0.71	0.39
9	0.71	0.16	0.87	0.59	0.21
Mean	0.61	0.46	0.92	0.68	0.44
St. Dev	0.33	0.29	0.05	0.22	0.26

Table 4.4. Standard Error of Estimate in dB for Linear Regressions of Engine Sound Level with Vehicle Operating Parameters

Vehicle Number	Operating Parameter(s)								
	Single Variables					Multiple Variables			
	V	A	R	VA	VA/R	R&A	R&VA	R&VA/R	R, A, & V
1	3.2	3.3	1.1	1.2	3.3	1.2	1.0	1.1	1.1
2	5.5	3.0	2.8	3.1	3.6	2.6	2.6	2.6	2.6
3	1.9	3.3	1.3	2.1	4.5	1.2	1.1	1.1	1.1
4	5.1	5.9	1.8	5.5	5.9	1.2	1.3	1.2	1.2
5	5.2	5.5	2.8	5.2	5.5	2.0	2.2	2.1	2.0
6	4.1	4.9	2.2	4.5	5.0	1.4	1.4	1.2	1.3
7	2.5	4.2	1.8	2.9	4.2	1.4	1.3	1.3	1.3
8	4.0	5.8	2.3	4.3	5.6	2.1	2.2	2.2	2.0
9	3.3	4.7	2.3	3.8	4.6	1.7	1.8	1.8	1.7
Mean	3.9	4.5	2.0	3.6	4.7	1.6	1.7	1.6	1.6
St. Dev.	1.2	1.1	0.6	1.4	0.9	0.5	0.6	0.6	0.5

Table 4.5. Correlation Coefficients of Pairs of Vehicle Operating Parameters

Vehicle Number	Operational Parameters				
	V vs R	A vs R	VA vs R	VA/R vs R	A vs V
1	0.87	0.88	0.99	0.85	0.59
2	-0.23	0.85	0.80	0.71	-0.37
3	0.93	0.79	0.90	0.56	0.83
4	0.55	-0.05	0.18	-0.09	0.15
5	0.43	-0.11	0.08	-0.12	0.14
6	0.63	0.03	0.24	-0.02	0.06
7	0.88	0.15	0.60	0.14	0.01
8	0.89	0.22	0.69	0.34	0.02
9	0.89	-0.20	0.34	-0.10	-0.32
Mean	0.65	0.28	0.54	0.25	0.12
St. Dev.	0.38	0.44	0.33	0.38	0.38

From this table it can be seen that speed and acceleration are most independent of each other, followed by "torque" and RPM, acceleration and RPM, "power" and RPM, and speed and RPM, in that order. Examining only those correlations with RPM, it is seen that the "torque" is the most independent of RPM.

In general, it is desirable to model a dependent variable, in this case, the engine sound level, in terms of independent variables that are uncorrelated with each other. Thus the model chosen to represent the engine sound level was that relating it to engine RPM and to the torque-like quantity, VA/R. The regression coefficients for each vehicle for this model are shown in Table 4.6 along with the corresponding standard errors of estimate.

4.4 Acoustic Energy Emission Distribution Function

To develop an acoustic emission distribution function, the A-weighted acoustic energy emitted by the engine at the speed-acceleration-RPM combination corresponding

Table 4.6. Multiple Linear Regression Equation Relating Engine Sound Level to Engine RPM and "Torque":

$$L_{Engine}\ (R,\ VA/R) = C_1\ R + C_2\ (VA/R) + C_3$$

L_{Engine} = A-weighted, fast response sound level of engine, driveline, and exhaust in dB,

R = engine RPM,

V = vehicle speed in mph, and

A = vehicle acceleration in g's.

Vehicle Number	Regression Coefficient			St. Err. of Estimate
	C_1	C_2	C_3	
1	0.00741	3458	39.8	1.1
2	0.00924	4673	32.4	2.6
3	0.00971	2692	35.9	1.1
4	0.00528	2092	46.0	1.2
5	0.00847	1879	40.8	2.1
6	0.00513	2327	46.4	1.2
7	0.00600	1551	47.6	1.3
8	0.01003	545	40.3	2.2
9	0.00733	2069	42.3	1.8

to each bin must be divided by the total of such energy contributions for all bins. The resulting fraction, when multiplied by 100, gives the percentage of the total acoustic energy emission for each bin.

In order to accurately determine the A-weighted acoustic energy emission for a given bin, the A-weighted sound levels for the operating parameters corresponding to that bin should be determined at a large number of points spread evenly over a surface enclosing the source and the corresponding acoustic intensities calculated. The sum of all of these intensity contributions is proportional to the total acoustic power output of the source. The typical acoustic energy output during a trip for this bin is then obtained by multiplying this power output by the amount of time that the operating conditions corresponding to that bin occur; i.e., by the value of the joint probability distribution for that bin, which was computed in Section 3.

This procedure is quite complex since it requires developing a mathematical model for sound level as a function of both vehicle operating conditions and position in space relative to the source. This, in turn, necessitates knowing the details of the angular distribution of sound level about the source.

In this study, an approximation to the acoustic emission distribution function, which requires modeling the sound level at only one point relative to the source, is computed. The mathematical model developed above, which estimates the A-weighted sound level at a point 50 feet to the side of the vehicle along a line perpendicular to its path, is used to compute a single acoustic intensity contribution at this one point in space corresponding to each speed-acceleration-RPM bin. This intensity contribution is multiplied by the corresponding value of the joint speed-acceleration-RPM probability distribution to determine the energy emission contribution at that point in space for the bin. This energy contribution is then multiplied by 100 and divided by the sum of all such energy contributions for the total set of bins, to obtain the percentage of the total energy at the 50 feet location that corresponds to the given bin.

The acoustic intensity at a given point in space corresponding to a given speed (V)-Acceleration(A)-RPM(R) bin is given by:

$$I\ (V,\ A,\ R) = \frac{P_{ref}^2}{\rho c} \times 10^{L\ (V,\ A,\ R)/10} \quad \text{watts/m}^2 \qquad (1)$$

where

$L(V, A, R)$ is the sound level at that point in space for the given V-A-R combination

P_{ref} is the reference pressure of 20μPa, and

ρc is the acoustic impedance of air of 406 mks Rayls.

The corresponding acoustic energy per unit area at the given point in space is then:

$$e(V, A, R) = I(V, A, R) \times \Delta t(V, A, R) \quad \text{watt-sec/m}^2 \qquad (2)$$

where

$\Delta t(V, A, R)$ is the total time in sec, spent at the given V, A, R operating conditions.

In terms of the joint probability distribution developed in Section 3, the quantity Δt is given by:

$$\Delta t\ (V, A, R) = \frac{P_t(V, A, R)}{100} \times T_{tot} \quad \text{sec} \qquad (3)$$

where

$P_t(V, A, R)$ is the percentage of trip time corresponding to a given V, A, R operating condition and,

T_{tot} is the total duration of the trip in sec.

$\therefore$ The total acoustic energy per unit area emitted during the trip at the given point is just the summation of $e(V, A, R)$ over all V, A, R bins:

$$e_{tot} = \sum_V \sum_A \sum_R e(V, A, R) \qquad (4)$$

Combining equations (1) to (4), the percent of acoustic energy at the given point corresponding to a given V, A, R bin is given by:

$$P_E(V, A, R) = 100 \times \frac{e(V, A, R)}{e_{tot}} = \frac{100 \times P_t(V, A, R) \times 10^{L(V, A, R)/10}}{\sum_V \sum_A \sum_R P_t(V, A, R) \times 10^{L(V, A, R)/10}} \qquad (5)$$

If the vehicle is assumed to be an omnidirectional sound source radiating over a half-plane, then the total acoustic energy emission during the trip is given by:

$$E_{tot} = 2\pi r^2 \, e_{tot} \quad , \quad \text{watt-sec} \qquad (6)$$

where r is the distance from the source, in meters, at which the sound level measurements $L(V, A, R)$ were made.

The multiple-linear-regression equation for engine sound level developed in the previous section for each vehicle was used to provide the values of $L(V, A, R)$ needed in Equation (5) for each operating parameter bin corresponding to non-negative accelerations. For bins corresponding to negative acceleration (deceleration), values of $L(V, 0, R)$ were substituted into Equation (6), thus taking zero acceleration sound levels to approximate the sound level in deceleration modes.[20] Similarly, substituting these relations for sound level into Equation (6) resulted in estimates of the total engine acoustic emission for each vehicle.

4.5 Summary of Results

This section contains a summary of the engine acoustic energy emission distributions that resulted for each of the nine vehicles tested.

Figures 4.1(a) through 4.1(i) illustrate pictorially the structure of the peaks in these distributions of relative energy emission for each vehicle. For simplicity, only those bins corresponding to at least 1 percent of the total acoustic energy emitted by the engine during the trip are shown.

These figures are similar to those of Figures 3.3(a) through 3.3(i), which are described in Section 3.5. The only difference is that in Figure 3.3 the vertical axis represents percent of total trip time, while in Figure 4.1 the vertical axis represents percent of total acoustic energy emission by the engine.

This pictorial representation not only allows comparisons of acoustic energy distribution functions between vehicles to be made, but also allows comparisons with the temporal distribution function for the same vehicle. Thus, it is readily apparent that, whereas the 0-5 mph, 0.0g acceleration, idle RPM condition is the most common condition occurring during the trip, it does not contribute a correspondingly large amount of acoustic energy to the environment.

A listing of the data presented in these figures is contained in Appendix I, which gives in order of decreasing rank, the forty highest bins for the engine acoustic energy distribution for each vehicle.

Figures 4.2(a) through 4.2(i) show the percentage of engine acoustic energy emission as a function of the individual vehicle operating parameters of speed, acceleration, and engine RPM. The estimate of total acoustic energy emission from Equation (6) is shown at the top of each figure. Also shown for comparison are the temporal distributions for these parameters, which were previously presented in Figure 3.4. Since, as will be shown in Section 5, relatively little acoustic energy is associated with deceleration, only the non-negative portion of the acceleration curves have been shown in each set of figures. The results shown in Figure 4.2 were obtained from the joint V-A-R acoustic energy distribution function by summing over appropriate pairs of variables. Thus, for example, the distribution of energy with speed is obtained by summing the joint distribution over all accelerations and all RPM's. Listings of the data in each of these figures is given in Appendix J.

In Appendices K, L, and M are listed the joint engine acoustic energy distributions for the pairs of variables speed-acceleration, speed-RPM, and RPM-acceleration, respectively. Each of these was calculated from the joint V-A-R engine acoustic energy distribution by summing over the appropriate variable (e.g., the joint speed-acceleration distribution is obtained by summing over RPM).

