Federal Test Procedure Review Project:

Preliminary Technical Report

May 1993

EPA 420-R-93-007
Certification Division
Office of Mobile Sources
Office of Air & Radiation
U.S. Environmental Protection Agency

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Executive Summary

Pursuant to Section 206(h) of the Clean Air Act, as amended in 1990 (Act, or CAA), EPA has undertaken a review of the Federal Test Procedure (FTP) used to test light duty vehicle and light duty truck emissions to determine whether it adequately represents actual current driving conditions. The driving cycle used for the FTP was adopted over twenty years ago and accumulated research suggests that it may no longer adequately represent overall vehicle emission control performance under current driving conditions.

Project Overview

The principal subject of this report is driving behavior, including acceleration and trip start patterns. After reviewing existing research on driving behavior, the Agency determined that new surveys were needed to assess current driving in U.S. urban nonattainment regions. A parallel study of current technology vehicle emissions under the full range of driving conditions is also in progress. Results from these efforts will be combined in determining the need for test procedure revisions.

This preliminary technical report discusses how the driving surveys were conducted, presents analyses of the results, and compares the data to the existing FTP. Quantitative assessments of the emission impacts are still in progress and are not discussed in this report.

With support from the American Automobile Manufacturers Association (AAMA) and the Association of International Automobile Manufacturers (AIAM), EPA conducted surveys of driving behavior in Baltimore, MD, and Spokane, WA. Two methods of data collection were employed. In an instrumented vehicle study, 113 Baltimore and 102 Spokane vehicles were equipped with "3-parameter" datalogger packages that recorded second-by-second speed and two other variables during periods of operation. As part of the same surveys, the manufacturers recruited 79 vehicles for study using "6-parameter" instruments designed to measure additional variables.

The instrumented vehicles were observed for seven to ten day periods. A separate chase car study collected similar speed data in the two cities using a laser device mounted on a patrol car that tracked in-use target vehicles. This produced relatively short sequences of data on a much larger sample of vehicles.

The Baltimore and Spokane surveys are supplemented by data collected in two other cities. EPA's Office of Research and Development sponsored an instrumented vehicle study in Atlanta, GA. Finally, the California Air Resources Board (CARB) sponsored a chase car study in Los Angeles similar to the chase car studies in Spokane and Baltimore.

For reasons relating to representativeness, availability, and precision of the survey data, most of the discussion in this report is confined to driving observed in the Baltimore 3-parameter instrumented vehicle study. Participants in the instrumented vehicle study in Baltimore were recruited from two different centralized Inspection/Maintenance stations, one in central Baltimore and one in a suburb just outside Baltimore. The urban site yielded driving characteristics similar to those in Spokane and the suburban site was similar to Atlanta and Los Angeles. As it was not possible to obtain detailed analyses of the Atlanta and Los Angeles data in time for this report, EPA decided to use just the Baltimore data for purposes of this report. This should yield a more representative picture than also including the Spokane data. Future research will include further analyses of data obtained from the other sources.

EPA also entered into a cooperative agreement with the New York State Bureau of Air Research to obtain test data and analyses of the engine and catalyst cooldown processes and factors affecting the cooldown rates. These data are used to assess the condition of the engine and catalyst during engine start-up.

Preliminary Indications of Actual Driving Behavior

Speed and Acceleration

Speeds were much higher in Baltimore than are represented on the FTP. The average speed in Baltimore was 24.5 mph (median speed was 23.7). The speeds observed ranged to almost 95 mph; 6.4% were above 60 mph and 2.6% above 65 mph. By comparison, the FTP has an average speed of 19.6 mph with a maximum of 56.7 mph. About 8.5% of all speeds in Baltimore exceeded the FTP maximum.

Acceleration rates in Baltimore were also significantly higher than those on the FTP. The acceleration rates observed ranged up to 15 mph/sec, with a standard deviation of 1.5.[1] The FTP has a maximum acceleration rate of 3.3 mph/sec and a standard deviation of 1.4. About 2.5% of all driving in Baltimore exceeded 3.3 mph/sec.

Power-related measures also indicate that the observed driving behavior was more aggressive than the FTP. Specific power[2] for the Baltimore sample ranged up to 558 mph^2/sec and averaged 46.0, with a median of 34.7. The FTP has a maximum power of 192, average of 38.6, and median of 21.6. An analysis was also done of the scatter of speed-acceleration points occurring in the Baltimore sample outside the FTP envelope of speed and accelerations. These points represent about 18% of total Baltimore driving time.

Driving Behavior Determinants

Vehicle Type - Speed distributions were fairly similar for each of the three categories analyzed; trucks, sedans, and high

[1] Mean acceleration rates generally average to zero and are not a useful measure of comparison.

[2] The power needed from an engine to accelerate a vehicle is proportional to both the vehicle speed and the acceleration rate. Thus, neither variable, by itself, is a good measure of the load placed on the engine during acceleration. The joint distribution of speed and acceleration is the best measure, but it must be examined in three dimensions, which is difficult to visualize and comprehend. While not as good as the joint distribution of speed and acceleration, the best two-dimensional measure is "specific power," which is roughly equivalent to (2 * speed * acceleration). This measure is used extensively in this report and has the units mph^2/sec.

performance vehicles. However, high performance vehicles demonstrated more aggressive driving behavior than the other classes, with over twice as much operation at power levels above 200 mph^2/sec.

Vehicle Age - Newer vehicles (1983 and later) had higher average speeds than older vehicles (25.1 mph v. 21.2 mph), were driven somewhat longer and farther per day, and averaged fewer trips and slightly fewer stops per mile. The data indicate that newer vehicles spend more time at high speeds and are used for longer trips than older vehicles. However, analyses of the aggressiveness of the driving behavior, as measured by acceleration and power distributions, indicate very little difference between older and newer vehicles.

Time of Day - Average speeds were lowest during the evening rush period of 4-7 pm (23.0 mph) and highest during the morning rush period of 6-9 am and night driving period of 9 pm to 1 am (25.4 mph). Extremes of acceleration and specific power were not highly associated with time of day. About twice as many trips began during the evening rush period as during the morning rush period. The morning peak period had the longest average trip lengths (6.8 miles), while mid-day trips averaged only 4.4 miles.

Time of Week - Average weekend speeds were substantially higher than on weekdays; 26.3 mph and 23.9 mph, respectively. This is due, in part, to increased high speed driving; 13.6% of all driving during the weekend exceeded 55 mph, compared to 9.8%

during weekdays. Weekend driving also produced substantially higher average time, distance, and number of trips than weekdays. However, acceleration and specific power measures do not indicate that weekend driving is more aggressive than on weekdays.

Trip Patterns

Average in-use trip lengths are much shorter than the FTP, which represents a 7.5 mile trip. The average observed trip[3] covered 4.9 miles. The median value of trip distance indicates that "typical" trips are even shorter, only 2.5 miles. One of the in-use impacts of shorter trips is that a much higher proportion of overall driving is done within 0.67 mile of vehicle starts (12.0% v. 8.9% on the FTP), prior to engines and catalysts reaching normal operating temperatures. The frequency of stops on the FTP is also uncharacteristic of in-use trips; the average distance between stops on the FTP is only 0.41 miles compared to 0.87 in Baltimore. Despite these differences, the FTP and Baltimore trips disagree only slightly in the proportion of time spent in the four operating modes: idle, cruise, acceleration, and deceleration.

Vehicle Soaks

The in-use data contains a large proportion of intermediate soak periods (that is, the time between the end of a previous

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[3] For the purposes of this report, a trip has been defined as beginning when the engine is turned on and ending when the engine is shut off (although engine off times of less than 18 seconds are ignored).

trip and the beginning of the next one) that are not reflected on the FTP. The FTP contains soak periods of 10 minutes and 12-36 hours; almost 40% of all soak periods in Baltimore were between 10 minutes and 2 hours. As catalysts cool off much faster than engines and most are almost completely cold in about 45-60 minutes, this is a potential emission concern. Analyses indicate that only about 30% of all in-use starts occur with catalysts hot enough to be immediately effective; the FTP implicitly assumes that 57% of all starts occur with hot catalysts. On the other hand, the FTP implicitly assumes that 43% of all starts occur with cold engines, while less than 25% of in-use starts occur with cold engines.

Trip Start Driving Activity

While the FTP has lower speeds and is less aggressive than in-use driving behavior, overall, the reverse occurs for the first few minutes after a vehicle start. The average observed speed during the first 80 seconds of all trips (the initial idle period was not included in this period) was only 14.4 mph, compared to 23.1 mph for the first micro-trip on the FTP. The average in-use speed 81-240 seconds into the trip was 22.8 mph, compared to 29.8 for a comparable period on the FTP. The aggressiveness of the FTP was also off substantially, with the first micro-trip on the FTP substantially less aggressive than in-use driving and the second micro-trip greatly overaggressive.

Under similar ambient air temperature conditions, the initial idle time on the FTP after a cold start is similar to observed data. However, after a hot start the initial idle time on the FTP is much longer than observed data. The FTP uses an initial idle time of 20 seconds after both cold and hot starts; observed initial idle times after cold starts averaged 28 seconds with a median of 9 seconds, while initial idle times after hot starts averaged only 12 seconds with a median of 5 seconds.

Emission Impact Assessment Plans

The analysis of data obtained from the driving surveys described here indicates significant differences exist between actual driving behavior and the FTP. The driving survey data will serve as the primary input into programs to assess the difference between emissions predicted by the FTP and emissions that occur in actual driving. This assessment requires the development of driving cycles that are more representative of the driving behavior information obtained from the surveys. EPA, in cooperation with the California Air Resources Board, has investigated cycle generation alternatives and developed improved methods. Cycles generated from the driving survey data using these methods will be used in test programs to quantify in-use emissions.

Chapter 1. Introduction

The cornerstone of the Clean Air Act is the effort to attain and maintain National Ambient Air Quality Standards (NAAQS). Regulation of emissions from on-highway, area, and stationary sources prior to enactment of the Clean Air Act Amendments (CAAA) of 1990 has resulted in significant emission reductions from these sources. However, many air quality regions have failed to attain the NAAQS, particularly for ozone and CO. This is due to many factors, including the number of vehicles on the road and a corresponding increase in the number of miles driven by the in-use fleet which, even though single vehicles have experienced significant emission reductions, has increased total emissions from the motor vehicle fleet.

The Clean Air Act, as amended (CAA, or Act), contains a large number of provisions to further improve ambient air quality. Section 206(h) of the Act requires that EPA review its regulations for the testing of motor vehicles and revise them if necessary to ensure that motor vehicles are tested under circumstances reflecting actual current driving conditions. This preliminary technical report discusses the driving behavior research conducted by the EPA in its review of the Federal Test Procedure (FTP) under Section 206(h) of the Act. The report discusses the need for the research, methods and approaches, and analyses of the driving behavior observed. Results from previous research are not included in this report; nor are quantitative assessments of the emissions impact of such driving behavior (although qualitative implications are discussed).

Chapter 2 discusses background information, including the history of the Federal Test Procedure and the Act's provisions for EPA review of the FTP. Chapter 3 provides an overview of the goals and general approach to the entire FTP project, including assessing the emissions impact of actual driving behavior and development of proposed rules. Chapter 4 describes the survey methods and programs used to determine actual driving behavior. Chapter 5 discusses the analytical methods used to evaluate the driving survey data. Chapter 6 presents the results of the Agency's analyzes of driving behavior and provides comparisons to the existing test procedures. Chapter 7 describes the methodologies developed to generate test cycles from the survey data.

Chapter 2. Background

2.1. The Air Quality Problem

Motor vehicles are a well known major source of volatile organic compounds (VOC) and oxides of nitrogen (NOx), both of which are precursors of ground level ozone, or smog. Motor vehicles are also a major source of carbon monoxide (CO) emissions. While significant progress has been made over the past two decades in controlling motor vehicle emissions, as of August 1990, 96 air quality control regions still failed to meet the national ambient air quality standard (NAAQS) for ozone, and forty-one regions failed to attain the NAAQS for CO.[4]

As an example of the impact of motor vehicles, estimates of ozone precursors can be used. Volatile organic compounds and NOx interact in sunlight to form ozone. Motor vehicles are estimated to contribute approximately 25% of VOC emissions nationally during the summer months.[5] Small "area sources" such as bakeries, dry cleaners, and consumer solvents contribute 45% and large point sources such as petroleum refineries contribute 10% of VOC emissions.[6] Additionally, motor vehicles are estimated to contribute approximately 42% of nationwide CO emissions during

[4]EPA, Office of Public Affairs, Environmental News, August 16, 1990.

[5]Nonroad Engine and Vehicle Emission Study--Report, U.S. EPA, EPA-21A-2001, November 1991.

[6]Ibid.

the winter months.[7] Clearly, motor vehicles are a major source of ozone precursor and CO emissions in nonattainment areas.

2.2. History of the Federal Test Procedure

The FTP is the test procedure used to determine compliance of light-duty vehicles (LDV) and light-duty trucks (LDT) with federal emission standards.[8] As designed, the FTP was intended to represent typical driving patterns in primarily urban areas.

Preproduction vehicles are tested using the FTP as part of the motor vehicle certification process. The certification process is used to establish that each vehicle is designed to comply with emission standards for its full useful life. The FTP is also used to test production line and in-use vehicles for compliance with appropriate emission standards.