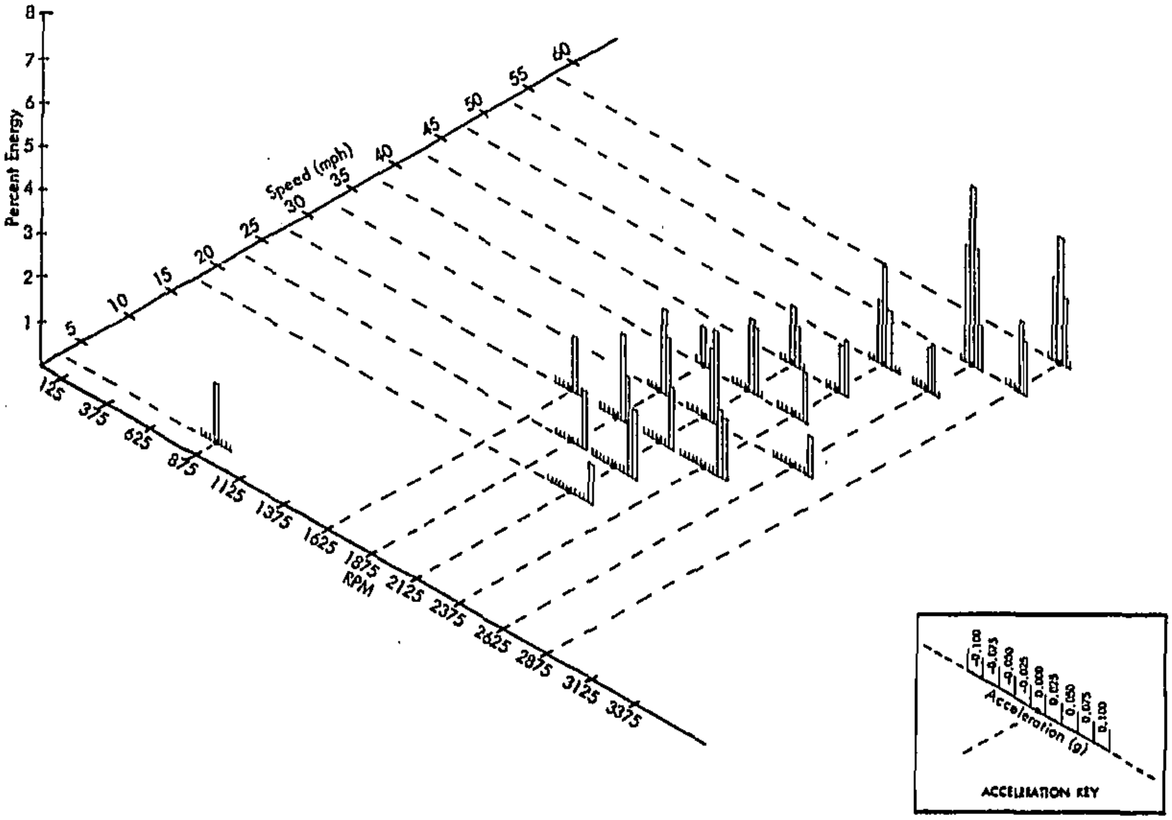

Figure 4.1(a). Percentage of Acoustic Energy Emitted by Engine For Vehicle 1 – Ford Pinto (L4, 3A).

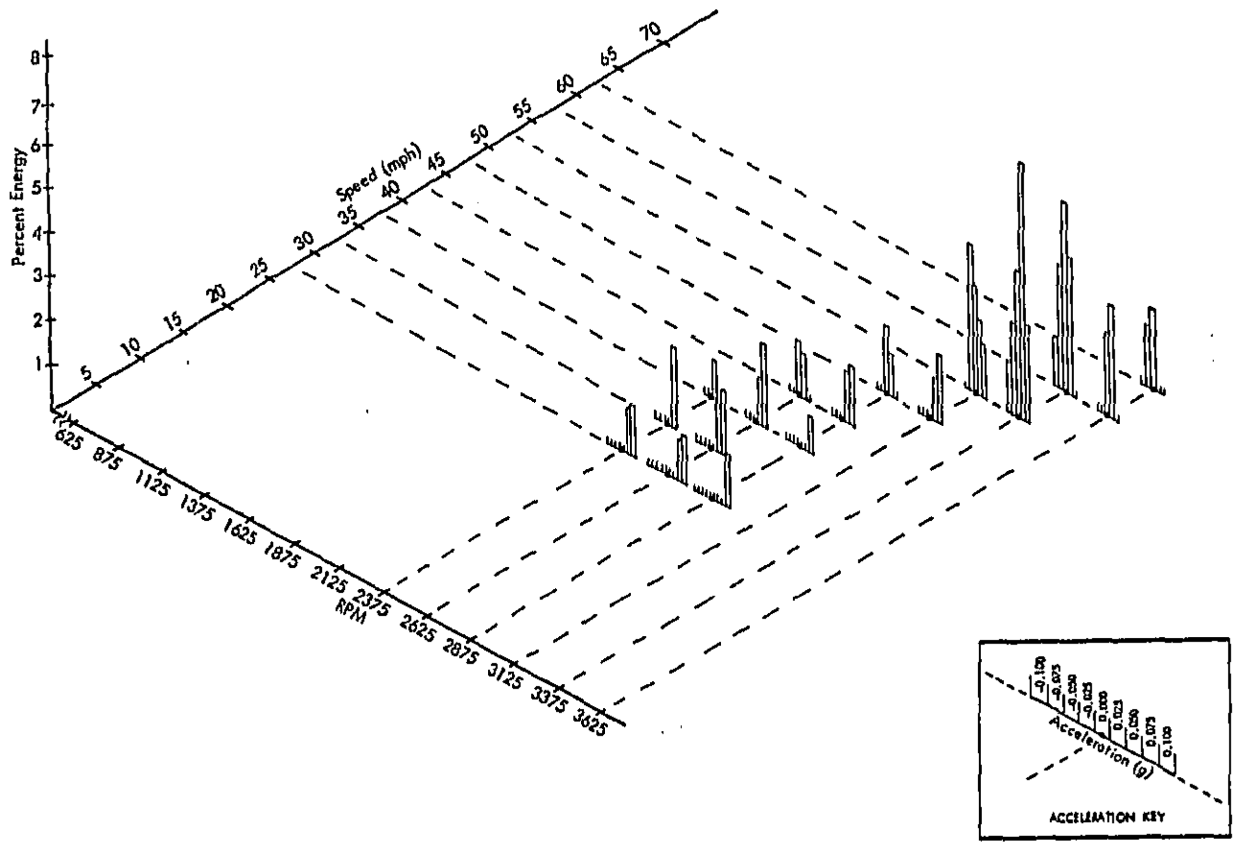

Figure 4.1(b). Percentage of Acoustic Energy Emitted by Engine For Vehicle 2 – Chevrolet Chevette (L4, 3A).

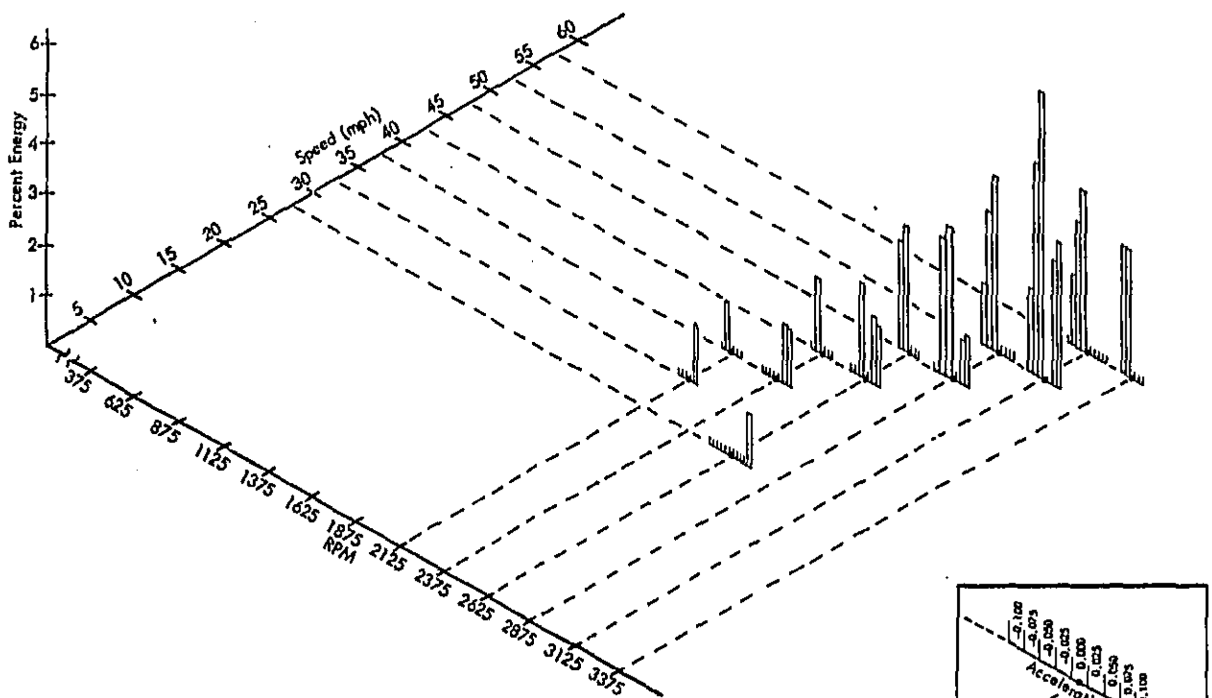

Figure 4.1(c). Percentage of Acoustic Energy Emitted by Engine For Vehicle 3 – Ford Pinto (L6, 3A).