The FTP is more than just a driving cycle; it provides a way to consistently and repetitively measure concentrations of HC, Nox, CO, and carbon dioxide (CO2)emissions which occur when a vehicle is driven over a simulated urban driving trip.[9] The principal elements of the test are designed to test the

[7] Ibid.

[8] The regulations that encompass the many aspects of the FTP are generally contained in 40 CFR Part 86, Subparts A and B.

[9] For further discussion on the development of this cycle, see: Kruse, Ronald E., and Thomas A. Huls, SAE Paper #730553 "Development of the Federal Urban Driving Schedule," 1973. A speed-time trace of this cycle is contained in 40 CFR Part 86, Appendix I.

evaporative and exhaust emissions under several simulated situations. Evaporative emissions are tested after heating the fuel tank to simulate heating by the sun (the diurnal test) and again after the car has been driven and parked with a hot engine (the hot soak test). Exhaust emissions are measured by driving the vehicle (placed on a dynamometer) on a simulated urban driving trip under two conditions: with a cold start designed to represent a morning start-up after a long soak (a period of non-use) and with a hot start that takes place while the engine is still hot. The FTP also encompasses all factors relevant to vehicle testing, such as fuel, vehicle preconditioning, ambient temperature and humidity, aerodynamic loss, and vehicle inertia simulations. In addition to evaporative and exhaust emissions, the FTP is also used in evaluating fuel economy.

The driving cycle used for the FTP was derived to simulate a vehicle operating over a road route in Los Angeles believed to be representative of typical home to work commuting. The original road route was selected in the mid-1960s[10] by trial-and-error to match the engine operating mode distribution (based on manifold vacuum and rpm ranges) obtained in central Los Angeles using a variety of drivers and routes with the same test vehicle.

Using an instrumented 1964 Chevrolet, recordings were made of actual home-to-work commute trips by employees of the state of California's Vehicle Pollution Laboratory. By trial and error, a specific street route in the vicinity of the Lab was found that

[10]G.C. Hass, et. al., "Laboratory Simulation of Driving Conditions in the Los Angeles Area," SAE Paper No. 660546, August, 1966.

matched the average speed/load distribution on the commute trips. That 12 mile route was called the "LA4."

In an effort to develop an improved Federal Test Procedure (based on speed-time distributions rather than manifold vacuum and rpm ranges), six different drivers from EPA's West Coast Laboratory drove a 1969 Chevrolet over the LA4 route. The six traces were analyzed for idle time, average speed, maximum speed, and number of stops per trip. The total time required for the six trips ranged from 35 to 40 minutes, with an average of 37.6 minutes. One of the six traces demonstrated much harder acceleration rates than the other five and was discarded. The other five traces were surprisingly similar. Of those five, the trace with the actual time closest to the average was selected as the most representative speed-time trace. That trace contained 28 "hills" of non-zero speed activity separated by idle periods and had an average speed of 19.2 miles per hour.

Based on a 1969 report on driving patterns in Los Angeles,[11] the average trip length was estimated to be 7.5 miles. Several of the hills and portions of others were eliminated in order to shorten the cycle to 7.5 miles while maintaining the same average speed. The shortened route, designated the LA4-S3, was 7.486 miles in length with an average speed of 19.8 mph. Slight modifications to some of the speed-time profiles were also made in cases where the acceleration or deceleration rate exceeded the 3.3 mph/s limit of the belt-driven chassis dynamometers in use at

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[11] D.H. Dearm and R.L. Lamoureux, "Survey of Average Driving Patterns in the Los Angeles Urban Area," TM-(L)-4119/000/01, February 28, 1969.

the time. Mass emission tests comparing the shortened cycle to the full cycle showed very high correlation. The final version of the cycle was designated the LA4-S4 cycle and is 7.46 miles in length with an average speed of 19.6 mph.

This cycle is now commonly referred to as the "LA4" or the Urban Dynamometer Driving Schedule (UDDS). It has been the standard driving cycle for the certification of LDVs and LDTs since the 1972 model year. Beginning with the 1975 model year, the cycle was modified to repeat the initial 505 seconds of the cycle following a 10 minute soak at the end of the cycle. This allows emissions to be collected on a "hot" start (the engine is still warm) as well as after a cold start and during operation. The test then provides a more accurate reflection of typical customer service than running just one 7.46 mile cycle from a cold start.

2.3. Statutory Provision

Section 206(h) of the Act directs that EPA "review and revise as necessary" the regulations pertaining to the testing of motor vehicles to "insure that vehicles are tested under circumstances which reflect the actual current driving conditions under which motor vehicles are used, including conditions relating to fuel, temperature, acceleration, and altitude."

This preliminary technical report documents technical aspects of EPA's review process to date. This study does not attempt to determine or justify the need for revisions to the

FTP. Such a justification would be part of any regulatory decision making that EPA may conduct on FTP modifications.

2.4. Areas of Potential Concern

Section 206(h) of the Act specifically requires that EPA consider actual driving conditions under which motor vehicle are used, including conditions relating to these four areas: fuel, temperature, altitude, and acceleration. Following is a discussion of these conditions, plus a discussion of other driving conditions of potential concern when reviewing the adequacy of the FTP.

2.4.1. Fuel

Gasoline - The composition of the gasoline used for the FTP (commonly referred to as indolene) was established by regulation over 20 years ago.[12] While it was representative of in-use fuel at the time, commercial or in-use fuel properties have changed significantly since then, in some cases having a major impact on vehicle emissions, both tailpipe and evaporative.[13] Studies conducted during the 1980s indicated that vehicles tend to have higher emissions during operation on commercial gasoline than on indolene, particularly through evaporative losses.

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[12] 40 CFR §86.113-94.

[13] Evaporative emissions include diurnal, hot soak, refueling, and running losses.

To address this concern, EPA has established volatility limits for gasoline and alcohol blended fuels. These regulations capped the allowable Reid vapor pressure for commercial gasoline during the summer months. The second phase of these controls became effective in the summer of 1992.[14] As a result of these actions, the emissions of a vehicle fueled with indolene are more representative of the emissions from vehicles fueled with commercial gasoline.

Diesel fuel - The Agency has taken steps to reduce the sulfur content of in-use diesel fuel. Regulations published on May 7, 1992, to reduce the sulfur content in diesel fuel, are scheduled to take effect on October 1, 1993.[15]

Alcohol and Other Fuels - The Agency promulgated regulations in 1989 which established emission standards and test procedures for vehicles fueled with methanol and proposed similar regulations in 1992 for vehicles fueled with natural gas and liquefied petroleum gas. At this early stage of alternative fuel development, it is impossible to know what the real-world fuel compositions will be for any of these fuels when used in automotive applications. In each of these rulemakings, EPA has avoided adoption of narrow fuel specifications, specifying instead that test fuels be representative of typical in-use fuels.

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[14] 55 FR 23658 (June 11, 1990).

[15] 57 FR 19535 (May 7, 1992).

2.4.2. Temperature

The FTP is conducted between 68°F and 86°F and includes a cold start in its driving cycle.[16] As ambient air temperatures decrease, cold start emissions increase because a richer air/fuel mixture must be employed to ensure the presence of sufficient fuel vapor for combustion. In addition, colder temperatures lead to longer warm-up times.

This is not a major concern for ozone, which is primarily a summertime phenomenon, but it is for CO. Most CO exceedances occur from December to March and over half occur at temperatures below 45°F.

To reduce the emissions generated from motor vehicles during cold temperature operation, EPA recently issued 20°F CO emission standards and test procedures. These regulations were issued on July 17, 1992, and are scheduled for phase-in beginning with the 1994 model year.[17] The regulations also establish interim temperature defeat device criteria to maintain proportional CO emission control between the 20°F standard and the warm temperature standards. These regulations ensure that the Agency's test procedures properly reflect the impact of temperature on CO emissions. As the cold CO regulations will prevent emission step-functions just below 68°F that could also

[16] An engine start is considered to be a "cold" start if it is preceded by a long uninterrupted soak, such as those starts that occur after an overnight soak.

[17] 57 FR 31888 (July 17, 1992).

impact HC emissions, they will also ensure that the FTP is representative of HC emissions at colder temperatures.

At warmer temperatures the primary emission concern is increased fuel evaporation. The Agency has recently published regulations revising its evaporative test procedures to address a number of concerns, including temperature.[18] The final regulations are expected to specify ambient test temperatures of 95°F. These new test requirements should ensure that vehicles can control evaporative emissions for most in-use events.

2.4.3. Altitude

It has long been recognized that without compensation for the lower air density at high altitude locations engines tend to operate at rich air/fuel mixtures more frequently and, therefore, have excessive HC and CO emissions. Virtually all LDVs have been required to meet emission standards at both low and high altitudes without adjustment or modification since the 1984 model year. Light-duty trucks and light-duty vehicles have had separate high altitude standards since the 1982 model year. Regulations published on June 5, 1991, will require LDTs to meet emission standards at both low and high altitudes without adjustment or modification beginning with the 1997 model year.[19] The cold temperature CO regulations require that both LDVs and LDTs meet the cold temperature CO standard at both low and high

[18] 58 FR 16002, March 24, 1993.

[19] 56 FR 25724, June 5, 1991.

altitudes without modification. The FTP does not specify an altitude range in which the test must be conducted. In effect, the regulations allow the FTP to be conducted at any altitude and this, in fact, occurs.

2.4.4. Driving Behavior (Including Acceleration)

Current technology vehicles have achieved impressive reductions in emissions during normal operation, primarily due to catalyst technology development. Catalyst conversion efficiencies (that is, the rate at which HC and CO are oxidized into carbon dioxide (CO_2) and water vapor, or the rate at which oxides of nitrogen (Nox) are reduced to nitrogen and oxygen) in a modern, properly operating, warmed-up vehicle can simultaneously exceed 98% for HC, 99% for CO, and 90% for Nox. This includes typical transient operation in urban traffic situations, such as that represented by the FTP. However, these simultaneous catalyst conversion efficiencies are only achievable by a three-way catalyst in a very narrow range of air/fuel ratios around the minimum theoretical air requirement for complete combustion (called stoichiometry). Thus, modern, properly operating vehicles are designed to operate at stoichiometry as much as possible during the FTP.

Two types of operation make it difficult to operate an engine at stoichiometry. The first type of operation is a cold start. Fuel must be vaporized with air to combust properly. When the engine is cold, not enough heat is available to properly vaporize the fuel, requiring the addition of more fuel for proper operation. Cold start emissions are also increased due to the lack of conversion activity in the catalyst until it heats up (little catalyst activity occurs below roughly 600°F). Thus, emission rates during cold starts can be 20 to 100 times the emission rates during stoichiometric operation. In fact, the majority of emissions from modern, properly operating vehicles operating over the FTP occur during the first 10% of the test, before the engine and catalyst have warmed up. This raises a concern within the Agency as to whether or not the cold start portion of the FTP properly reflects the proportion of time vehicles actually spend in the warm-up mode.

The second type of operation that makes it difficult to operate an engine at stoichiometry is high engine loads. High loads on an engine running at stoichiometry can dramatically increase engine and catalyst temperatures. These elevated temperatures increase engine-out NOx emissions and can cause engine knock and/or damage to the catalyst. The performance and driveability of an engine under high load can be improved by running with a richer air/fuel mixture. Thus, to prevent over-temperature damage to the catalyst, and to ensure the best possible driveability and performance, vehicles are often designed to operate rich under high engine loads. While such a design has little effect on NOx emissions,[20] it increases HC and CO by almost the same 20 to 100 times factor as cold start

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[20]Engine-out NOx emissions decrease under rich operation, but NOx reduction efficiencies in the catalyst also drop. Overall, there may be a slight increase in tailpipe NOx emissions under rich operation, but the effect is relatively minor and varies from vehicle to vehicle.

operation. This also raises a concern within the Agency as to whether or not a significant amount of high engine load operation occurs in-use that is not properly reflected on the FTP. Due to the nonlinear nature of the emission rates, this amount of driving could actually be fairly small and still have a significant emission impact.

A wide variety of in-use factors impact the amount of time vehicles spend in either a warm-up or high-load mode. Factors related to warm-up include distributions of trip length, time between trips (referred to as "soak time"), ambient air temperature, initial idle time, and driving behavior. Factors that can cause high loads on an engine include high acceleration rates, high speeds, positive road grades, air conditioning operation, or some combination of factors (such as moderate acceleration up a moderate grade). Complicating the assessment is that different vehicles have very different calibration strategies. Thus, the impact on emissions of the exact same driving behavior may vary widely from vehicle to vehicle.

2.4.5. Test Procedure Modifications

For repeatability, it is necessary to conduct certification and enforcement testing in a laboratory. This gives rise to a number of procedures designed to simulate the actual forces and conditions a vehicle would experience on the road. The most significant of these is the dynamometer itself, which must simulate the inertial mass of the vehicle (which doesn't actually move in the laboratory), aerodynamic losses, and duplicate tireto-road traction and rolling losses. Other potential areas of concern are the type and amount of external air provided for vehicle cooling, the manner in which air conditioning losses are simulated, and manual transmission shift points.

The impact of these test procedure factors on emissions has been investigated at various times in the past. As a result of these investigations, the Agency has already begun the process of converting from small turn-roll waterbrake dynamometers to large single-roll electric dynamometers in its own laboratory in Ann Arbor, Michigan.

2.5 Heavy-Duty Vehicles and Engines

This preliminary report discusses the test procedures for light-duty vehicles and light-duty trucks, but does not address the very different procedures employed for testing heavy-duty engines.[21] The Agency believes this is consistent with the intent of Congress, as expressed in the text of the Act and its legislative history. Section 206(h) requires that EPA review test procedure regulations issued under Section 206 for a specific purpose - to insure that vehicles are tested under real world conditions. While the test procedure for light-duty vehicles and trucks involve vehicle testing, heavy-duty engines are tested differently, using an engine only test. Since the purpose of this provision is to review and, if necessary, revise EPA's regulations for testing motor vehicles, it is reasonable

[21]Light-duty is defined as less than or equal to 8500 pounds gross vehicle weight.

for EPA's review to address light-duty vehicle test procedures and not heavy-duty engine test procedures. The legislative history confirms that the review required under Section 206(h) is to address EPA's test procedures for light-duty vehicles and trucks.[22] This interpretation is confirmed by the fact Congress separately addressed the adequacy of EPA's test procedures for urban bus engines, a subset of heavy-duty engines. Section 219(e) requires that test procedures used for urban bus emission standards "reflect actual operating conditions." If Section 206(h) addressed both light and heavy-duty test procedures this provision would amount to surplusage.[23]

EPA of course has the discretion to review the test procedure for heavy-duty engines, and in fact did conduct such a review in the recent past. EPA conducted a large-scale, in-depth study over several years of heavy-duty vehicle driving conditions in the late 1970s and early 1980s. Based on that study, EPA revised the heavy-duty engine test procedures and driving cycle in 1983.[24] It was not considered either necessary or feasible to re-examine the heavy-duty test procedures in this review process, given the deadlines imposed by the CAAA and the fact that it previously took over 8 years to assess actual heavy-duty driving behavior and revise the heavy-duty engine test procedures.

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[22] See Senate Report No. 101-228, 101st Congress, 1st Session 106-107 (1989).

[23] In a recent rulemaking EPA addressed whether the current heavy-duty engine test procedure reflected actual operating conditions for heavy-duty engines used in urban buses, and determined there was no need to change the test procedures. [58 FR 15781, March 24, 1993]

[24] 48 FR 52170, November 16, 1983.

Chapter 3. Project Overview

It is a basic premise that motor vehicle emission levels determined through the FTP should adequately reflect in-use vehicle emissions. If in-use driving modes exist that generate significant amounts of emissions that are not reflected on the FTP, then the anticipated benefits from motor vehicle standards are not being fully achieved.

It is also generally agreed that no test procedure can reasonably duplicate all in-use conditions. The overall goal of the Agency's review of the FTP is to aid in determining whether or not the FTP should be modified to reflect in-use conditions not currently found in the test and, if so, what modifications should be made. To meet this goal it is not enough to simply examine factors such as ambient temperature ranges, in-use fuel characteristics, or driving patterns. For example, qualitative evidence has existed for years that certain types of actual driving behavior are not represented on the FTP, such as high acceleration rates. However, it would be counterproductive to modify the FTP unless two conditions are met. First, the driving behavior or other condition not represented properly by the FTP should contribute a significant amount to motor vehicle emissions. If it does not, then modifying the FTP could incur substantial costs and disruption with little or no air quality benefit. Second, any modification to the FTP should be expected to promote design improvements to vehicles and thereby create real improvements in controlling in-use emissions. If the current FTP is already effective in reducing emissions during non-FTP type driving or other conditions, then modifying the FTP could again incur substantial costs with little or no air quality benefit. Even if off-cycle emissions exist that are not properly controlled by the FTP, it is critical to ensure that FTP modifications will actually promote the proper design improvements. The Agency believes this approach is a reasonable way to implement the requirements of Section 206(h) of the Act.

This chapter of the report outlines the various research programs undertaken by the Agency to assess the FTP. The purpose is to provide a context for the driving survey data and analyses presented in Chapters 4-6. Section 3.1. discusses the reasons behind the Agency's decision to conduct large-scale surveys of in-use driving behavior. Section 3.2. outlines the methods and test programs being developed by the Agency to assess the emission impact of the driving survey information presented in this preliminary report. Section 3.3 outlines some of the issues and options that need to be addressed as part of the rulemaking development process.

3.1. Research on Driving Behavior

Based upon the logic outlined in Section 2.4., EPA compared conditions on the FTP and in-use for fuels, temperature, altitude, and driving behavior and determined that driving behavior was the most important area on which to focus the FTP review. EPA has also already initiated work on dynamometer improvements necessary to correct the inherent limitations of the small twin-roll waterbrake dynamometer currently in use. This work to upgrade the Agency's dynamometers is currently in progress.

Shortly after enactment of the 1990 amendments to the CAA, EPA evaluated existing data on actual driving behavior. Because one of the primary concerns with the FTP is fuel enrichment, as discussed in Section 2.4.4., quantitative assessments of acceleration rates were a high priority. It quickly became apparent that very little information existed that could be used to assess the frequency and magnitude of high acceleration rates.[25] The only existing sources of second-by-second speed measurements were from the Operational Characterization Study (OCS) conducted by EPA in Columbus, Ohio, in 1983, the European Drive Project in six European cities, and work conducted by H. C. Watson and his associates in Melbourne, Australia. The European and Australian work, while interesting and informative, would not be considered directly representative of how vehicles are driven in the U.S.A.

The OCS study was more relevant, but contained some inherent limitations. The study installed instrumentation on several vehicles which were then loaned to study participants. The driving patterns of 47 private citizens in Columbus, Ohio, were monitored covering a total of 251 days of vehicle operation. However, only three different loaner vehicles were used (a Chevrolet Impala, a Ford Fairmont, and a Chevrolet Chevette),

[25]As acceleration is the rate of change of vehicle speed, highly accurate and frequent measurements of vehicle speed are necessary to properly compute acceleration.

making it difficult to match the participant's personal vehicle. Also, some doubts are raised as to whether loaner vehicles would be driven the same as the driver's personal vehicle. These potential problems with the loaner vehicles used in the study cast some doubt on how well the results represent overall driving behavior. More importantly, significant problems in data collection were encountered during the study, leading to concerns regarding data validity.

These problems with the OCS data, combined with concerns about using 8-year old data and the ability of Columbus, Ohio, to represent major nonattainment areas throughout the country, led EPA to conclude that it would not be appropriate to evaluate potential revisions to the FTP based upon the OCS results. However, this left the Agency with choosing between three undesirable options. The first option was to proceed quickly with a new cycle and standard, based upon best engineering judgment, designed to control high acceleration enrichment. However, without knowledge of actual acceleration behavior, this approach had a high risk of both forcing excessive controls for driving that rarely occurs (increasing vehicle costs without attendant emission benefits) or of missing acceleration modes that cause significant in-use emissions.[26] In addition, this approach would not allow investigation of other factors that could potentially affect in-use emissions, such as driving behavior during the vehicle warm-up period and catalyst cooldown

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[26]Testing by the California Air Research Board on 10 vehicles over different high acceleration modes had demonstrated that the mode generating the highest emissions varied greatly from vehicle to vehicle.

after the vehicle has been turned off. Because of the risk of overlooking important test procedure modifications and of causing excessive costs, the Agency concluded that this would not be an appropriate route to take.

Another option was to take the position that there was no available information upon which the Agency could justify revisions to the FTP and, therefore, that no revisions were necessary. The Agency quickly rejected this option because it appeared to violate the spirit of Section 206(h)'s requirements and of EPA's general goal to provide a healthy environment.

The third option was for EPA to conduct basic research into actual driving behavior and conditions prior to deciding whether to initiate rulemaking. The Agency concluded that this was the only feasible alternative to simply ignoring any potential modifications to the FTP and was important since the relative impact of off-cycle emissions are likely to increase as emissions represented by the FTP are reduced.

Other CAA mandates, such as the Tier I emission standards and longer useful life, should reduce the baseline emissions derived through FTP testing. If adopted, Tier II emission standards would have a like effect. Thus, any off-cycle emissions will become relatively more important in the future. The research program undertaken by the Agency is designed both to quantify any emission impacts from off-cycle driving behavior, and to provide information needed to determine whether or not EPA should make regulatory changes to the FTP.

The program developed by the Agency to evaluate driving behavior contains three basic components. First, to determine how vehicles are actually driven, the Agency monitored an extensive amount of actual vehicle operation. This is described in the Chapter 4 of this report, "Driving Survey Methods and Approach." Second, the data from the vehicle monitoring has been analyzed to determine cycle and trip information and the impacts of different factors on driving behavior. These analyses are discussed in Chapter 6, "Discussion and Analysis of Driving Survey Results." The Agency has also worked toward developing new driving cycles that represent the complete range of actual driving behavior. This part of the program is described in Chapter 7, "Test Cycle Development Methods and Approach."

3.2. Emission Assessment of In-Use Driving

3.2.1. Cycle Development

To assess the impact of non-FTP driving, it is necessary to estimate the difference between emissions predicted by the FTP cycle and emissions that occur in actual driving. Using either computer models or dynamometer testing, this assessment requires the development of one or more driving cycles that are representative of the real world. The driving survey data discussed in Chapters 4 through 6 will serve as the primary input to this component of the project.

Several approaches to cycle development have been used in the past. These vary considerably in level of subjectivity. One approach, used in developing the current FTP, is to splice together segments of real speed patterns that are selected from the survey data. A final cycle is obtained by matching summary features of the resulting speed-time trace with those of the full sample. A virtue of this and related approaches is their basis in real driving experience that can be reproduced in dynamometer testing. The choice of segments and matching criteria are potential difficulties.

The speed-time trace used for the heavy-duty engine test cycle was generated using Monte Carlo simulation. With this method, each second-by-second value is chosen according to statistical criteria derived from the survey data. Cycles are subjected to matching criteria in order to screen out unsatisfactory candidates. This is likely to be a more efficient method of producing different cycles, but these cycles are wholly "unreal" in comparison to the splicing approach described above and have some potential of yielding driving segments that could arguably be unrealistic.

Because of the concerns over the available cycle generation methods, the Agency, in cooperation with the California Air Resources Board, initiated a program to investigate cycle generation alternatives and develop improved methods. The results of this work are discussed in Chapter 6.

3.2.2. Emission Simulation Model

In analyzing data from the in-use driving surveys it is essential to consider the emissions impact of the real world driving patterns that are not represented by the current FTP driving cycle. As discussed in Section 2.4.4., this requires assessment of a wide range of driving behavior, factors influencing emissions, and manufacturer calibration strategies. In order to perform these large scale assessments, EPA is developing a computer model which simulates vehicle emissions over any desired driving cycle.

EPA is using the modeling approach because it affords flexibility in analyzing the emission impact of the driving survey data. Even if EPA had adequate time to do all the emission assessments with vehicle testing, many analyses can be done much more efficiently and quickly with a computer simulation model. A simulation model will allow the emission assessment of a number of unedited and/or composite driving cycles over a large number of vehicles with relative ease. Thus, while the Agency intends to use vehicle test results as the core for emission impact assessments, the model will be used to fill in holes in the test data, assess factors that were not included in the test program, and conduct quick assessments of potential changes to the cycles and factors after the testing has been completed. Vehicle testing will also be used during the course of the emission assessment effort in order to validate the results of the computer simulation model.

The simulation model computes instantaneous fuel and emission rates based on instantaneous vehicle speed. This model is currently being developed as two components, known as VEHSIM (short for "VEHicle SIMulation") and VEMISS (short for "Vehicle EMISSions").

The VEHSIM component was originally developed by GM and later revised by the Department of Transportation. The VEHSIM model takes instantaneous (generally second-by-second) vehicle speed inputs and calculates instantaneous engine speed and load. These calculations of engine speed and load are performed utilizing vehicle information regarding vehicle aerodynamics, drivetrain, transmission, and engine accessories stored in a database known as a "part library".

The second component of the model, VEMISS, was developed by EPA to provide fuel and emission rate calculations based on the engine speed and load inputs produced by VEHSIM. VEMISS uses a series of lookup tables, known as engine maps, to simulate the fuel and emission rates for a particular vehicle. An engine map contains fuel and emission rates over a matrix of engine speed and load. VEMISS implements an interpolation method with the engine map in order to calculate fuel and emission rates for an instantaneous engine speed and load.

Cold start emission simulations also need to be developed to estimate the impact of cold start driving behavior and soak time. As the cold start simulation will calculate emissions using the warm engine-out emission maps as the starting point, development of the cold start module is being sequenced behind the warm component of the model. Once the warm component is satisfactorily validated, the cold operation component will be developed based on existing test data, integrated into the model, and validated.

Upon completion of VEHSIM and VEMISS, these components will be linked to produce a fully functioning model capable of simulating instantaneous fuel and emission rates for an entire vehicle trip based on an inputted speed/time trace.

3.2.3. Vehicle Testing Programs

EPA is in the process of developing a joint testing program with the California Air Resources Board and the vehicle manufacturers. This program will provide a base of test data addressing the emission impacts of high speeds and acceleration rates. The primary goals of the program are to quantify the increase in in-use emissions caused by high speed/acceleration on modern technology vehicles, investigate potential certification cycles for control of high speed/acceleration emissions, and investigate the feasibility of reducing the amount of enrichment allowed during high speed/acceleration conditions. A secondary goal of the test program is to investigate the emission benefits and feasibility of insulating catalysts to decrease the rate at which the catalyst cools off after the vehicle has been shut off. This testing is expected to begin around May 15, 1993 and be completed by the end of July, 1993.