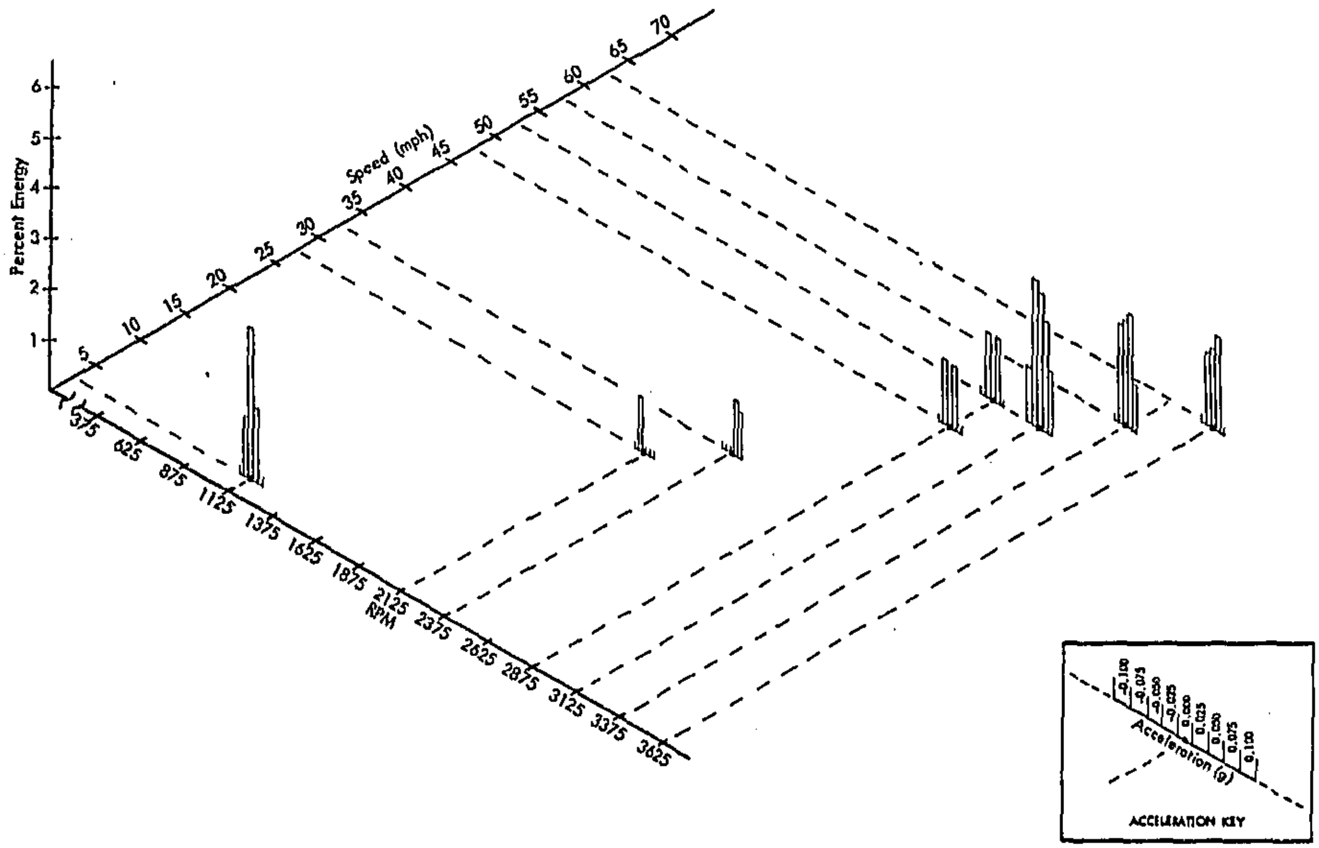

Figure 4.1(d). Percentage of Acoustic Energy Emitted by Engine For Vehicle 4 – VW Rabbit (L4, 4M).

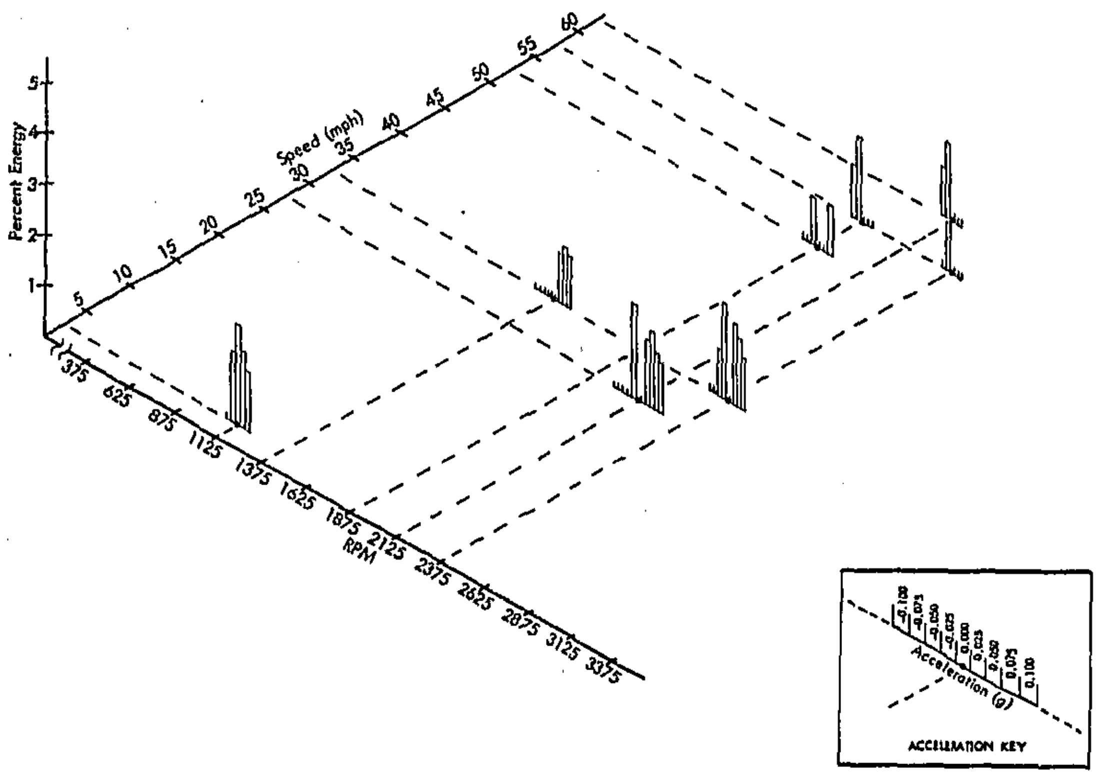

Figure 4.1(e). Percentage of Acoustic Energy Emitted by Engine For Vehicle 5 – Ford Granada (L6, 4M).

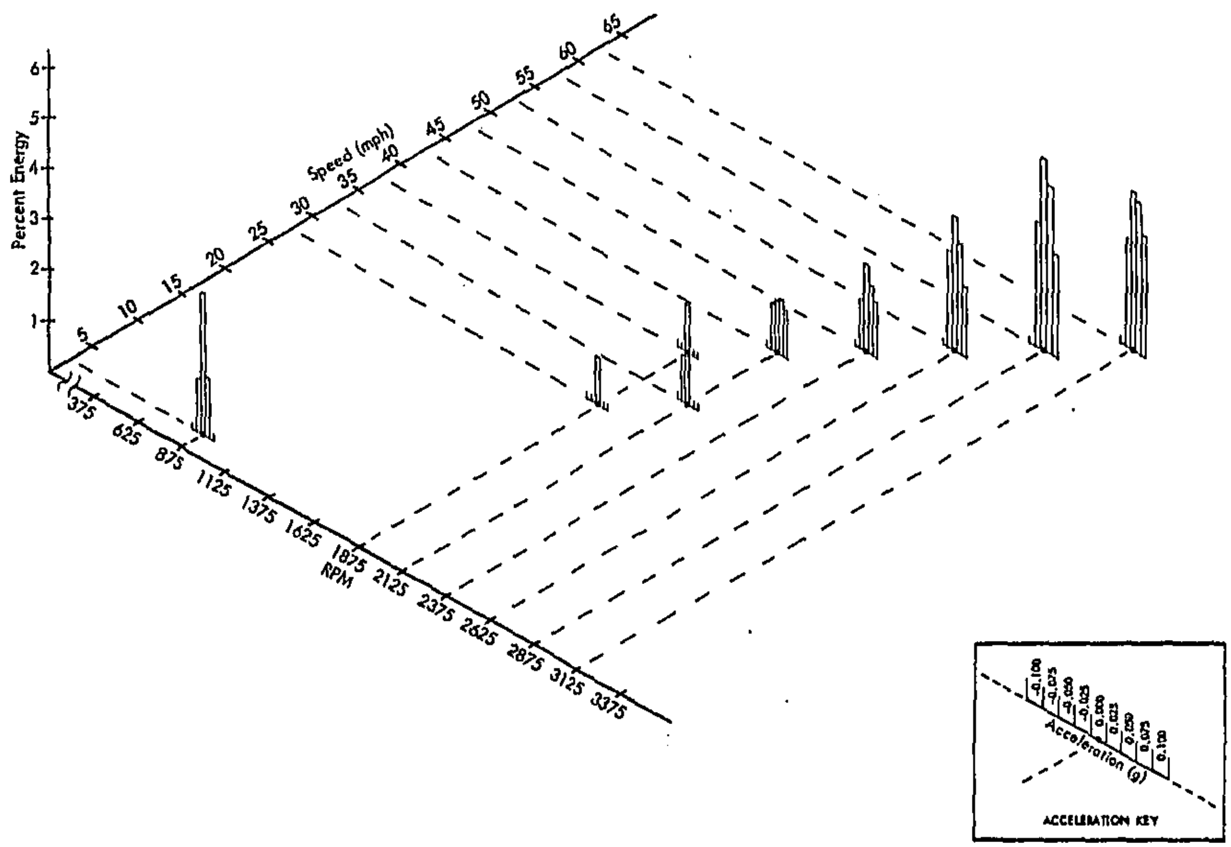

Figure 4.1(f). Percentage of Acoustic Energy Emitted by Engine For Vehicle 6 — Datsun 280Z (L6, 4M).

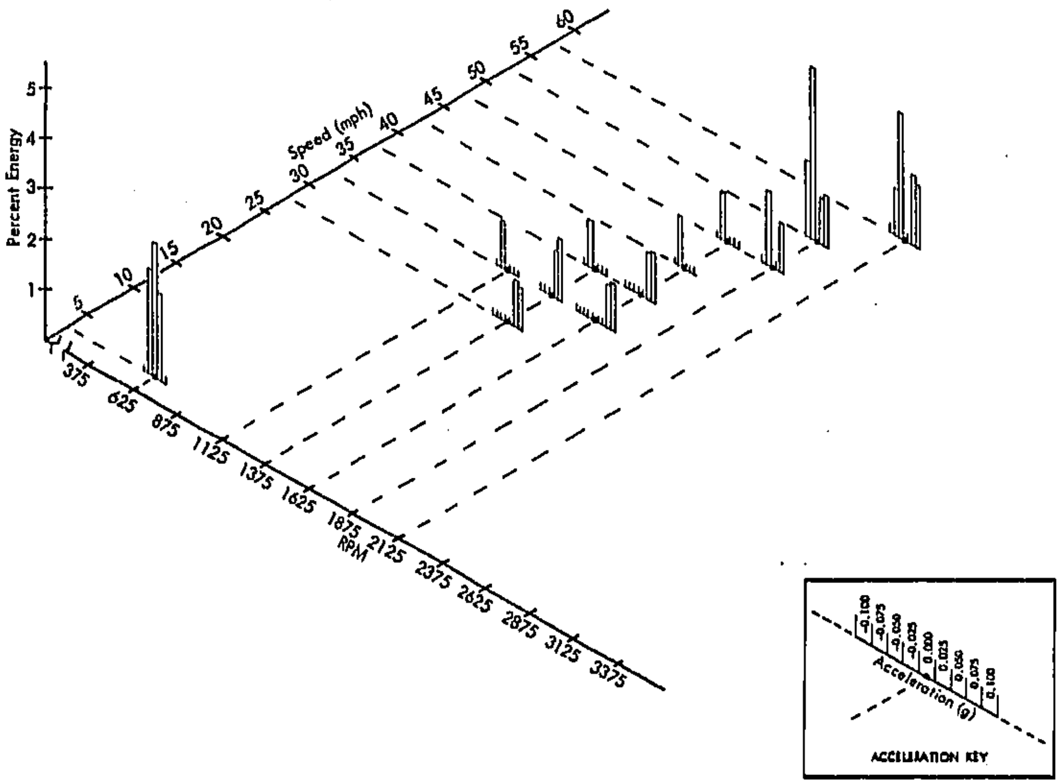

Figure 4.1(g). Percentage of Acoustic Energy Emitted by Engine For Vehicle 7 – Dodge Monaco (V8, 3A).

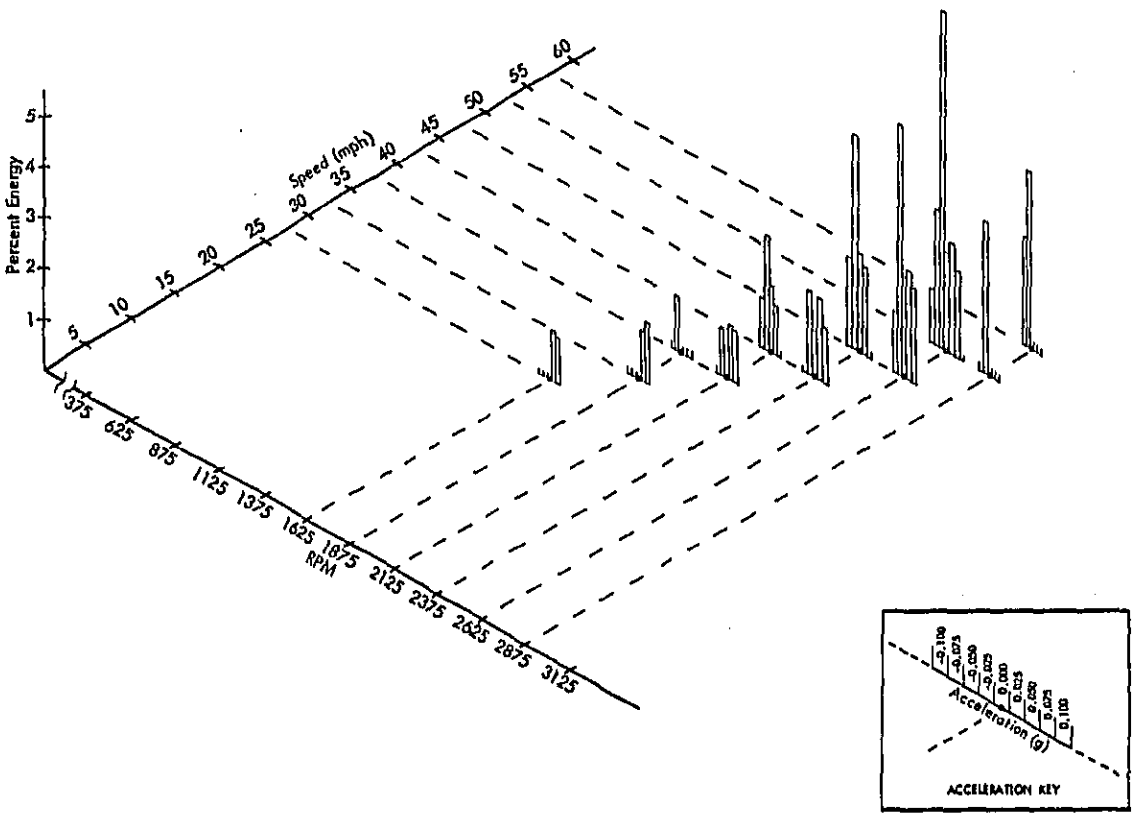

Figure 4.1(h). Percentage of Acoustic Energy Emitted by Engine For Vehicle 8 – Oldsmobile Cutlass (V8, 3A).

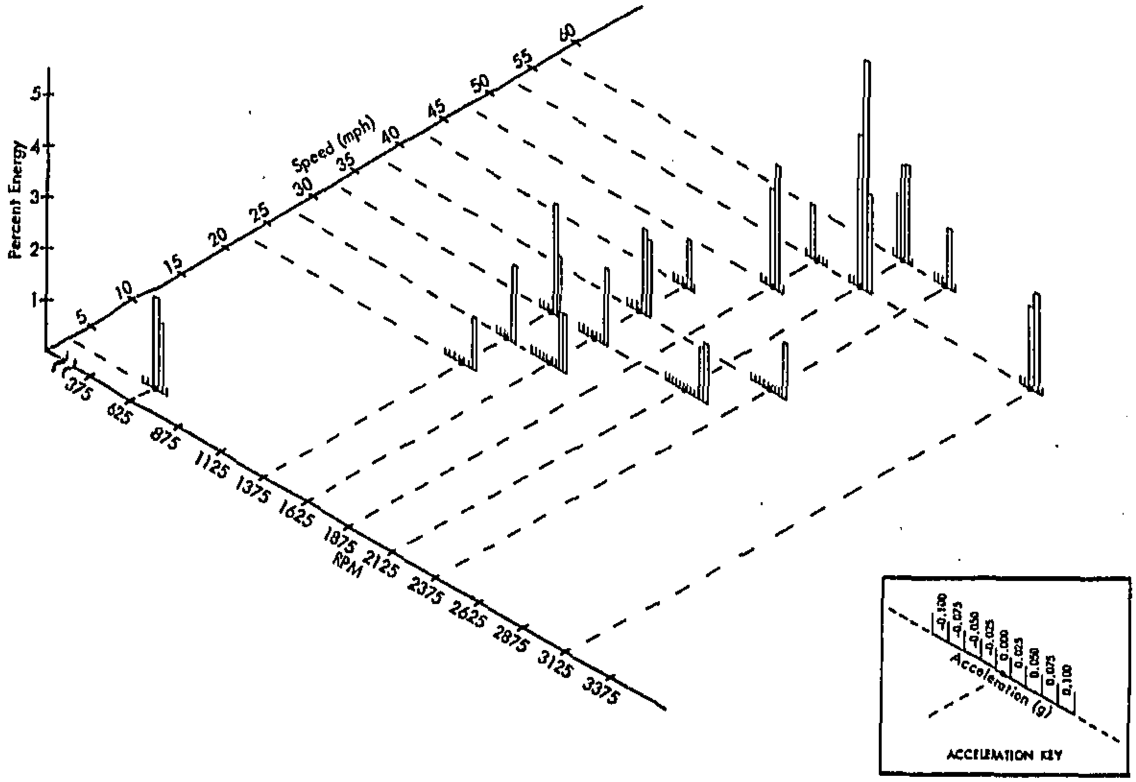

Figure 4.1(i). Percentage of Acoustic Energy Emitted by Engine For Vehicle 9 — Buick Skylark (V6, 3A).

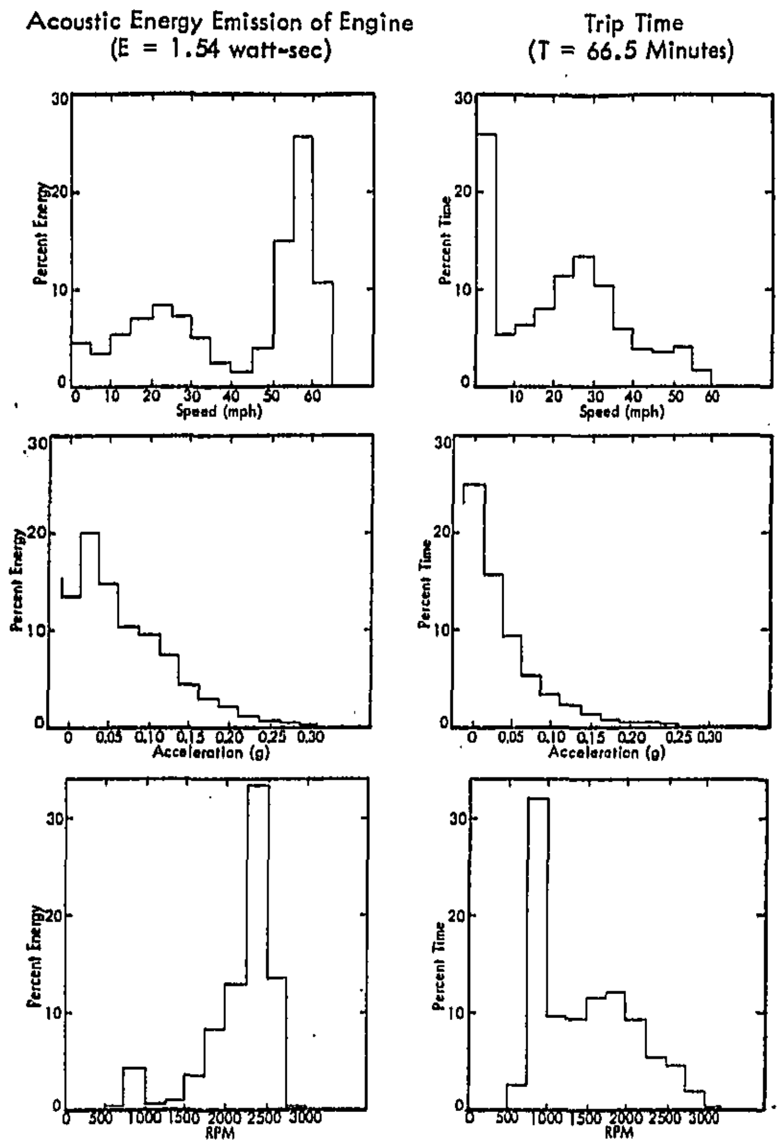

Figure 4.2(a). Percentage of Acoustic Energy Emission and Percentage of Trip Time as Functions of Speed, Acceleration, and RPM For Vehicle 1 – Ford Pinto (L4, 3A).