3.3. Notice of Proposed Rulemaking Development

The Agency will use the analyses described in the preceding section when determining whether or not the driving cycle or other aspects of the FTP should be revised to properly represent vehicle emissions during actual driving conditions. However, in any proposal to revise the FTP, EPA would also need to consider various other issues, including:

- Technology assessment
- Type of revision needed
- Lead time
- Cost and cost effectiveness analyses

The technology assessment includes determining the changes needed for manufacturers to reduce emissions during the identified off-cycle condition, the level of reduction achievable with different technologies and/or calibration strategies, and the feasibility of making the technology changes. Closely related issues are cost and lead time, as greater levels of technology change or added component requirements will increase the cost of the regulation and, possibly, increase the lead time needed for manufacturers to implement the changes.

The type of revision to the FTP would also have to be considered. For example, revisions to the existing cycle would impact the usefulness of the vast array of historical data and would require assessments of the impact on Corporate Average Fuel Economy requirements and on the stringency of the emission standards. It will likely be much more cost effective, instead, to establish a new cycle and standard (much as was done for cold temperature CO emissions, where a new 20 degree cycle was established with a separate standard). If the emission benefits prove to be relatively minor, or if it appears that emissions could be effectively reduced without standards, it might be desirable to simply promulgate stronger defeat device requirements. The basic strategy to improve the FTP would have to be evaluated, as well as the impacts on costs and emission benefits.

Evaluation of this wide array of control strategies, technology requirements, standard stringency, costs, and benefits is a complex task. Due to the time constraints the Agency is under, several potential new test cycles to control high speed/acceleration emissions are being investigated as part of the vehicle testing program described in Section 3.2. The level of complexity will be significantly impacted by the results of the study in regards to the level of off-cycle emissions and the type of driving generating the emissions.

Chapter 4. Driving Survey Methods

The process for selecting driving survey methods and sites is reviewed in Section 4.1. A discussion of each method and how it was implemented follows in Sections 4.2. and 4.3. Also provided are results obtained at each survey site. Section 4.4. reviews bias issues for the two survey methods. The chapter concludes with a discussion of the principal data set which serves as the basis for the analyses in the remainder of this report.

4.1. Survey Options

4.1.1. Choosing Survey Approach

Prior to collecting data on in-use driving behavior, EPA had two contractors, Radian Corporation and Sierra Research, review previous efforts to obtain such information. Contractor reports evaluated four alternative approaches to gathering driving patterns data and included recommendations for this study. Table 4-1 presents the principal features of these approaches.[27]

In exploring survey method options, EPA sought input from interested parties and researchers working on the subject. To this end, EPA's Office of Research and Development (ORD) sponsored a two-day meeting in Atlanta, GA, in June of 1991 to discuss alternatives for collecting the in-use driving behavior

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[27] Radian Corporation,"Evaluation of Driving Pattern Measurement Techniques: Technical Note," Draft Report to U.S. EPA, June 17, 1991, p. 4-14.

data. Experts from industry, government, and academia critically evaluated the approaches presented by EPA's two contractors. As a result of the meeting, EPA's Office of Mobile Sources (OMS) concluded that two complementary approaches--chase car and

Table 4-1.
Alternative In-Use Driving Survey Methods

	Instrumented Private Car	Data Logger on Private Car	Driving Diary	Chase Car	Stationary Observer
SOURCES OF BIAS					
Driver does not know he is being monitored	-	-	-	+	+
Representative of vehicle population	-	-	-	+	+
Representative of drivers	-	-	-	+	+
Nonintrusive installation of data logging equipment	-	-	+	+	+
Representative of all types of trip segments	+	+	+	-	-
TECHNICAL					
Follows each car all the time - moving or not	+	+	-	-	-
Contains high frequency information	+	P	-	+	-
Measures average speeds	+	P	+	+	-
Measures instantaneous speeds	+	P	-	+	-
Measures accelerations	+	P	-	+	-
Measures number of cold starts	+	P	+	-	+
Measures during cold starts	+	P	-	-	-
Measures number of warm starts	+	P	+	-	+
Measures during warm starts	+	P	-	-	-
Measures distance travelled	+	P	+	-	-
Contains load information	+	-	-	-	-
Permits various data analysis techniques	+	-	+	+	+
Correct observables not needed at beginning of study	+	-	+	+	+
Generates small quantity of data	-	+	-	-	-
Can measure drive train operation	+	-	-	-	-
COST					
Low procurement cost	-	-	-	+	+
Low installation cost per car	-	-	+	+	+
High capacity storage medium not required	-	+	+	-	+
Data recovery does not require personnel at vehicle	-	-	+	+	-
Does not require data keypunching	+	+	-	+	-

P = Measurable if pre-processor is programmed appropriately

instrumented vehicles--were needed to address issues critical to the FTP study.

The Atlanta meeting also helped produce an extraordinary level of cooperation among the participants. The California Air Resources Board (CARB) and EPA's Office of Mobile Sources (OMS) joined together to develop the chase car approach. The auto industry, represented by the American Automobile Manufacturers Association (AAMA, formerly MVMA) and the Association of International Automobile Manufacturers (AIAM), committed to providing technical and financial support for the implementation of the instrumented vehicle method. And finally, EPA's ORD agreed to sponsor an instrumented vehicle study in Atlanta, GA.

4.1.2. Selecting Survey Sites

After settling on survey methods, the next step was to select the cities where the surveys would be conducted. EPA's budget for the driving surveys necessitated limiting the study to two sites. EPA gave consideration to several factors in selecting the survey sites: geographical representation, population of nonattainment area, and the type of nonattainment area (CO or ozone). The site selection process was complicated by special requirements of the two survey methods. The instrumented vehicle approach required that the survey site have a centralized Inspection-Maintenance (I/M) program; an up-to-date urban transportation network model was a requisite of the chase car method.

EPA's criteria and the survey method requirements quickly limited the list of candidate cities. Baltimore, MD, was chosen to represent a Northeast, medium-sized, ozone nonattainment area. For the second site, a suitable midwest city was desired, but could not be found. The best alternative was Spokane, WA. This Northwest city is fairly small, but owing to its geographical features, it is typical of a CO nonattainment area. In addition to these two cities, two other cities had already been selected for related studies. CARB was sponsoring a chase car study in Los Angeles, CA, and Atlanta, GA, was the site of an instrumented vehicle study sponsored by EPA's ORD. Overall, EPA felt these four cities provided a good representation of urban nonattaiment areas.

4.2. Instrumented Vehicle Approach

This section discusses the principal features of the instrumented vehicle approach and presents the field results. The reader should note that a draft report prepared by the contractor, Radian Corporation, provides a much more comprehensive review of the instrumented vehicle study.[28]

4.2.1. Key Features

EPA chose the method of instrumenting privately-owned vehicles for several principal reasons. First, this approach

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[28] Radian Corporation, "Light-duty Vehicle Driving Behavior: Private Vehicle Instrumentation, Volume 1: Technical Report," Draft Report to U.S. EPA, August 24, 1992.

collects second-by-second driving behavior data. Real-time information is crucial for studying the full range of vehicle operation. The instrumented vehicle method also obtains important information on the start and finish time of trips, driving behavior following the start of a trip, and the amount of time vehicles are shut off between trips (soak time).

EPA had concerns with certain features inherent to an instrumented vehicle approach. The cost and time required to recruit and instrument privately-owned vehicles necessarily limited the number of vehicles to be instrumented. Equally important, the driver's knowledge of the instrumentation and the possible impact it could have on driving behavior was a concern. The contractor, Radian Corporation, took these concerns into account in the design of the actual project plan for collecting instrumented vehicle data.

The basic features of EPA's instrumented vehicle study can be summarized as follows. Participants were recruited from centralized I/M stations. A monetary incentive was offered to drivers for participating in the study. While the car owner waited, mechanics installed a small datalogger under the hood of the vehicle to collect vehicle speed, engine RPM, and manifold vacuum. The participants were truthfully informed on the nature of the instrumentation; however, the contractor did not explicitly discuss the monitoring of vehicle speed. The dataloggers remained on the vehicle for about one week. At the end of the week, the driver returned to the I/M station for removal of the datalogger.

The contractor installed two types of instrumentation packages: a three-parameter datalogger and a 6-parameter datalogger. The latter was sponsored by a group of domestic and foreign auto manufacturers. In fact, the auto industry's participation was of great value in the overall instrumented vehicle study. Through the Ad Hoc Panel on FTP, comprised of AAMA and AIAM members, the industry worked together with EPA in the development and implementation of the study. Financial support from participating auto manufacturers significantly increased the number of vehicles instrumented in Spokane and Baltimore.

3-parameter Base Program

Under EPA contract, Radian Corporation custom built 55 compact 3-parameter dataloggers, each capable of recording 54 hours of second-by-second data. Initially, the contractor manufactured 10 prototype dataloggers for testing. After testing and making some refinements, the remaining dataloggers were produced. The dimensions of these 45 datalogger boxes were 5" x 7" x 1.5"; the 10 prototypes were slightly larger. All of the logger components were tested to 85 degrees Centigrade. The compact size and durability of the dataloggers allowed mechanics to install them under the hood of the vehicles, completely out of the sight of the driver. The dataloggers recorded vehicle speed, engine RPM, and manifold vacuum each second of vehicle operation.

In addition, the logger recorded the date and time on a real-time basis.

Driver Recruitment

Centralized I/M stations were selected as recruitment sites in order to obtain the most representative sampling of drivers and vehicles possible. In Spokane, all gasoline-powered light-duty cars and trucks are required to be tested at the sole I/M station. Baltimore requires testing of all vehicles less than 20 years old. There are a number on I/M stations in and around Baltimore. EPA selected two stations for recruitment: a suburban site (Rossville station) and an urban site (Exeter station).

EPA's contractor solicited the driver after the vehicle passed emission testing. A monetary incentive of up to $100 was offered to drivers to compensate for their time and inconvenience. If the driver passed an initial screening and agreed to participate, the contractor mechanics installed the logger at the I/M station. Typically, the installation of the datalogger took between 30 minutes and an hour.

In order to try and minimize sampling bias due to refusals, the recruitment procedure included a driver\vehicle replacement strategy. The solicitor recorded information on vehicle age, vehicle type, vehicle's country of origin (foreign or domestic), and driver age for all solicited drivers. If a driver refused to participate, a replacement driver\vehicle was found which matched the four recorded characteristics.

Supplemental 6-parameter Program

The program of installing 6-parameter dataloggers on manufacturer-sponsored vehicles solicited from I/M stations was conducted in parallel with the 3-parameter study. The purpose of this supplemental program was to collect additional vehicle operating information. Like the 3-parameter datalogger, speed, RPM, manifold vacuum were recorded, but, in addition, the 6-parameter dataloggers obtained coolant temperature, throttle position, and air/fuel ratio collected downstream of the catalyst. Each participating auto manufacturer developed customized interfaces for the 6-parameter dataloggers. Typically, the loggers were installed in the vehicle's trunk. Two major differences existed between the 3-parameter and 6-parameter program. Only late-model vehicles were eligible for the 6-parameter program and candidates were further limited to high-volume models among the participating manufacturers.

4.2.2. Instrumented Vehicle Field Results

EPA's instrumented vehicle study was the largest study of real-time, in-use driving patterns ever conducted in the U.S. Nearly 300 vehicles were instrumented in Baltimore and Spokane. The dataloggers recorded over 6 million seconds of driving behavior in the two cities.

EPA's contractor carried out a one week pilot study in Spokane in January, 1992. The pilot study tested alternative recruitment strategies and logger installations in the field. The success of the pilot study permitted the start of the full Spokane Instrumented Vehicle Study on February 3. Datalogger retrieval in Spokane was completed by the first week in March. At that time, the contractor began work in Baltimore. The contractor finished all field work by the first week of April.

In the two cities, a total of 730 drivers were solicited for participation in the program. 331 of the solicited drivers agreed to participate, and from that group, 294 vehicles were successfully instrumented. Table 4-2 gives a summary of the field study results.

Table 4-2.

Summary of Instrumented Vehicle Field Results

City	Datalogger Type	Vehicles Solicited	Screen Passes	Drivers Participating	Participa-tion Rate (%)	Complete Instal-lations
Both cities	3 and 6	727	571	331	58	294
	3	479	374	226	60	215
	6	248	197	105	53	79
Spokane	3 and 6	246	222	168	76	144
	3	161	144	111	77	102
	6	85	78	57	73	42
Baltimore	3 and 6	481	349	163	47	150
	3	318	230	115	50	113
	6	163	119	48	40	37

The driver participation rate was substantially higher in Spokane than in Baltimore. About three-quarters of the solicited Spokane who passed the screening agreed to participate in the driving patterns study. In contrast, the participation rate in Baltimore was only 47 percent.

After completing the field work, the contractor began the processing of this immense data set. All data were passed through a rigorous quality control software program to check for errors in the data. This procedure identified 216 error-free vehicle data sets and 78 "suspect" vehicle data sets. A subsequent review of the "suspect" vehicles resulted in the recovery of a number of vehicles. The final count of vehicles for which there was good data was 217, including 168 3-parameter and 59 6-parameter vehicles.

4.2.3. Atlanta Instrumented Vehicle Study

Atlanta, GA, is the site of an intensive emission inventory study by EPA's ORD. The objective of the instrumented vehicle study in Atlanta was to provide important vehicle operation data for ORD's mobile source emission inventory analysis, while also serving to supplement OMS's instrumented vehicle database.