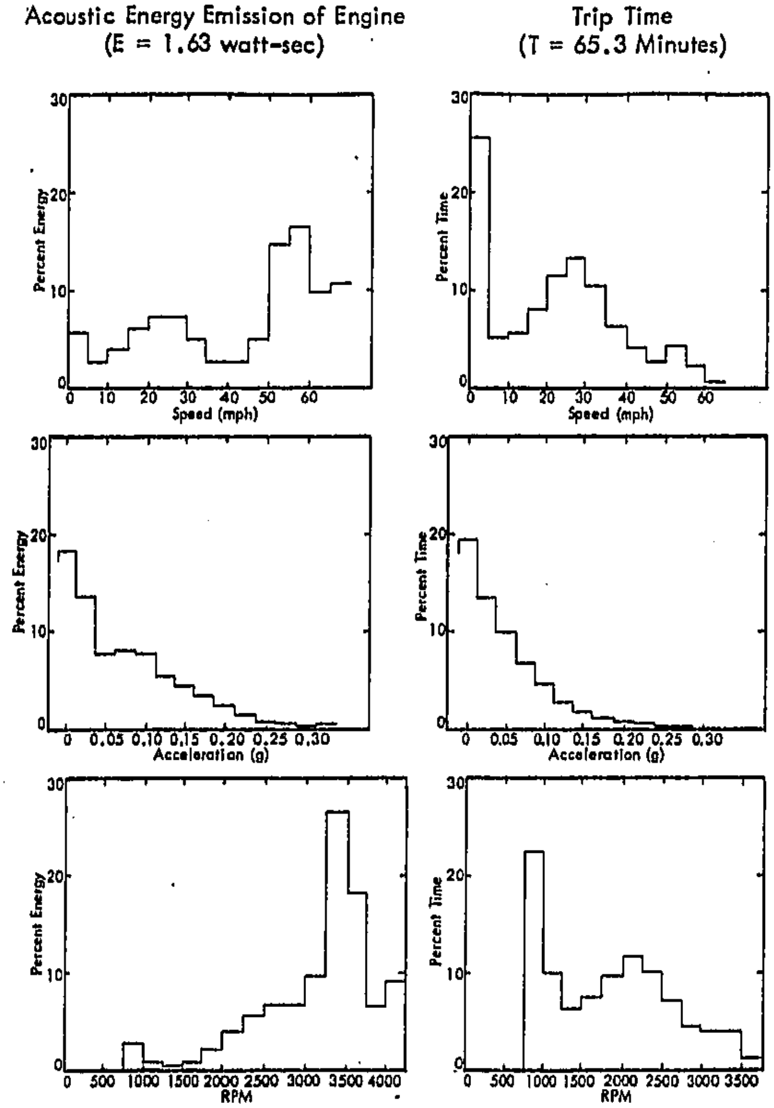

Figure 4.2(b). Percentage of Acoustic Energy Emission and Percentage of Trip Time as Functions of Speed, Acceleration, and RPM For Vehicle 2 – Chevrolet Chevette (L4, 3A).

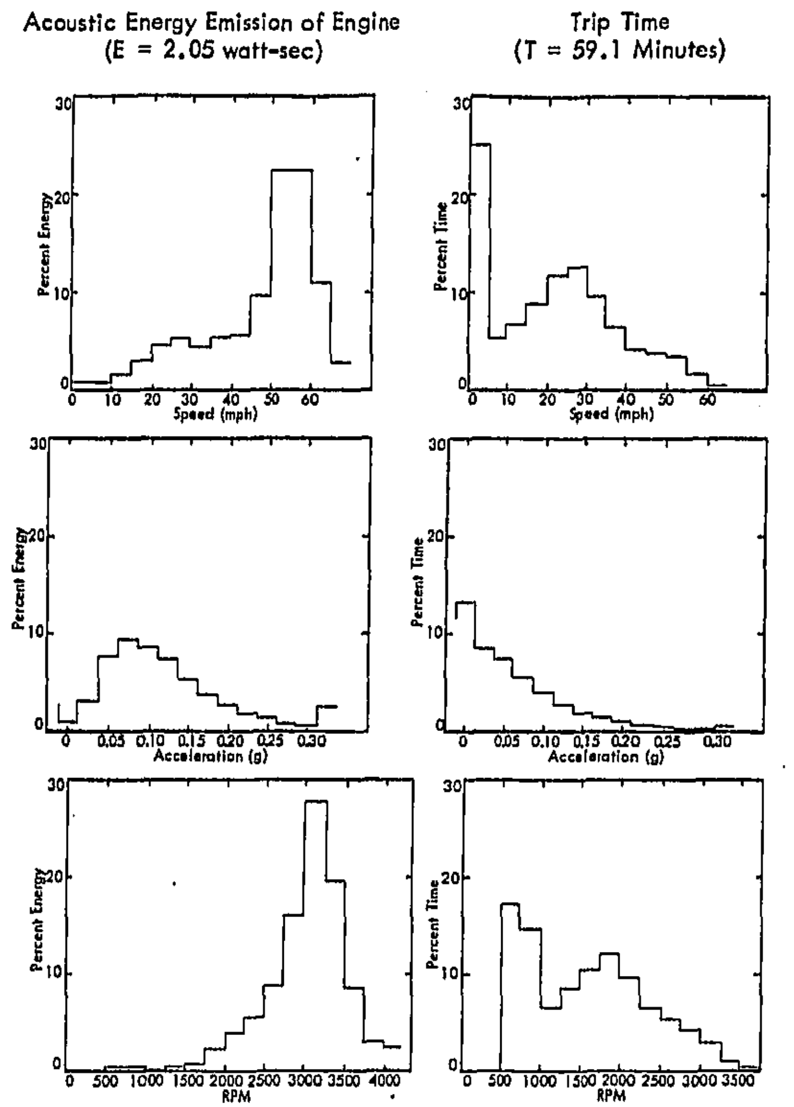

Figure 4.2(c). Percentage of Acoustic Energy Emission and Percentage of Trip Time as Functions of Speed, Acceleration, and RPM For Vehicle 3 – Ford Pinto (L6, 3A).

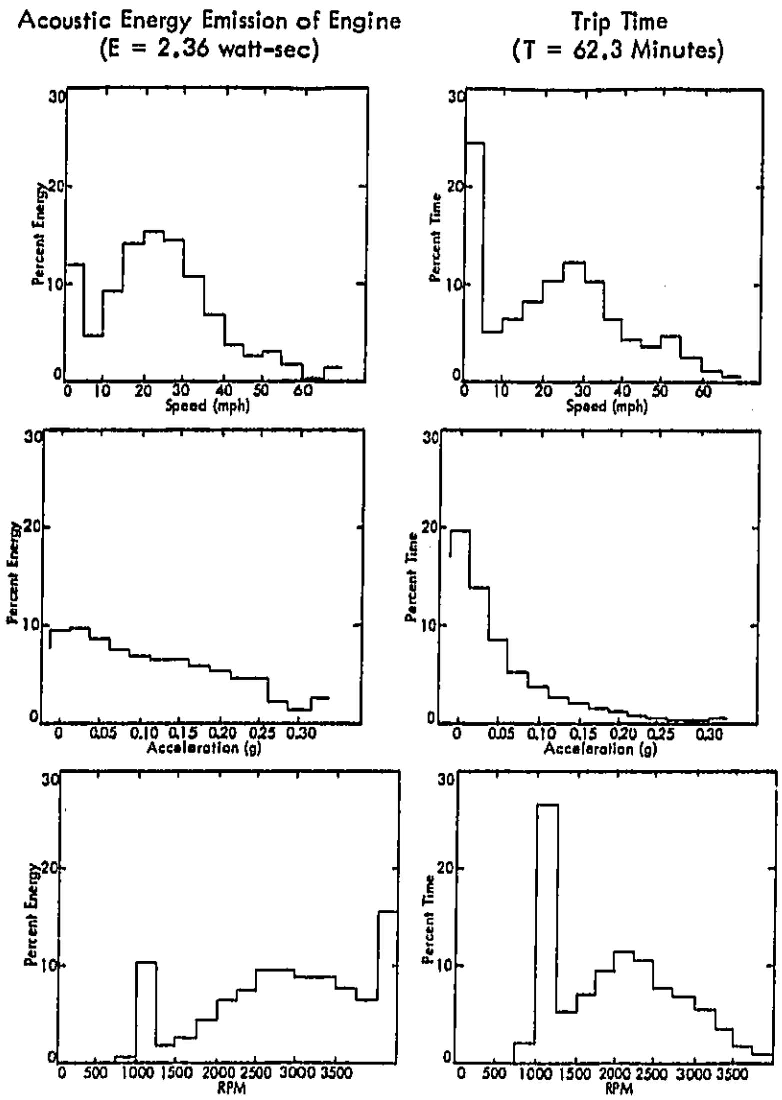

Figure 4.2(d). Percentage of Acoustic Energy Emission and Percentage of Trip Time as Functions of Speed, Acceleration, and RPM For Vehicle 4 — VW Rabbit (L4, 4M).

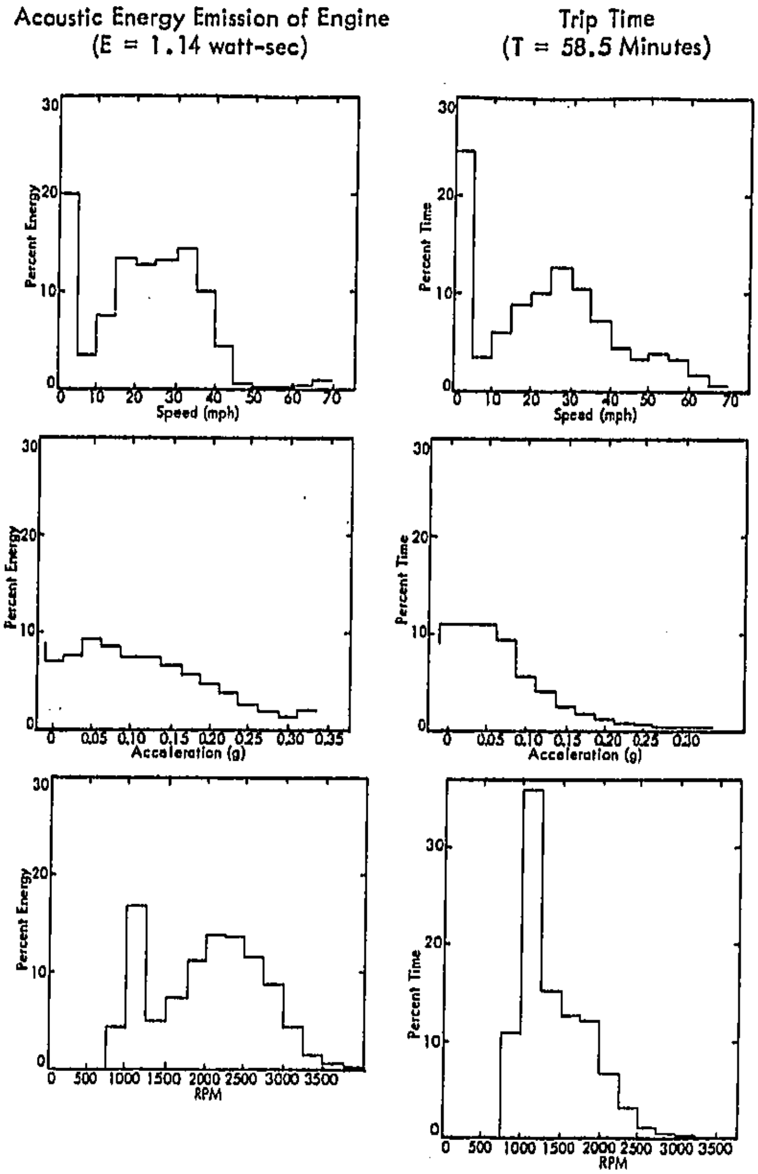

Figure 4.2(e). Percentage of Acoustic Energy Emission and Percentage of Trip Time as Functions of Speed, Acceleration, and RPM For Vehicle 5 – Ford Granada (L6, 4M).

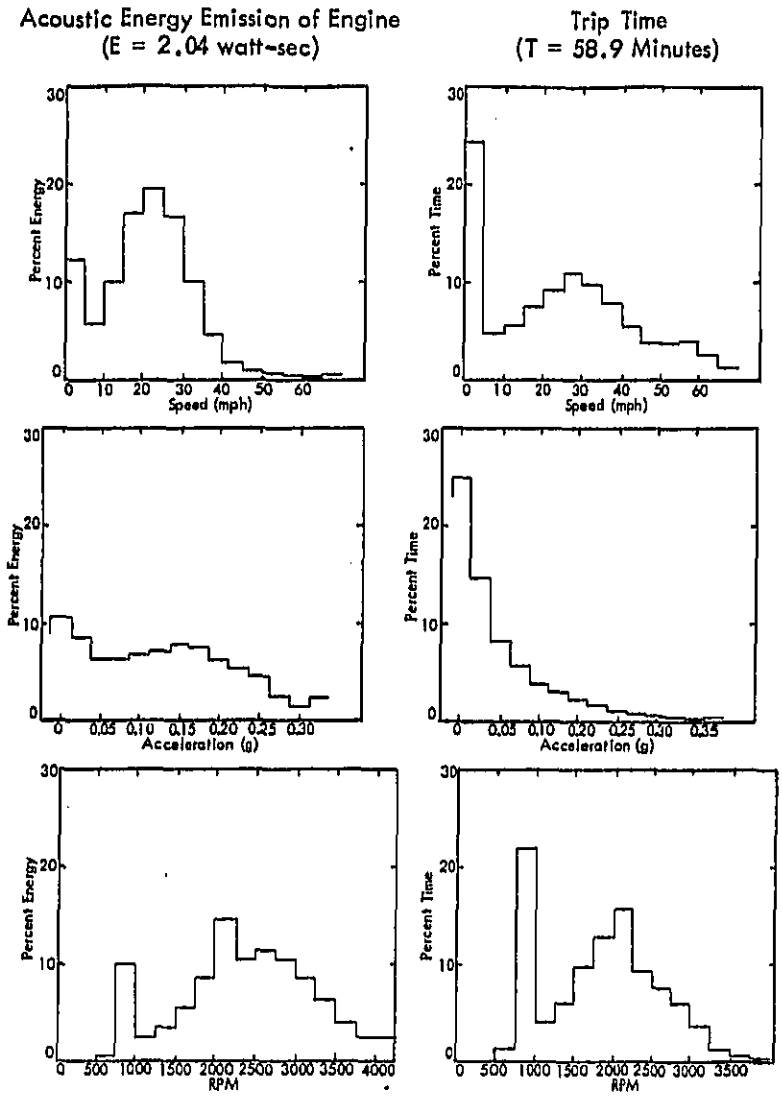

Figure 4.2(f). Percentage of Acoustic Energy Emission and Percentage of Trip Time as Functions of Speed, Acceleration, and RPM For Vehicle 6 – Datsun 280Z (L6, 4M).

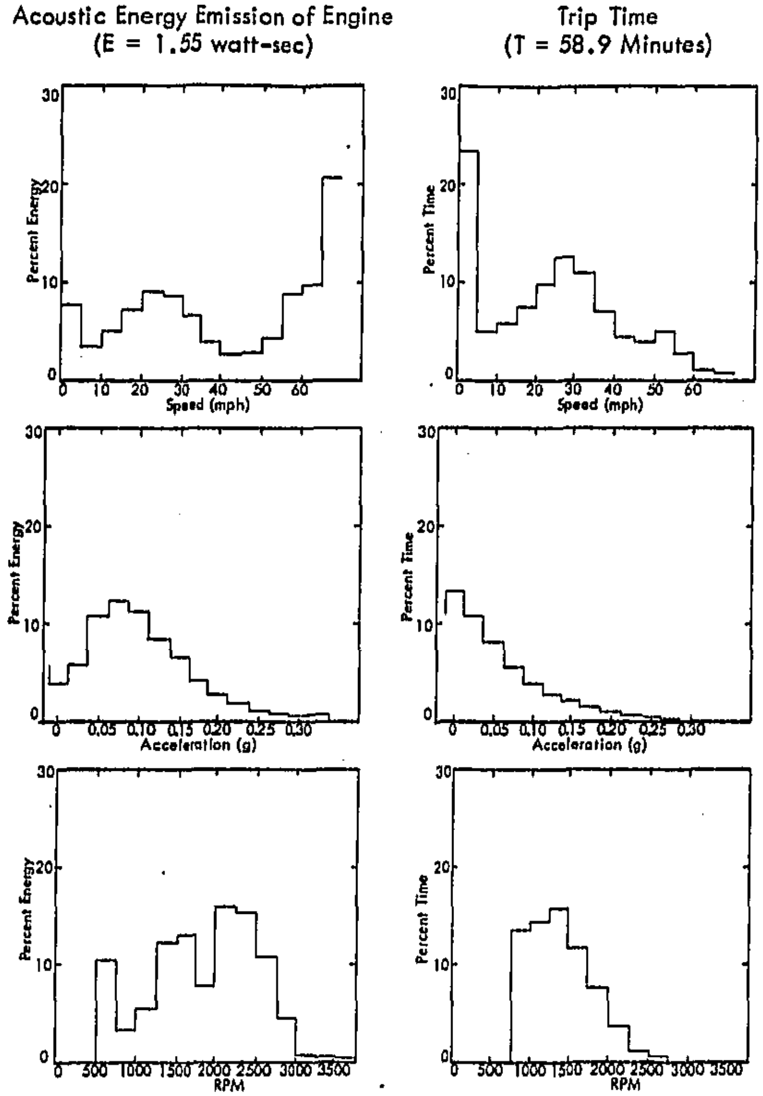

Figure 4.2(g). Percentage of Acoustic Energy Emission and Percentage of Trip Time as Functions of Speed, Acceleration, and RPM For Vehicle 7 – Dodge Monaco (V8, 3A).

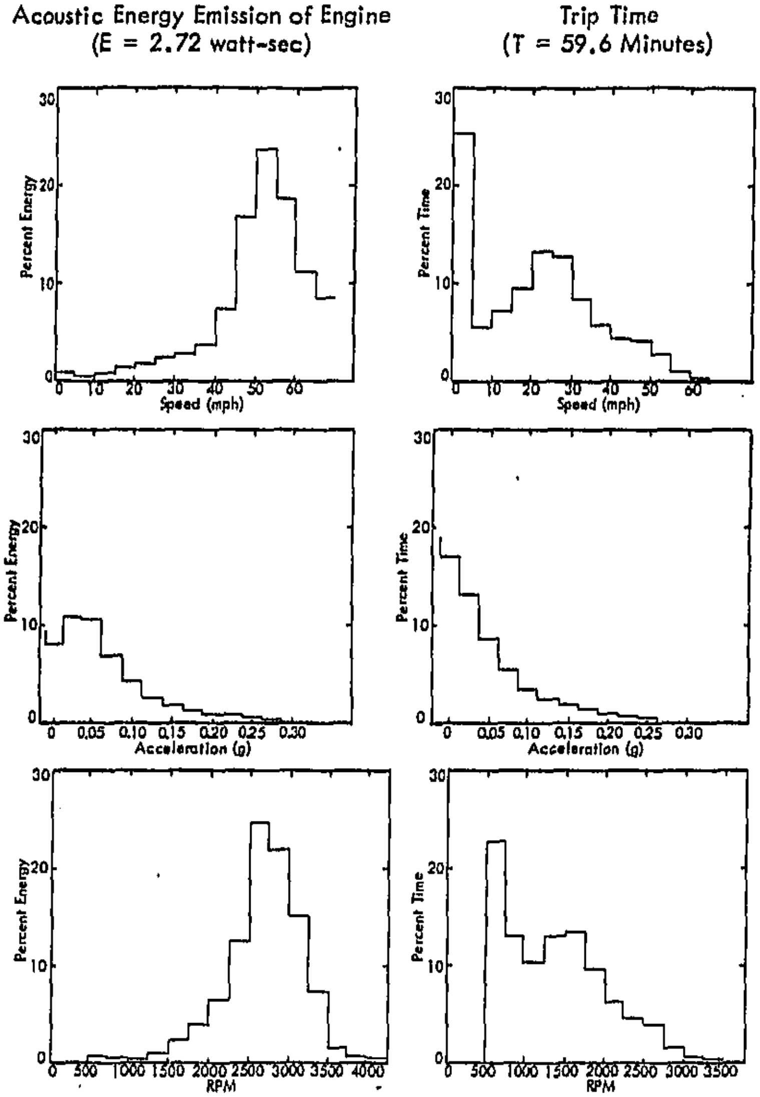

Figure 4.2(h). Percentage of Acoustic Energy Emission and Percentage of Trip Time as Functions of Speed, Acceleration, and RPM For Vehicle 8 – Oldsmobile Cutlass (V8, 3A).