Under a cooperative agreement with ORD, the Georgia Institute of Technology conducted the instrumented vehicle study in the summer of 1992. The 3-parameter dataloggers were installed on a fleet of privately-owned vehicles. The Atlanta study followed the procedures used in Spokane and Baltimore, whenever possible. The most significant difference in Atlanta was the method for recruiting drivers. Atlanta's use of a decentralized I/M program made it impossible to use I/M stations as a driver recruitment location. However, Atlanta does have a centralized driver's license renewal system which requires drivers to renew their licenses in person at one of a limited number of Driver's License Stations. The recruitment method utilized three such stations to recruit a representative cross-section of Atlanta drivers.

Georgia Institute of Technology conducted a successful pilot study in the first week in July of 1992. The full study was carried out from July through the beginning of October; mechanics instrumented a total of 101 vehicles. The successful completion of the study served to add a third city to the instrumented vehicle database.

EPA contracted with Radian Corporation to process the Atlanta data set using the exact procedures employed in the processing of Baltimore and Spokane data. Due to contract delays, only initial processing of the data is complete. Preliminary data are available for 68 vehicles from Atlanta. This limits the usefulness of the Atlanta data for this preliminary report; however, it is expected that further analyses will use data from a finalized Atlanta data set.

4.3. Chase Car Approach

The use of chase cars to collect driving patterns data has a fairly long history. The EPA Highway fuel economy driving cycle was based on driving patterns data collected by driving a chase car over 1000 miles of non-urban roadways.[29] For the FTP study, EPA felt the chase car approach could complement the instrumented vehicle approach in several areas. First, a chase car allows for the collection of driving behavior data in a non-intrusive manner. The chase car method also provides a cost-effective way to collect data for a large sample of vehicles. Finally, information on the driving environment--road type, congestion level--can be obtained using chase cars.

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[29] Austin, Thomas C., Karl H. Hellman, and C. Don Paulsell, "Passenger Car Fuel Economy During Non-Urban Driving," SAE Paper 740592, August, 1974.

The traditional chase car approach has a major drawback. It is assumed that the driver of the chase car can simulate typical driving patterns, either by following specific "target" vehicles or by "flowing" with traffic. However, EPA's objective was to not only capture "typical" driving patterns, but also to study the entire spectrum of drivers and driving patterns, including low frequency behavior found in the "tails" of the driving behavior distribution. Clearly a single chase car driver could not be expected to adequately achieve such a goal.

4.3.1. Key Features

Under contract with both CARB and EPA, Sierra Research developed an enhanced chase car equipped with a grill-mounted, laser rangefinder which can infer the speed of the "target" vehicle.[30] The laser rangefinder utilizes the same technology found in hand held laser guns currently used by many police departments to measure vehicle speed. The laser measures the distance between the "target" vehicle and the chase car (patrol car). The patrol car itself is instrumented to collect the vehicle speed; knowing the patrol car's speed and the change in the distance between the patrol car and target car, the target's car's speed can be calculated. The laser measures the distance 20 times a second and calculates a one second average. The laser-enhanced chase car method makes it possible to get an

[30] Sierra Research Inc., "Design and Operation of an Instrumented "Chase Car" for Characterizing the Driving Patterns of Light-Duty Vehicles in Customer Service," Draft Report to U.S. EPA, February 28, 1992.

accurate representation of the driving behavior of the target vehicle.

The use of the a laser rangefinder is the most prominent feature of Sierra Research's chase car approach. Other important characteristics of this approach are in the following discussion.

Instrumentation

The patrol car was a 1991 Chevrolet Caprice with sufficient room behind the grill to install the custom-built laser rangefinder. The car was equipped with a videotape recorder mounted between the front bucket seats. In addition, the patrol car speed and manifold pressure were collected once per second. A road grade measurement system was developed using two unidirectional accelerometers mounted on the vehicle floor pan to collect longitudinal and lateral acceleration. All of the data were directed to an on-board laptop computer operated by the "co-pilot." The co-pilot was responsible for working a handheld switch box for recording road type, traffic level, and target vehicle information.

Route Selection

It was imperative that the routes over which the patrol car would travel and collect information reflect road conditions, trip conditions, and vehicle/driver variation which are characteristic of the overall driving patterns for the particular city being studied. The chase car study employed transportation planning models for the generation of representative routes. These computer-based transportation planning models are used by urban areas to track travel activity over the road network. Information from periodic travel surveys are a principal input into these models, providing trip information such as trip origin, destination, purpose, and length. Additional information on land-use patterns are also incorporated into the model. Representative routes are generated using a four-stage process of trip generation, trip distribution, model choice, and route choice. The contractor worked with local transportation authorities to generate 300 routes for each city.[31]

Target Selection

A detailed road map was generated for each route. At a pre-determined time and start location, the patrol car began the route and sought its first target vehicle. Target vehicles were selected at random from candidate vehicles (cars and light trucks) traveling on the same route as the chase car. If the target vehicle left the pre-defined route, the chase acquired a new target vehicle according to prescribed protocol.

Trip ends

Inherent to the chase car approach is an inability to measure vehicle activity at very beginning and very end of a trip. Recognizing this, Sierra Research conducted trip ends

[31] Ibid.

surveys in Sacramento and Los Angeles.[32] Information on idle time and driving time and behavior prior to accessing the road network were recorded by observers in the field. The information can be used in conjunction with the chase car data to give a more complete profile of driving behavior.

4.3.2. Chase Car Field Results

Sierra Research conducted the first chase car study in Baltimore during November and December of 1991. After completion of the data collection effort in Baltimore, the contractor processed and quality checked the data. Chase car survey work continued in the spring of 1992 with the Los Angeles study sponsored by CARB. The Spokane chase car study was carried out in July of 1992.

Table 4-3 presents a summary of the field results for Spokane and Baltimore. The chase car study collected data on over two hundred routes in each city. A large number of targets were acquired in each city, although the fraction of total route time with a target was disappointingly low. The bias analysis, in Section 4.4, discusses the significance of these results.

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[32] Sierra Research Inc., "Characterization of Driving Patterns and Emissions from Light-Duty Vehicles in California," Draft Final Report to California Air Resources Board, March 5, 1993.

Table 4-3.
Summary of Chase Car Field Results

Characteristic	Both Cities	Baltimore	Spokane
Number of Routes	467	218	249
Total driving time (seconds)	366,256	191,119	175,137
Number of targets	1,641	770	871
Total target time (seconds)	143,668	69,528	74,140
Target time as percent of total	39	36	42

4.3.3. Los Angeles Chase Car Study

CARB's Los Angeles chase car study ran concurrent with EPA's studies in Baltimore and Spokane. The first chase car work in Los Angeles was in conducted in the fall of 1991. Due to data acquisition problems and revisions to the route selection methodology, these data were not acceptable to CARB. The contractor returned to Los Angeles to conduct additional chase car runs in April and May of 1992. The chase car collected data for 102 routes, encompassing 28 hours of vehicle operation. The data collection methods and data processing used in Los Angeles were entirely consistent with those employed in Baltimore and Spokane. Section 6.1 presents a limited analysis of the Los Angeles data.

4.4. Analyses of Potential Bias

The objective of both driving survey approaches was to obtain the most representative characterization of in-use driving behavior. While the design features of the two survey methods attempted to explicitly account for all areas of foreseeable biases, it is the surveys' results which ultimately determine the success of the two approaches. This section provides a largely qualitative assessment of the "representativeness" of the chase car and instrumented vehicle data for Baltimore and Spokane.

4.4.1. Analysis of Instrumented Vehicle Method

EPA's contractor, Radian Corporation, conducted a post-survey study of several issues pertaining to possible survey bias.[33] Sampling bias sources included improper representation of vehicle age, make and manufacturer, and performance type. Nonsampling sources included accuracy of speed measurement and the effect on driving behavior of the presence of the datalogger.

Vehicle Selection

The sampling frame in the 3-parameter instrumented vehicle surveys was the set of vehicles scheduled for inspection during the month in which the survey was conducted. Radian obtained lists from Spokane and Baltimore of all vehicles tested during the survey periods. For both cities these vehicles were classified by model year (age) and make and compared to the corresponding distributions found in the sample. Goodness-of-fit

[33] Radian Corporation, "Private Vehicle Instrumentation Survey: Data Bias Analysis Technical Note," Draft Report to U.S. EPA, September 30, 1992.

statistics showed no significant difference except in the case of the Spokane vehicle make variable, in which Mazdas were somewhat overrepresented.

Vehicle performance type is a rather subjective measure, and EPA was unable to obtain sufficient information on performance criteria for all vehicles tested in the two cities during the survey periods. Therefore, the representativeness of the sample was judged by comparing the final sample vehicles to the set of all vehicles that were randomly solicited, which are assumed to be representative of the target population.

Using power-to-weight values and some subjective judgment about the "image" of the vehicle, vehicles were classified as "High-Performance" or otherwise. In Spokane, 3 of 99 (3.0%) randomly solicited vehicles were classified as High-Performance; in the final sample, 1 of 75 (1.3%) were High-Performance. For Baltimore, there were 6 of 86-144[34] (4.2-7.0%) High-Performance random solicitations, and 4 of 93 (4.3%) High-Performance vehicles in the final sample. These numbers suggest the possibility that High-Performance vehicles were underrepresented in the final sample; EPA has not yet developed a reasonable adjustment method for this factor. This may be an area for further study prior to completion of a NPRM.

Speed Measurement

[34]The selection method was not recorded for 58 vehicle solicitations in Baltimore.

Accurate vehicle speed data were critical to the success of the instrumented vehicle study. The 3-parameter dataloggers used three different methods for obtaining vehicle speed: magnets on a drive shaft, OEM speed sensor, or an aftermarket cruise control attached to the speedometer cable. The acceptable accuracy for the vehicle speed parameter was +/- .4 mph.[35]

A fifth wheel test track study was conducted by the contractor to test the accuracy of the three speed measurement methods. The OEM sensor and driveshaft magnet methods showed very good correlation with the fifth wheel at all tested speeds (1 to 50 mph). The speedometer cable approach performed well at speeds greater than 10 mph; however, at low speeds the speedometer cable approach proved less accurate due to jerky rotation of the cable.[36] In the field, every attempt was made to keep the speedometer cable straight to minimize the potential for such erratic low-speed data. Upon quality checking of the data, EPA does not consider this to be a significant problem.

The vehicle speed resolution for 6-parameter vehicles varied among manufacturers. The speed data were obtained directly from the engine's computer (ECU), and were therefore limited by the resolution required by the vehicle's production specifications. Typically, a fine speed resolution is not necessary for a vehicle's dashboard speedometer. Thus, many of the 6-parameter

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[35] Radian Corporation, "Light-Duty Vehicle Driving Behavior: Private Vehicle Instrumentation, Volume 1: Technical Report," Draft Report to U.S. EPA, August 24, 1992.

[36] Ibid.

vehicles only recorded speeds to the nearest 1 mph or less. As a consequence, the lower precision of the 6-parameter vehicles' speed is a potential problem, particularly at low speeds. More importantly, this problem results in low resolution (that is, 1 mph/sec) and an upward bias in the calculated acceleration rates.[37]

Datalogger Presence

A driver may alter his or her vehicle operation in response to the datalogger presence. Reasons for this change in behavior might include concern that the data could be used as evidence of illegal or unsafe driving. It is most likely that bias introduced in this way would tend in the direction of more conservative driving, that is lower speeds or lower rates of acceleration.

EPA and Radian conjectured that, if it exists, this type of bias might be most evident during the initial phase of instrumentation and would decline as the driver adjusted to the presence of the datalogger. This motivated an examination of possible bias based on the "Observation Phase" in which speed and related values were observed.

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[37]Systems Applications International, "Stratified Comparison and Rounding Effect Analysis of Driving Operation Patterns and Event Characteristics Between Three-Parameter and Six-Parameter Instrumented Vehicle Data," Draft Report to American Automobile Manufacturers Association, January 7, 1993.

For each vehicle in the Baltimore 3-parameter sample, the speed observations were classified as belonging to the first day of instrumentation (Observation Phase 1) or later (Observation Phase 2). Various driving behavior measures were computed for the two phases. (Section 5.1 contains a discussion of speed-related driving variables analyzed in this study.) It was found that during Observation Phase 1, drivers operated at lower average speeds than in Phase 2, which appears to support the claim that the datalogger influenced driving behavior in the initial phase of instrumentation. However, further examination showed that the time of week also affects average speed: substantially higher speeds are observed in weekend driving than on weekdays. (See Section 6.2 for details.) Moreover, due to most vehicles being instrumented on weekdays, the proportion of Observation Phase 1 driving on weekends (17.9%) was lower than for Phase 2 (25.6%). If the average speed during Phase 1 is adjusted for this difference, it actually is higher than the same value in Phase 2. Thus, it was decided that driving behavior probably did not change substantially over the instrumentation period and that data for both observation phases should be included in subsequent analyses. Of course, this analysis leaves unanswered the question of whether instrumented vehicle driving was more conservative than normal over the full survey period.

4.4.2. Analysis of Chase Car Method

In terms of potential bias, the three areas of concern for the chase car study are the representativeness of the routes selected, vehicles, speed measurement, and driving behavior.

Each of these issues were reviewed following the completion of data collection.

Route Selection

The method for selecting routes was designed to match the overall distribution of trips by travel period or trip type, zone type, and trip length. This method assumes that the transportation model produces an accurate portrayal of in-use trip behavior. Accepting this, the subset of the selected routes which were actually run, closely matches the desired distribution (For a qualitative comparison see Appendix A, tables A-1 and A-2). However, the assumption that the transportation model produces an accurate portrayal of in-use trip behavior may not be appropriate, as discussed in Section 4.5.1.