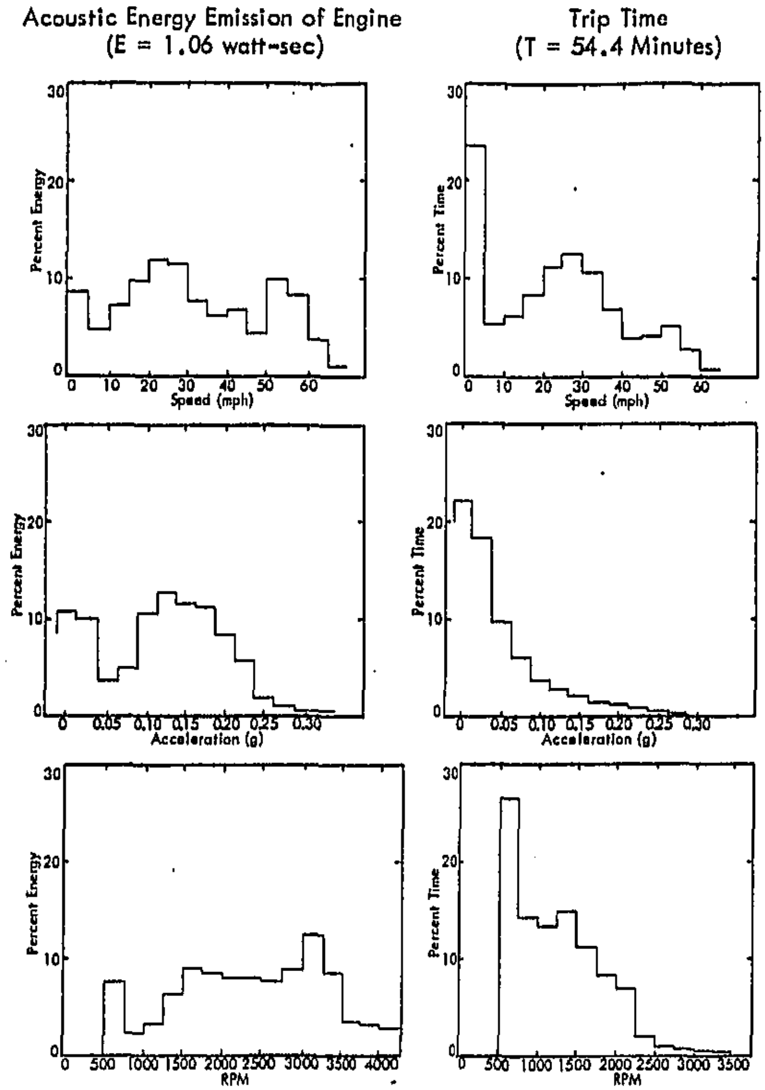

Figure 4.2(i). Percentage of Acoustic Energy Emission and Percentage of Trip Time as Functions of Speed, Acceleration, and RPM For Vehicle 9 — Buick Skylark (V6, 3A).

5.0 DEVELOPMENT OF A NOISE MEASUREMENT METHODOLOGY

5.1 Introduction

A suitable noise measurement methodology for light vehicles must include test conditions which are representative of the vehicle operating modes responsible for the majority of the noise emission into the community. Clearly, it is not necessary to include all operating modes, since most modes contribute little energy to the total noise emission. Only those modes that contribute significantly need be represented in the test conditions, and the fewer these are, the more practical will be the test procedure.

This section presents the rationale for selecting the operating modes that contribute most to noise emission and for defining the test conditions that are representative of these modes. The results of this analysis provide three candidate measurement methodologies — two bi-modal tests and a tri-model test. The advantages and disadvantages of each candidate test methodology are discussed.

5.2 Identification of Primary Noise Emission Operating Modes

As discussed above, one of the requirements for an acoustic measurement methodology is to test at operating conditions that correspond to maximum acoustic energy emission from the components of the vehicle which are of interest — in this case, the engine, driveline, and exhaust. In this section, the acoustic emission data base developed in Section 4 is analyzed to identify the regions of the joint speed-acceleration-RPM acoustic energy distribution which correspond to significant energy emission.

To accomplish this, Figures 4.1(a) - (i) and Figures 4.2(a) - (i) were compared so that prominent features in each distribution which are common to all vehicles could be identified. One such feature, which can easily be seen in Figures 4.2, is the existence of three broad peaks in the speed distribution for each vehicle. The speed ranges corresponding to each of these peaks are the same for all vehicles:

Low Speed Peak: 0 - 10 mph.
Intermediate Speed Peak: 10 - 45 mph.
High Speed Peak: >45 mph.

The existence of these speed regions can also be seen in Figures 4.1, although for several vehicles, the low speed peak does not appear because only bins corresponding to more than 1 percent of the acoustic energy emission have been drawn. Further examination of Figures 4.1 shows that, as would be expected, the low speed region corresponds to low engine RPM, the intermediate speed region corresponds to intermediate RPM, and the high speed region corresponds to high RPM. In addition, the intermediate speed region corresponds to higher vehicle accelerations than do the low and high speed regions.

Examination of the acceleration distributions in Figure 4.2 shows no distinct common structure that would allow deceleration, cruise, and acceleration ranges to be easily defined. The definition of such regions in acceleration space seems appropriate since the noise generating mechanisms occurring when a vehicle accelerates are somewhat different than those that occur when it is cruising or decelerating.

One could consider the cruise condition to imply exactly zero acceleration, in which case, given the bin widths used in this analysis, cruise would correspond to the acceleration bin extending from -0.0125g to +0.0125g. In reality, however, a vehicle is rarely driven at exactly zero acceleration; small accelerations and decelerations occur during the driving condition that is normally referred to as cruise.

In order to define a range of accelerations which can be considered to characterize the cruise condition, the percentages of time and of engine acoustic energy emission that would correspond to various cruise acceleration ranges were calculated from the temporal and acoustic energy distributions in Sections 3 and 4. These percentages were then averaged over the nine vehicles. The resulting average values are shown in Figures 5.1(a) and 5.1(b), the error bars indicating plus or minus one standard deviation.

There is no discontinuity in either of these figures that obviously distinguishes a range of accelerations appropriate to cruise mode from a range of accelerations appropriate to non-cruise modes However, certain ranges of acceleration can reasonably be excluded as candidates for the definition of cruise mode. The ±0.0125g acceleration range, which occurs 19 percent of the time and corresponds to 15 percent of the acoustic energy emission during the trip, does not occur sufficiently often to be representative of a cruise mode. Similarly, acceleration ranges broader than ±0.0625g, which occur for more than 75 percent of the time and correspond to more than 80 percent of the acoustic

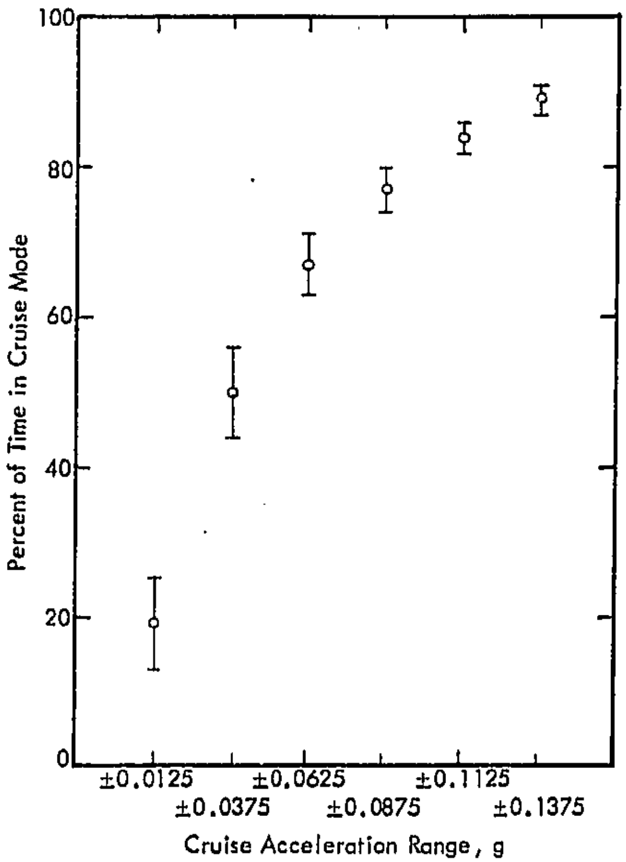

Figure 5.1(a). Percent of Time in Cruise Mode As a Function of Cruise Acceleration Range.

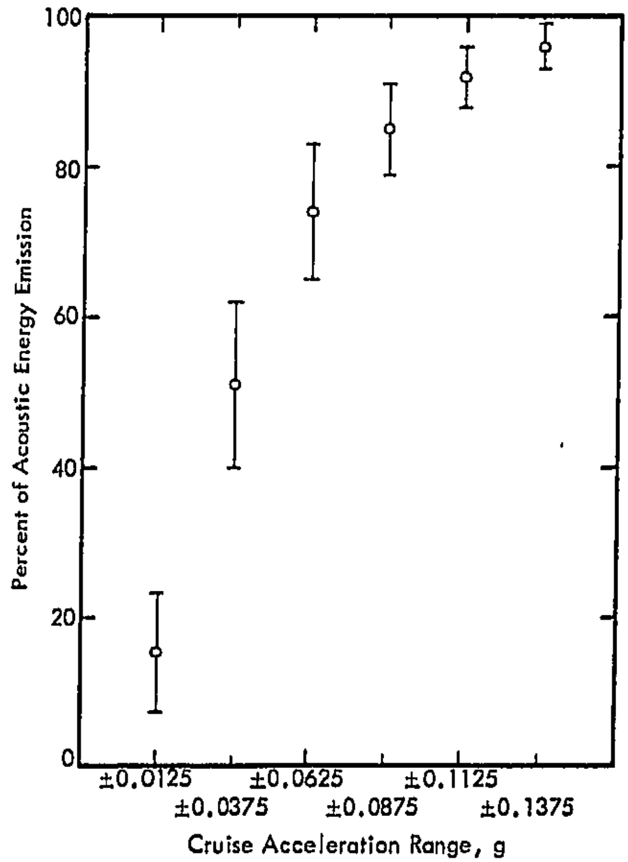

Figure 5.1(b). Percent of Acoustic Energy Emission From Non-Tire Sources in Cruise Mode as a Function of Cruise Acceleration Range.

Table 5.1

Average Percentage of Total Acoustic Energy Emission
For Each Speed-Acceleration Region

(a) ±0.0375g Cruise Acceleration Range

Acceleration Range	Speed Range			
	Low (0 mph ≤ V < 10 mph)	Intermediate (10 mph ≤ V < 45 mph)	High (V ≥ 45 mph)	ALL
Deceleration (A < -0.0375g)	0.9	5.3	6.3	12.5
Cruise (-0.0375g ≤ A < 0.0375g)	4.0	20.8	26.5	51.3
Acceleration (A ≥ 0.0375g)	1.2	29.1	5.9	36.2
ALL	6.1	55.2	38.7	100.0

(b) ±0.0625g Cruise Acceleration Range

Acceleration Range	Speed Range			
	Low (0 mph ≤ V < 10 mph)	Intermediate (10 mph ≤ V < 45 mph)	High (V ≥ 45 mph)	ALL
Deceleration (A < -0.0625g)	0.5	2.2	1.3	4.0
Cruise (-0.0625g ≤ A < 0.0625g)	4.9	32.8	35.8	73.5
Acceleration (A ≥ 0.0625g)	0.9	20.0	1.6	22.5
ALL	6.3	55.0	38.7	100.0

Table 5.2

Centroids of Each Speed-Acceleration Region
($\overline{V}$ in mph, $\overline{A}$ in g)

(a) ±0.0375g Cruise Range

Acceleration Range	Speed Range											
	Low			Intermediate			High			All		
	$\overline{V}$	$\overline{A}$	$\overline{R/R_{max}}$	$\overline{V}$	$\overline{A}$	$\overline{R/R_{max}}$	$\overline{V}$	$\overline{A}$	$\overline{R/R_{max}}$	$\overline{V}$	$\overline{A}$	$\overline{R/R_{max}}$
Deceleration	4.0	-0.087	0.201	29.4	-0.071	0.372	53.4	-0.053	0.588	37.4	-0.065	0.459
Cruise	2.7	-0.002	0.201	32.8	0.001	0.432	53.6	-0.006	0.608	40.7	-0.002	0.508
Acceleration	4.5	0.105	0.272	28.2	0.087	0.460	51.8	0.055	0.595	31.4	0.082	0.478
ALL	3.4	0.012	0.219	30.0	0.039	0.444	53.4	-0.002	0.604			

(b) ±0.0625g Cruise Range

Acceleration Range	Speed Range											
	Low			Intermediate			High			All		
	$\overline{V}$	$\overline{A}$	$\overline{R/R_{max}}$	$\overline{V}$	$\overline{A}$	$\overline{R/R_{max}}$	$\overline{V}$	$\overline{A}$	$\overline{R/R_{max}}$	$\overline{V}$	$\overline{A}$	$\overline{R/R_{max}}$
Deceleration	4.5	-0.112	0.204	25.3	-0.100	0.329	53.8	-0.076	0.616	25.4	-0.099	0.353
Cruise	2.8	0.000	0.200	32.4	0.010	0.437	53.5	-0.004	0.606	40.4	0.002	0.507
Acceleration	5.0	0.127	0.291	26.5	0.103	0.462	52.4	0.076	0.572	27.2	0.103	0.463
ALL	3.4	0.012	0.219	30.0	0.039	0.444	53.4	-0.002	0.604			

Considering only cruise and acceleration regions, the candidate test conditions are:

- Cruise: 41 mph, 0.00g, 51 percent rated RPM
- Acceleration: 29 mph, 0.09g, 47 percent rated RPM.

The advantage of this test methodology is that it consists of only two modes and thus is relatively simple. The disadvantage is that the speed of the cruise mode corresponds to a region of the speed distribution for each vehicle in which little energy is emitted (see Figure 4.2). This is due, to the fact that there are two major peaks in each speed distribution and thus an average over all speeds results in a point near the minimum midway between the major peaks.

Considering only intermediate and high speed regions, the candidate test conditions are:

- Intermediate Speed: 30 mph, 0.04g, and 44 percent rated RPM
- High Speed: 53 mph, 0.00g, and 60 percent rated RPM.

This test methodology also has the advantage of simplicity since it is bi-modal. However, it has the disadvantage that both modes correspond to rather low accelerations. Thus, the noise generating mechanisms present during higher accelerations may not be controlled by these test conditions.

Considering both speed and acceleration regions, the candidate test conditions are:

- Intermediate Speed Cruise: 33 mph, 0.00g, 43 percent rated RPM
- Intermediate Speed Acceleration: 27 mph, 0.10g, 46 percent rated RPM
- High Speed Cruise: 54 mph, 0.00g, 61 percent rated RPM.

This test methodology is more complex than those above, since it consists of three modes. However, it has the advantages that each test condition corresponds to regions of high acoustic energy emission and a relatively high acceleration is included.

It should also be noted that, for automatic transmission vehicles, the intermediate speed acceleration test condition is essentially the same as Test Condition 2 in the EPA Urban Acceleration Noise Test Procedure for light vehicles,[4] which specifies an acceleration of 0.12g at 25 mph, corresponding in practice to 0.12g at 47 percent of maximum rated engine speed.

5.4 Recommendations

The result of the current program has been to identify three candidate test methodologies — two consisting of bi-modal test conditions, the third consisting of tri-modal test conditions. Each of the proposed methodologies has advantages and disadvantages, thus a policy decision must be made as to which test procedure is most appropriate.

In order to assist in the decision making process, it is necessary to validate each set of test conditions on a larger number of light vehicles to ascertain if, indeed, they can be attained for all such vehicles. Such has been shown to be the case for the intermediate speed acceleration test conditions.

In addition, concurrent tests should be performed to determine how tire noise can be minimized for each of the proposed operating conditions. One possibility may be to perform the high-speed cruise tests at the engine speed indicated, but in a gear that produces a lower speed. Assuming that transmission noise is not a major factor, this procedure should produce the same noise levels as the given test conditions. Consideration must also be given to performing such a modified low speed "cruise" test at a slight acceleration in order to simulate the load on the engine due to drag at the higher speed. Finally, additional experiments should be conducted to investigate the feasibility of replacing some of these moving tests with stationary test procedures and the feasibility of locating the measuring microphone at distances other than 50 feet from the vehicle.

Once such information is in hand, informed decisions can be made as to the selection of a specific test methodology. Then detailed test conditions, instrument specifications, and field site requirements can be developed for the selected test methodology.

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INTRODUCTION TO APPENDICES

In order to maintain compatibility with previous studies of vehicle operating parameters a mixed system of English units has been used for vehicle speed and acceleration in the tables that follow. The conversion factors relating the units used in these tables and standard metric units are:

1 mph = 1.609 km/hr
1 g = 35.32 km/hr/sec

In addition, the conversion from acceleration in g's to acceleration in mph/sec is:

1 g = 21.94 mph/sec

The lower limit, center, and upper limit of each speed, acceleration, and RPM bin used in these tables is shown in English and metric units in Tables I, II, and III.

Finally, the symbols "LE" and "GE", which are used in the tables in Appendices D-M, have the following meanings:

LE: less than or equal to
GE: greater than or equal to

Table 1. Vehicle Speed Bins

	Speed (mph)			Speed (km/hr)		
Bin	Lower Limit	Center	Upper Limit	Lower Limit	Center	Upper Limit
1	0.0	2.5	5.0	0.0	4.0	8.0
2	5.0	7.5	10.0	8.0	12.1	16.1
3	10.0	12.5	15.0	16.1	20.1	24.1
4	15.0	17.5	20.0	24.1	28.2	32.2
5	20.0	22.5	25.0	32.2	36.2	40.2
6	25.0	27.5	30.0	40.2	44.2	48.3
7	30.0	32.5	35.0	48.3	52.3	56.3
8	35.0	37.5	40.0	56.3	60.3	64.4
9	40.0	42.5	45.0	64.4	68.4	72.4
10	45.0	47.5	50.0	72.4	76.4	80.5
11	50.0	52.5	65.0	80.5	84.5	88.5
12	55.0	57.0	60.0	88.5	92.5	96.5
13	60.0	62.5	65.0	96.5	100.6	104.6
14	65.0	-	-	104.6	-	-

Table II. Vehicle Acceleration Bins

	a(g)			a(mph/sec)			a(km/hr/sec)		
Bin	Lower Limit	Center	Upper Limit	Lower Limit	Center	Upper Limit	Lower Limit	Center	Upper Limit
1	-	-	-0.3125	-	-	-6.9	-	-	-11.0
2	-0.3125	-0.3000	-0.2875	-6.9	-6.6	-6.3	-11.0	-10.6	-10.2
3	-0.2875	-0.2750	-0.2625	-6.3	-6.0	-5.8	-10.2	-9.7	-9.3
4	-0.2625	-0.2500	-0.2375	-5.8	-5.5	-5.2	-9.3	-8.8	-8.4
5	-0.2375	-0.2250	-0.2125	-5.2	-4.9	-4.7	-8.4	-7.9	-7.5
6	-0.2125	-0.2000	-0.1875	-4.7	-4.4	-4.1	-7.5	-7.1	-6.6
7	-0.1875	-0.1750	-0.1625	-4.1	-3.8	-3.6	-6.6	-6.2	-5.7
8	-0.1625	-0.1500	-0.1375	-3.6	-3.3	-3.0	-5.7	-5.3	-4.9
9	-0.1375	-0.1250	-0.1125	-3.0	-2.7	-2.5	-4.9	-4.4	-4.0
10	-0.1125	-0.1000	-0.0875	-2.5	-2.2	-1.9	-4.0	-3.5	-3.1
11	-0.0875	-0.0750	-0.0625	-1.9	-1.6	-1.4	-3.1	-2.6	-2.2
12	-0.0625	-0.0500	-0.0375	-1.4	-1.1	-0.8	-2.2	-1.8	-1.3
13	-0.0375	-0.0250	-0.0125	-0.8	-0.5	-0.3	-1.3	-0.9	-0.4
14	-0.0125	0.0000	0.0125	-0.3	0.0	0.3	-0.4	0.0	0.4
15	0.0125	0.0250	0.0375	0.3	0.5	0.8	0.4	0.9	1.3
16	0.0375	0.0500	0.0625	0.8	1.1	1.4	1.3	1.8	2.2
17	0.0625	0.0750	0.0875	1.4	1.6	1.9	2.2	2.6	3.1
18	0.0875	0.1000	0.1125	1.9	2.2	2.5	3.1	3.5	4.0
19	0.1125	0.1250	0.1375	2.5	2.7	3.0	4.0	4.4	4.9
20	0.1375	0.1500	0.1625	3.0	3.3	3.6	4.9	5.3	5.7
21	0.1625	0.1750	0.1875	3.6	3.8	4.1	5.7	6.2	6.6
22	0.1875	0.2000	0.2125	4.1	4.4	4.7	6.6	7.1	7.5
23	0.2125	0.2250	0.2375	4.7	4.9	5.2	7.5	7.9	8.4
24	0.2375	0.2500	0.2625	5.2	5.5	5.8	8.4	8.8	9.3
25	0.2675	0.2750	0.2875	5.8	6.0	6.3	9.3	9.7	10.2
26	0.2875	0.3000	0.3125	6.3	6.6	6.9	10.2	10.6	11.0
27	0.3125	-	-	6.9	-	-	11.0	-	-

Table III. Engine RPM Bins

Bin	RPM Lower Limit	RPM Center	RPM Upper Limit
1	0	125	250
2	250	375	500
3	500	625	750
4	750	875	1000
5	1000	1125	1250
6	1250	1375	1500
7	1500	1625	1750
8	1750	1875	2000
9	2000	2125	2250
10	2250	2375	2500
11	2500	2625	2750
12	2750	2875	3000
13	3000	3125	3250
14	3250	3375	3500
15	3500	3625	3750
16	3750	3875	4000
17	4000	-	-