Vehicle Selection

As discussed in Section 4.3.1, the protocol for selecting target vehicles was designed to obtain a random sampling of vehicles. In the field this method proved practical; however, obtaining and maintaining a lock on the target vehicles was only a limited success. The overall proportion of total route time with a target locked on was 36 percent in Baltimore and 42 percent in Spokane. The general availability of candidate vehicles was a significant factor in the low percentage. In fact, 10 percent of the routes in Baltimore had no target vehicle data. The corresponding percentage for Spokane was 13.

Maintaining a constant laser lock-on for a given target vehicle also contributed to the lack of target data. A break in the laser-lock often occurred due to change in grade, on turns, or lane changes. In order to investigate the lock-on problem, EPA contracted Sierra Research to analyze the video tapes for Baltimore and Spokane to identify reasons for losing targets.[38] Table 4-4 presents the results of this analysis.

A second issue related to vehicle selection is the representativeness of the target vehicle sample relative to the vehicle population. The video tape review also helps address this topic. The contractor tabulated the distribution of target vehicles by vehicle type, model year, and manufacturer, for Baltimore and Spokane (For a summary of the results see Appendix A, Table A-3).

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[38]Sierra Research Inc., "Chase Car Video Tape Review," Draft technical memos to U.S. EPA, October 9, 1992 and October 29, 1992.

Table 4-4.

Reasons for Chase Car Losing Target

Reason for losing target	Baltimore		Spokane	
	Number	Percent	Number	Percent
Target turned off route	250	12.9	331	18.4
Patrol changed roadways to continue route	249	12.8	211	11.7
End of route	14	0.7	24	1.3
Lost target over hill or around corner	684	35.2	653	36.3
Target and patrol car out of alignment while in same lane	216	11.1	131	7.3
Changed lanes (patrol car)	27	1.4	98	5.5
Lost target while merging with heavy traffic	15	0.8	5	0.3
Patrol stuck at traffic light	19	1.0	23	1.3
Another vehicle came between target and patrol car	36	1.9	23	1.3
Lost target because of aggressive driving	14	0.7	0	0.0
Suspect target driver realized they were being followed	7	0.4	4	0.2
Target changed lanes	186	9.6	235	13.1
Turned off switch to read map	21	1.1	22	1.2
Navigator bumped switch	28	1.4	19	1.1
Laser error, sunlight interference	95	4.9	0	0.0
Other reason	81	4.2	19	1.1

Aggressive driver

From the start, EPA was aware of, and concerned about, the ability of the chase car approach to capture aggressive driving behavior. There was some small fraction of vehicles which were operated in such a fashion that it was either impossible or unsafe for the patrol car to "chase" them. It is not possible to quantify the incidence of these occurrences. A partial answer can be found, however, from the review of the target vehicle videotape. As shown in Table 4-4, less than 1 percent of the cases in which the target was lost was attributable to aggressive driving behavior of the target (the classification was based on the videotape reviewer's best judgment). In addition, some fraction of the reason "lost due to lane change" (10 percent in Baltimore and 13 percent in Spokane), can be attributed to aggressive driving on the part of the target vehicle.

Speed Measurement

The use of the laser was designed to produce an accurate measurement of the target vehicle's speed on a second-by-second basis. The preliminary testing of the laser suggested that the laser provided an accurate measurement of target speed. However, in the process of comparing the chase car data and instrumented vehicle data, EPA identified a problem with the target vehicle speed resolution which resulted in skewed acceleration data under certain situations. Post-processing of the target speed data using a smoothing algorithm greatly improved the "fit" of the laser-based target data.[39]

4.5. Selection of Principal Data Set

4.5.1. Comparison of the Two Surveys Results

EPA's contractors conducted the chase car and instrumented vehicles studies in Baltimore and Spokane within a nine month period in 1991 and 1992. A variety of constraints prevented simultaneous data collection in each city. Except for potential seasonal differences, it is valid to compare the results for the chase car and instrumented vehicle approach. Such a comparison cannot validate or invalidate an approach, since the absolute truth is not known. Rather, the comparison serves to identify substantial differences and allows for an evaluation of these differences.

In looking at the results from the two fundamentally different survey approaches, it was reassuring to see that they paint like portraits of driving behavior, especially in terms of differences between Baltimore and Spokane. Both methods indicate higher average speed in Baltimore than Spokane (see Table 4-5). This is also true for average specific power.[40] The surveys also

[39] Sierra Research Inc. "Characterization of Driving Patterns and Emissions from Light-Duty Vehicles in California," Draft Final Report for California Air Resources Board, March 5, 1993.

[40] Specific power is a single measure for the combined effect of speed and acceleration. See Section 5.1.1 for more detailed discussion of this measure.

agree in the direction of the differences of trip time and distances; Baltimore trips averaged about 0.5 miles longer than Spokane trips and the duration of trips in Baltimore were about three minutes longer than in Spokane.

While the two surveys agree in terms of differences between the cities, the actual estimates of various driving behavior measures are clearly different. The chase car method estimates much higher average speeds than the instrumented vehicle approach. This difference is, however, consistent with expectations, given the methodological differences. The chase car's lack of trip end information (see Section 4.3.1) is likely to be the primary reason for the higher average speed.

Table 4-5.

Comparison of Chase Car and Instrumented Vehicle Driving Behavior

Driving Behavior Measures	Baltimore		Spokane	
	Chase Car	Instrumented Vehicle	Chase Car	Instrumented Vehicle
Speed (mph)				
Average	30.70	24.50	29.80	23.24
Maximum	79.50	94.46	83.20	77.55
Standard deviation	21.00	20.52	19.50	17.71
Number of observations	191,119	3,365,504	175,137	2,081,199
Acceleration (mph/sec.)				
Minimum	-20.80	-19.49	-11.30	-15.46
Maximum	8.13	15.19	7.79	15.95
Standard deviation	1.39	1.50	1.42	1.46
Power (mph^2/sec)				
Average*	22.2	19.28	20.0	17.01
Maximum	577.30	557.69	403.00	672.28
Average trip length (miles)	7.48	4.89	5.83	3.56
Average trip time (minutes)	14.61	12.03	11.72	9.18

* The average power values presented in this table use total number of seconds of vehicle operation as the denominator. This differs from average power values cited in Chapter 6, which use total seconds of positive acceleration as the denominator. The alternative definition used here was necessary in order to have consistent average power values for the chase car and instrumented vehicle data.

The differences in the surveys' estimates of trip time and distance suggest two distinct perspectives on trip-making activity. Using engine on/off to define a trip (see Section 5.1.2), the instrumented vehicle approach identified a large number of short trips. In contrast, the chase car routes are developed using the transportation network model's concept of a trip which is based on trip purpose. A given chase car route may be a result of the implicit connection of two or more engine on/off events. As an example, a single home-to-work chase car trip could be viewed as 2 separate trips in the instrumented vehicle approach--home-to-day care and day care-to-work. The instrumented vehicle's trip patterns perspective, which captures the full-range of trip behavior, is most consistent with the objectives of the FTP study.

4.5.2. Rationale for Choosing 3-parameter Instrumented Vehicle data

For this preliminary technical report, EPA feels the 3-parameter instrumented vehicle data are the best representation of in-use driving behavior currently available. This data set provides detailed driving behavior for a large cross-section of vehicles and drivers. All substantive issues on bias or data integrity have been satisfactorily addressed for the 3-parameter data set.

The 6-parameter instrumented vehicle data are a valuable addition to the overall data set; however, two factors limit their usefulness for this preliminary report. As discussed in Section 4.2, speed measurement problems impact the accuracy of the acceleration-based measures for the 6-parameter data set. In addition, the vehicle selection process for the 6-parameter vehicles did not attempt to obtain a representative sample; weighting factors will need to be developed in working with the data in the future.

In choosing the 3-parameter instrumented vehicle data over the chase car data, one factor was just the sheer volume of data obtained by the instrumented vehicle approach. In Baltimore and Spokane, 3-parameter instrumented vehicles collected over 1500 hours of driving behavior data compared to 100 hours of chase car data. EPA also considered the surveys' ability to provide data on a representative cross-section of vehicles and driving. While we are largely satisfied with the results of the instrumented vehicle bias analysis, the results of the chase car surveys are less reassuring. The majority of data from the chase car is for only one vehicle--the patrol vehicle. The target vehicle data does capture a large number of vehicles, but typically, the data are obtained for a very small amount of time. Finally, the routes (or trips) driven in the chase car approach are considerably longer than typical trips from the instrumented vehicle data, casting doubt on whether the chase car routes properly reflect the range of in-use driving conditions.

Chapter 5. Analytical Methods and Considerations

This chapter describes driving behavior variables and methods for their analysis based on the survey data discussed in Chapter 4. Analytical methods consist primarily of traditional descriptive techniques: arithmetic summary measures, variable frequency distributions, and supporting graphs. Formal statistical inference is omitted, in part due to large sample features of the survey. Nevertheless, choices and emphases in describing data can easily color the reader's impression of what those data say about the larger population of drivers and their vehicle operation. The final section reviews a study of engine and catalyst temperature cooldown undertaken as part of the project.

5.1. Driving Behavior Variables

Despite longstanding recognition of the importance of mobile sources to air quality, surprisingly little research has been done on driving behavior. This report gives a preliminary, broad description of the current survey results while concentrating on those issues that pertain most to vehicle emissions and test drive cycle policy. The data collected for this report offer a rich source for future study of driving behavior. EPA anticipates that researchers in different fields, with other perspectives, skills, and computing resources, will contribute new understanding of the information contained in these data.

5.1.1. Speed-Based Measures of Driving Behavior

In planning the survey, EPA attempted to collect basic measures known or believed to explain vehicle emissions. As noted earlier, the most fundamental variable, vehicle speed, was recorded for each second that a vehicle's engine was running. These "time series" data have been used to derive two other key measures: acceleration and specific power.

Acceleration

Acceleration, the change in speed per unit time, is computed as the simple difference in two successive speed values. This calculation results in a missing value for acceleration at the start of each (engine on) trip. By its very nature, the distribution of acceleration is centered at zero and tends to be symmetric and unimodal. Thus, the mean and median are not useful for comparing two or more distributions. Average measures of dispersion, such as the standard deviation, help describe how a set of accelerations vary. Percentiles are useful for summarizing extreme levels of acceleration and deceleration.

The problem with analyzing the acceleration rate is that, by itself, it has dubious significance. For a given acceleration rate, the load placed on the engine increases with the vehicle speed. Thus, the most appropriate measure is the joint distribution of speed and acceleration. However, this requires three dimensions to display, making it harder to visualize. As a useful compromise, the joint distribution of speed and acceleration can be approximated with a measure of "power" to allow two-dimensional analysis. This is described below.

Specific Power

Specific power is defined as the per second change in the square of vehicle velocity during positive accelerations:

$$\text{specific power} = V_f^2 - V_i^2, \qquad V_f > V_i$$

where V_i and V_f are the initial and final velocity, respectively, in a one-second interval. Interest in this variable is motivated by the work of Watson, et. al.,[41] who introduce a measure called "positive acceleration kinetic energy change per unit distance," or PKE. In their work, it is presumed that fuel economy and emissions are proportional to PKE when measured jointly over a given trip. Thus, PKE is a cumulative measure of increases in kinetic energy over a fixed travel distance.

As used in this study, specific power is determined for each second of driving, unadjusted for distance traveled. It is closely related to per second speed and acceleration by simple multiplication:

$$\text{specific power} \approx 2 \times \text{speed} \times \text{acceleration}$$

(for acceleration greater than zero). Preliminary work by EPA suggests that, for explaining second-by-second emissions,

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[41]Watson, H.C., E.E.Milkins, M.O. Preston, C. Chittleborough and B. Alimoradian, "Predicting Fuel Consumption and Emissions-Transferring Chassis Dynamometer Results to Real Driving Conditions," SAE Technical Paper Series, 830435, 1983.

specific power performs better than either speed or acceleration alone (although the joint distribution of speed and acceleration is best). In conclusion, specific power appears to give a useful univariate composite measure of the more intuitive speed and acceleration variables.

5.1.2. Trip-based Measures

Trip-based analyses provide an alternative, summarized perspective of driving behavior. The concept of what constitutes a trip appears intuitively simple; however, a number of practical issues require some discussion. This section reviews features of the instrumented vehicle trip definition and describes the main concepts used in the trip-based analyses.

Trip Definition

The instrumented vehicle survey used engine on-engine off to define the beginning and end of a trip. In reviewing the initial trip data it became evident that this definition resulted in including vehicle stalls as separate trips. To exclude stalls, EPA directed the contractor to make a slight modification to the original definition. Using the time between trips, or soak time, apparent stalls were connected to the appropriate contiguous trip. As an example, a vehicle sits in the driveway all night and in the morning the car is started, but stalls after 5 seconds because it is cold. It then takes 15 seconds to start the car again and the driver leaves on a 10 minute trip. Using just engine on-engine off as the trip definition criteria would result in having the stall treated as a separate, 5-second trip. However, if one uses the criteria that if the time between trips is less than a certain number of seconds, then the "stall trip" would be combined with the following "real" trip. Using 18 seconds as the soak time threshold, the 5 second "stall trip" would be connected to the following 10 minute trip and the 15 second soak in-between would be added to make the total trip time equal to 10 minutes and 20 seconds.

The formal trip definition is:

$$\text{if } Soak_t \leq 18 \text{ then,}$$

$$\text{New trip} = Trip_{t-1} + Soak_t + Trip_t$$

The selection of 18 seconds as a soak time threshold is based on the distribution of in-use soak times and it is consistent with similar analyses contracted by AAMA and AIAM.

An additional modification to the trip data was made to insure a representative sample of trips. As discussed in Section 4.2, the vehicles in the survey were recruited and instrumented at centralized I/M stations. After installation and testing of the datalogger, the datalogger was placed in a "run" to begin collecting in-use driving data. However, on many occasions the vehicle was driven by the mechanic to the front of the I/M station and parked. At such time the vehicle was shut off and the keys were turned over to the customer. This trip was recorded as the first trip for the vehicle. A similar scenario could occur when the vehicle was returned. EPA felt such trips were not representative of in-use operation and should be deleted. To accomplish this task, I/M station trips at the beginning and end of a vehicle's trip file were identified and deleted using a distance threshold of 0.2 mile (1,056 feet). This resulted in an elimination of 55 trips in Spokane and 67 trips in Baltimore.

Vehicle Operating Mode Definitions

A common measure in trip-based analyses is the proportion of time spent in the four vehicle operating modes: cruise, acceleration, deceleration, and idle. In defining the modes, EPA started with a definition for cruise. Driving at a constant speed is what is typically thought of as a cruise. However, a vehicle's speed is rarely constant. For this report, the cruise mode is defined as a driving period at least three seconds long during which all acceleration and deceleration are of an average magnitude of 0.5 mph per second or less over two second intervals, with speeds measured at one second intervals. The definitions for acceleration, deceleration, and idle modes fall out of this cruise definition. Computationally, the four modes are defined as follows:

1. Find the average 2-second acceleration:

$$A_t = (S_{t+1} - S_{t-1})/2$$

where, S_t= vehicle speed at time t

2. Cruise: If A_{t-1}, A_t, and A_{t+1} are less than or equal to 0.5 mph/sec. in absolute value, and S_t is

greater than 1, then values for time t-1, t, and t+1 are classified as Cruise.

Acceleration: If $A_t > 0.5$ and $S_t > 1$, then values for time t is an acceleration.

Deceleration: If $A_t < -0.5$ and $S_t > 1$, then values for time t is an deceleration.

Idle: If the value for time t does not meet the conditions for cruise, acceleration, or deceleration it is classified as idle. This definition of idle includes some non-zero speed driving and, thus, differs slightly from the idle definition used in the speed/acceleration sections of this report.

Stop Mode Definition

The number of stops per trip or the distance between stops is another commonly used trip measure. A stop at a traffic light or stop sign typically involves the vehicle' speed going to zero, but this is not always true, as in the case of "rolling stops." For this report, the stop mode is defined as beginning when the vehicle slows from above 10 mph to below 4 mph. The stop concludes when the vehicle's speed exceeds 4 mph, conditional on the speed exceeding 10 mph without falling below 4 mph. This definition allows for a "creep" mode within the stop mode.

5.1.3. Vehicle-Based Measures

An alternative measurement unit for describing driving behavior is the vehicle that generates the speed and trip patterns discussed previously. Vehicle-based measures are needed to judge the representativeness of the vehicle sample and for analyzing various vehicle factors that may influence driving behavior. Because this view of the data is less important to emission test cycle development than the speed- and trip-based measures, its discussion in this report is comparatively limited.

The final Baltimore and Spokane 3-parameter samples contained a total of 168 vehicles, by no means an extremely large sample. In the analyses presented in Chapter 6. The following variables measured for each vehicle are reviewed:

* Miles driven per day
* Number of trips per day
* Number of stops per hour of operation
* Number of minutes of operation per day

These and other vehicle-based variables are derived from the speed-time data or from trip-based variables constructed from those data.

5.2. Descriptive Methods

Summary statistics developed from the raw data are intended to paint a basic picture of in-use driving and to distill the large mass of detail into forms that are readily managed in searching for important and/or unexpected patterns. Standard arithmetic measures include a variable's mean, standard deviation, minimum, maximum, and count. Distributions of frequency, both percentage and cumulative percentage, furnish additional detail, along with the joint distribution of speed and acceleration. These also provide the basis for approximating distribution percentiles, such as the median. Two and three dimensional graphs of the distributions give a visual image of variation patterns.

For reasons discussed in Section 5.4, exact percentile calculations of speed-related data are not part of the standard measures generated for this report. These values can be approximated by interpolation from the frequency distribution of a given variable. The median, a widely used measure of central tendency, equals the 50th percentile of a distribution. The median usually is preferred to the mean (average) when describing data that are distributed highly asymmetrically, or skewed. Unlike the mean, it is unaffected by the tail values and outliers of the distribution and, thus, is more representative of the central mass of data. Of the three speed-related variables, specific power exhibits large positive skewness; speed data typically display more modest positive skewness; and acceleration data show little or no skewness. Therefore, in the analyses of Chapter 6, both mean and median often are reported for the specific power and speed variables. The distributions of several trip variables, such as trip time and distance, also tend to be skewed.

One of the principal goals of this study is to identify the presence of "aggressive" driving behavior patterns that may account for disproportionately high levels of vehicle emissions. While there is no commonly accepted measure of driving aggressiveness, it is generally accepted that this condition corresponds to high speed and/or acceleration levels. It follows that high levels of specific power also characterize aggressive driving. For all three variables, then, the upper percentiles, or "tails," of the frequency distribution provide a useful measure of this important driving feature.

"Tail" percentages corresponding to selected values of the measured variable are used to describe and compare driving aggressiveness patterns. For example, it was found that in the 3-parameter Baltimore sample, 2.61 percent of driving time is spent at speeds greater than 65 miles per hour. This is equivalent to saying that the 97.39th percentile of the speed distribution is 65 mph.

Note that percentiles associated with the distribution of specific power are based only on those data for which that variable is defined: during positive acceleration. This constitutes less than half of all driving time. In discussions of this variable, percentiles sometimes are also re-expressed in terms of the total of all driving time.

5.3. Statistical Accuracy

In describing and comparing results, it is important to recognize the basic unit that generates a particular measure. The "finest" unit of interest is the one-second period of time during which a vehicle's speed and other characteristics were recorded. These data form the basis for other variables aggregated by individual trip (engine-on to engine-off) and by vehicle.

Of course, a large volume of second-by-second data were obtained from the Spokane and Baltimore instrumented vehicle study: over 5.4 million observations for the 3-parameter vehicles alone. Such a large sample virtually guarantees that observed values give very accurate estimates of the true population measures that they represent. Questions about sampling error arise from the vehicle and trip sample sizes. For the Baltimore and Spokane 3-parameter vehicles, some 8,459 trip observations were made on 168 vehicles. Other potential problems involve nonsampling sources: the representativeness of the vehicle sample and the manner in which the vehicles were driven during instrumentation. These issues were addressed earlier in the discussion of possible bias sources.

In this report, primary attention is given to per-second and per-trip driving behavior measures because these bear directly on emission test cycle development. Driving measures based on the vehicle unit are reviewed cursorily.

5.4. Computer Resource Issues

Analysis of the instrumented vehicle speed data presents a substantial challenge to the management of computer resources. Routine statistical computations on the large data set collected in the study call for efficient, high-speed processing. At the same time, the unique nature of the problems and their analyses requires considerable application of non-routine exploratory techniques, which tend to be relatively inefficient.

EPA approached these issues by combining private contractor and Agency resources in order to draw on the strengths of both. At the contractor level, processing of the raw data on mainframe computers reduced the data to the level of "sufficient" statistics: means, standard deviations, frequency distributions, and other potentially useful descriptive measures. These outputs were then studied in more ad hoc fashion by Agency staff working on personal computers.

Resolving these resource concerns necessarily involved certain compromises in terms of analytical methodology. For example, exact calculation of some common descriptive statistics, such as the median and other quantiles (percentiles), is very computer-intensive. In most cases, these are excluded from the current analysis or are approximated from other summary results. In general, stratification of speed, acceleration, and specific power across two or more factors also are excluded.

5.5. Driving Conditions

The speed, trip, and vehicle-based measures discussed previously describe driving behavior over which the vehicle operator exercises more or less conscious control. The typical driver is less conscious of two other factors known to influence emissions: engine and catalyst temperature and road grade. As part of this study, EPA investigated the temperature issue in some depth. Road grade requires additional effort.

5.5.1. Engine and Catalyst Cooldown

In order to predict the effect of engine and catalyst temperature on emissions, it is necessary to estimate the proportion of time these vehicle systems spend at different temperature levels. Those levels are essentially constant after the vehicle is driven for a certain period. However, at engine start-up, engine and catalyst temperatures vary as a function of several factors, including the length of the preceding soak.

Starting temperatures decrease with soak time. Knowledge of the rate of these temperature drops, combined with the distribution of soak times, enables estimation of the distribution of start-up temperatures in-use. When this is further combined with information on emission-temperature relations, a picture of overall emissions during start-up emerges.

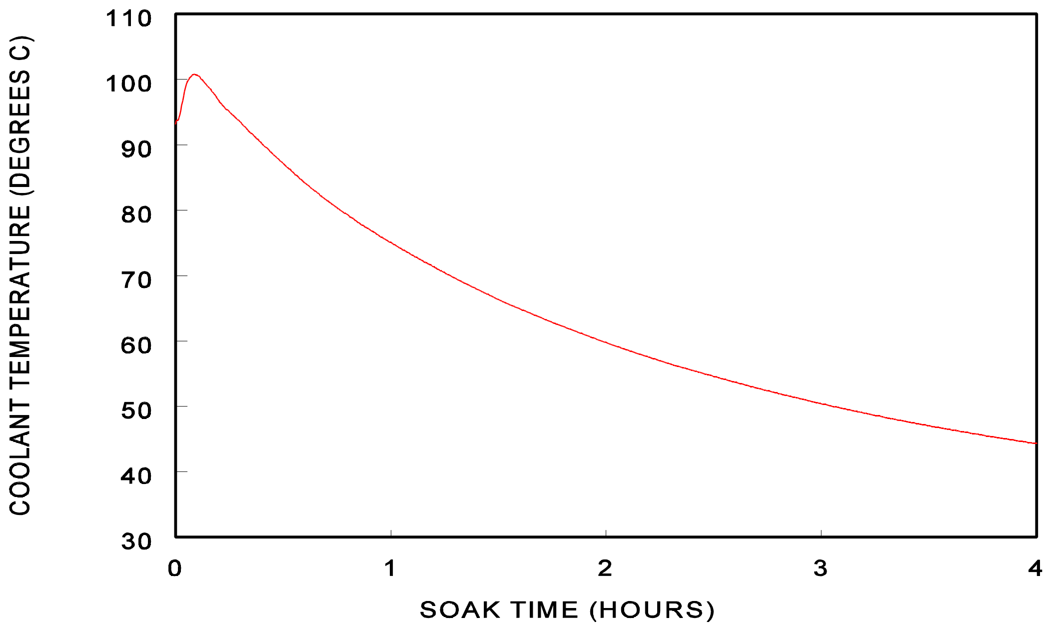
New Research

This section describes research into cooldown rates described above. In August, 1991, EPA entered into a cooperative agreement with the New York State Bureau of Air Research to obtain test data and analysis of the engine and catalyst cooldown processes and factors affecting the cooldown rates. Researchers at the Bureau's Albany Emissions Laboratory (AEL) performed a series of forty tests on six different vehicles. In each test, the vehicle was driven under actual road conditions until the engine and catalyst temperature were stabilized, typically for a period of about thirty minutes. The engine was then turned off to begin a soak, which varied from 2 to 10 hours. Throughout each test, component temperatures and other variables were recorded at intervals of fifteen seconds.

Figures 5-1 and 5-2 display measured temperature for engine coolant and catalyst, respectively, for one such test. After the engine has been turned off the engine coolant continues to rise for several minutes before beginning its decline toward ambient; catalyst temperatures begin the descent immediately.

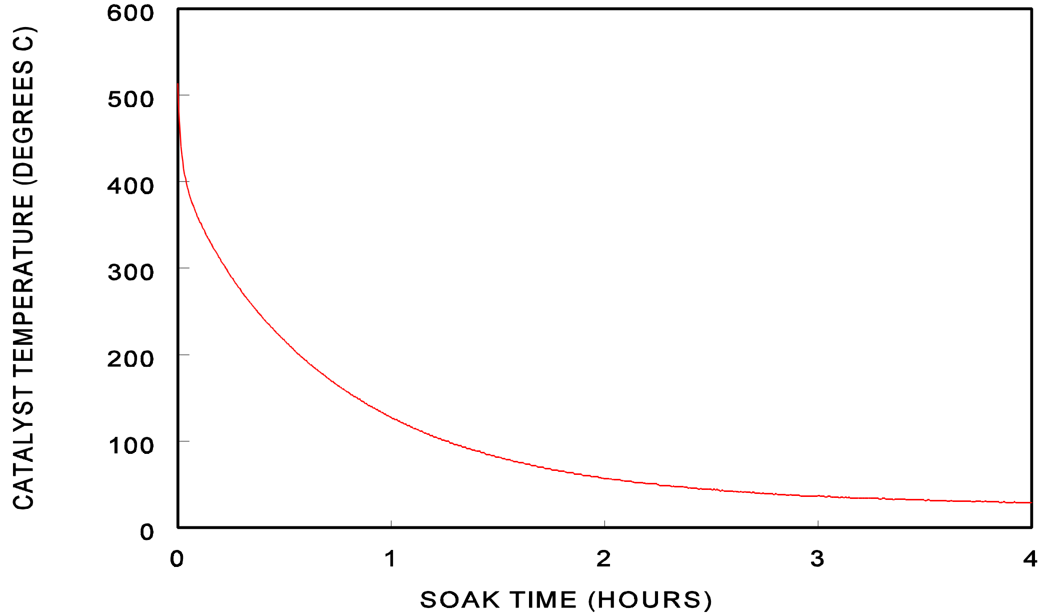
The goal of this study was to construct functions of engine coolant and catalyst temperature versus soak time. AEL researchers attempted to account for several vehicle and environmental factors expected to influence these functions, including engine size, ambient air temperature, wind speed, and pavement condition (wet or dry). In a quasi-experimental design, these factors were varied in an effort to fit a response surface

Figure 5-1
Plymouth Acclaim Engine Cooldown Curve



over a reasonable range of operating conditions.

Figure 5-2
Plymouth Acclaim Catalyst Cooldown Curve



Results

In a series of progress reports, AEL researchers adopted a two-stage approach to the problem of temperature prediction. The first step was to fit component temperature as a nonlinear function of soak time for each of the tests. This produced a set of equation coefficients that varied across tests. In the second step, these coefficients were regressed against the vehicle and environmental variables to enable prediction of the coefficients for any prespecified values of those variables.

Proposed forms for the engine coolant and catalyst temperature-time functions were based on known physical properties. Both are exponential functions of the form:

$$\text{Temperature} = K*\exp\{ß*\text{soaktime}\} + C$$

where K, ß, and C are constants for a given set of vehicle and environmental factors. In general, ß must be negative in order for temperature to decrease as soaktime increases. Using linear regression, the relations between the fitted coefficients and the vehicle and environmental variables were estimated in equations of the form:

$$\text{Coefficient} = b_0 + b_1*(\text{engine size}) + b_2*(\text{ambient temp}) + b_3*(\text{wind speed}) + b_4*(\text{pavement condition})$$

In validating the AEL coolant analysis, EPA applied this method to the 6-parameter data from the Baltimore and Spokane studies. The 6-parameter vehicles were instrumented to record engine coolant temperature (but not catalyst temperature). A data file was created with values for soak time and for coolant and ambient temperature at start and end of trip. While these data were generated in uncontrolled experimental conditions, they produced temperature-time equation fits similar to those of the AEL experiments.

In adapting the AEL results for application to the survey driving data, EPA considered several modifications of the AEL equations to better conform with the requirements of the current study. For the engine coolant formulas, this review failed to produce an appreciable improvement and the AEL equations were left intact for subsequent analyses. For several reasons, the catalyst equations were altered to some degree.

It was learned that one of the test vehicles, an Oldsmobile Cutlass, was equipped with a pelletized catalyst, an obsolete technology. It was therefore decided to delete from consideration the 10 tests performed on this vehicle. In addition, catalyst cooldown for the single truck, a Ford Ranger used for 11 tests, behaved very differently than in the cars. These tests were analyzed separately.

The final equations are used in Chapter 6 to help assess the impact on vehicle emissions of cold start driving behavior. They have the following form (t equals soak time):

$$\text{Engine Coolant Temperature} = k \cdot \exp\{\beta \cdot |t-\tau|\} + C$$

where

$$k = -\,0.6221 \cdot (\text{Average Ambient Temp}) - 0.0237 \cdot (\text{Pavement}) - 0.0058 \cdot (\text{Number of Cylinders}) + 0.9695$$

$$\beta = -\,0.0179 \cdot (\text{Average Wind Speed}) + 0.0394 \cdot (\text{Number of Cylinders}) - 0.7058$$

$$\tau = 0.1097$$

$$C = 0.9660 \cdot (\text{Average Ambient Temp}) + 0.0582$$

$$\text{Catalyst Temperature} = k_1 * \exp\{-4*t\} + k_2 * \exp\{ß*t\} + C$$

where

$$ß = 1.6269*(\text{Average Ambient Temp}) - 0.1588*(\text{Average Wind Speed}) + 0.2486*(\text{Number of Cylinders}) - 3.0453$$

$$k_1 = 0.5224$$

$$k_2 = 1.2482$$

5.5.2. Road Grade

As mentioned previously, the road gradient data collected through the chase car study may be of questionable value due to potential inaccuracies introduced by a variety of sources. Consequently, the Agency is currently not in a position to present data with respect to the distribution of road gradients in Baltimore. A 1980 EPA report to Congress summarized some U.S. Department of Transportation (DOT) data on the nationwide distribution of road gradient by the percent of vehicle-miles traveled (VMT) (See Table 5-1).[42] From these data it is also possible to calculate a nationwide VMT-weighted average for road gradient of 1.6 percent. Even though over time the mileage up will equal the mileage down, the response of vehicle emissions to road gradient is nonlinear and the increased emissions due to an increased load on an upgrade will not be compensated for by the decreased load experienced on an equal downgrade.

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[42] U.S. Environmental Protection Agency. "Passenger Car Fuel Economy: EPA and Road." Report No. EPA 460/3-80-010, September 1980, p.119.

Table 5-1

Road Gradient Distribution
by Percentage of Vehicle-Miles Traveled
(Miles Traveled Up = Miles Traveled Down)

Road Gradient (%)	**Percent of VMT**
< 0.5	35
0.5 - 1	20
1 - 2	15
2 - 3	10
3 - 4	8
4 - 5	6
5 - 6	4
> 6	2

Chapter 6. Discussion and Analysis of Driving Survey Results

This chapter provides a brief summary of the results obtained from driving surveys in all four cities: Baltimore, Spokane, Atlanta, and Los Angeles. A detailed discussion follows of the Baltimore survey results; EPA feels that Baltimore results are the most representative at this point. The chapter concludes with comparisons between the FTP and the Baltimore results.

6.1. Summary of In-Use Driving Results for Four Cities

The four cities for which driving patterns data were collected serve as the basis for EPA's study of urban, in-use driving behavior. In looking at the results, it is important to keep in mind that differences among cities are attributable to not only driver behavior differences, but also to transportation network differences, in terms of both the road network configuration and usage. The road network can be thought of as the driving environment faced by each driver and, as such, it can have a significant impact on driving behavior.

6.1.1. Driving Behavior - Second-by-Second Analysis

Table 6-1 provides summary measures of speed, acceleration, power, and several trip measures for each city. As discussed in Section 4.3.3, the chase car data for Los Angeles are not directly comparable with the data for the other cities; however, certain qualitative evaluations are still valid across cities.

Table 6-1

Comparison of Driving Behavior for Four Cities

Driving Behavior Measure	Baltimore			Spokane	Atlanta	Los Angeles
	Both sites	Exeter	Rossville			
Speed (mph)						
Average	24.50	20.90	28.11	23.24	28.80	28.35
Maximum	94.46	83.72	94.46	77.55	96.48	80.30
Standard deviation	20.52	18.47	21.80	17.71	22.60	20.15
Number of seconds	3,365,504	1,686,890	1,678,614	2,081,199	3,010,672	99,729
Acceleration (mph/sec.)						
Minimum	-19.49	-13.31	-19.49	-15.46	-18.62	-15.00
Maximum	15.19	15.19	14.65	15.95	16.69	10.41
Standard deviation	1.50	1.54	1.46	1.46	1.53	1.74
Number of seconds	3,360,550	1,684,228	1,676,322	2,077,008	3,006,675	99,625
Power (mph^2/sec.)						
Average	46.02	45.38	46.62	40.14	51.72	58.97
Maximum	557.69	557.69	479.82	672.28	723.12	769.10
Standard deviation	42.96	41.51	44.29	40.82	48.11	49.11
Number of seconds	1,407,908	686,347	721,561	880,258	1,318,072	45,251
Average trip length (miles)	4.89	3.99	5.89	3.56	6.04	7.78
Average trip time (minutes)	12.03	11.55	12.56	9.18	12.59	16.45

Average distance b/w stops	0.87	0.64	1.13	0.81	1.09	1.26
Percent idle operation	21.12	23.91	18.32	17.91	17.38	11.78

Speed

Atlanta had the highest average speed among the four cities, followed by Los Angeles, Baltimore, and Spokane. A look at the frequency distribution of speed affords a more interesting picture of driving behavior. Figure 6-1 compares the distribution of speeds for the four cities. The cities share a characteristic tri-modal distribution. The first mode, at idle, is similar for three of the cities: 17 percent for Atlanta, 18 percent for Spokane, and 21 percent for Baltimore. The low percentage of idle in Los Angeles, at 12 percent, is likely due to the chase car survey methodology which excludes trip ends information (see Section 4.3.1).

In Spokane, a second mode is very obvious for speeds between 30 and 35 mph. For Los Angeles and Baltimore this mid-speed mode is less significant; it is actually shifted out to 35 to 45 mph speed range for Atlanta. A third mode at 55 to 60 mph is distinct for Baltimore and Spokane; Los Angeles and Atlanta also have a slight mode at 60 to 65 mph. In both cases, this third mode is indicative of freeway operation.

Acceleration

As presented in Table 6-1, there are not large differences in the summary acceleration measures for the four cities. In addition, the analytical importance of acceleration rates is limited (see discussion in Section 5.1.1.).

Specific Power

The power term serves to combine speed and acceleration into a single variable, as discussed in Section 5.1.1. The average specific power was highest for Los Angeles (58.97 mph^2/sec) and

Figure 6-1
Distribution of Speed
Baltimore, Spokane, Los Angeles, Atlanta

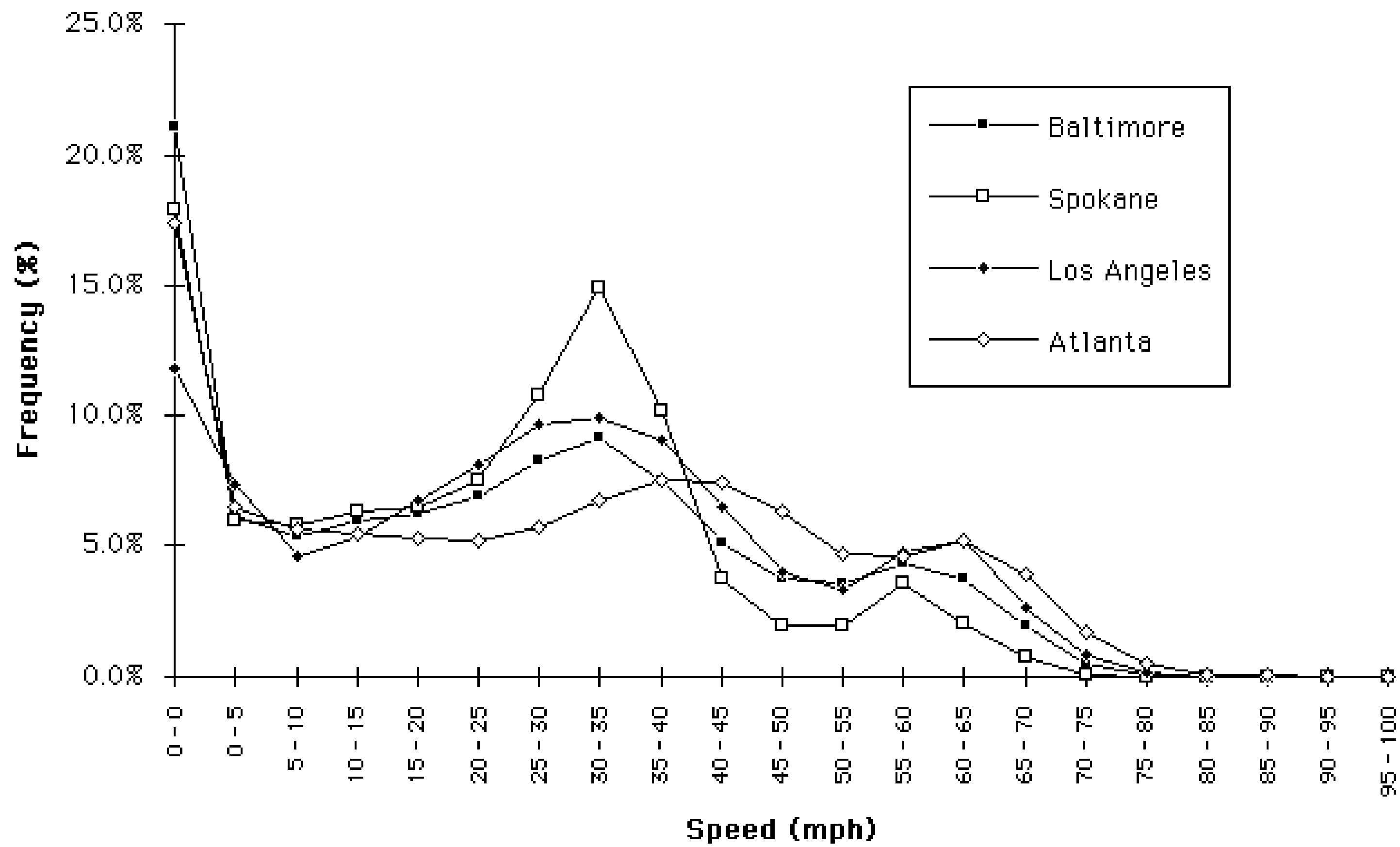
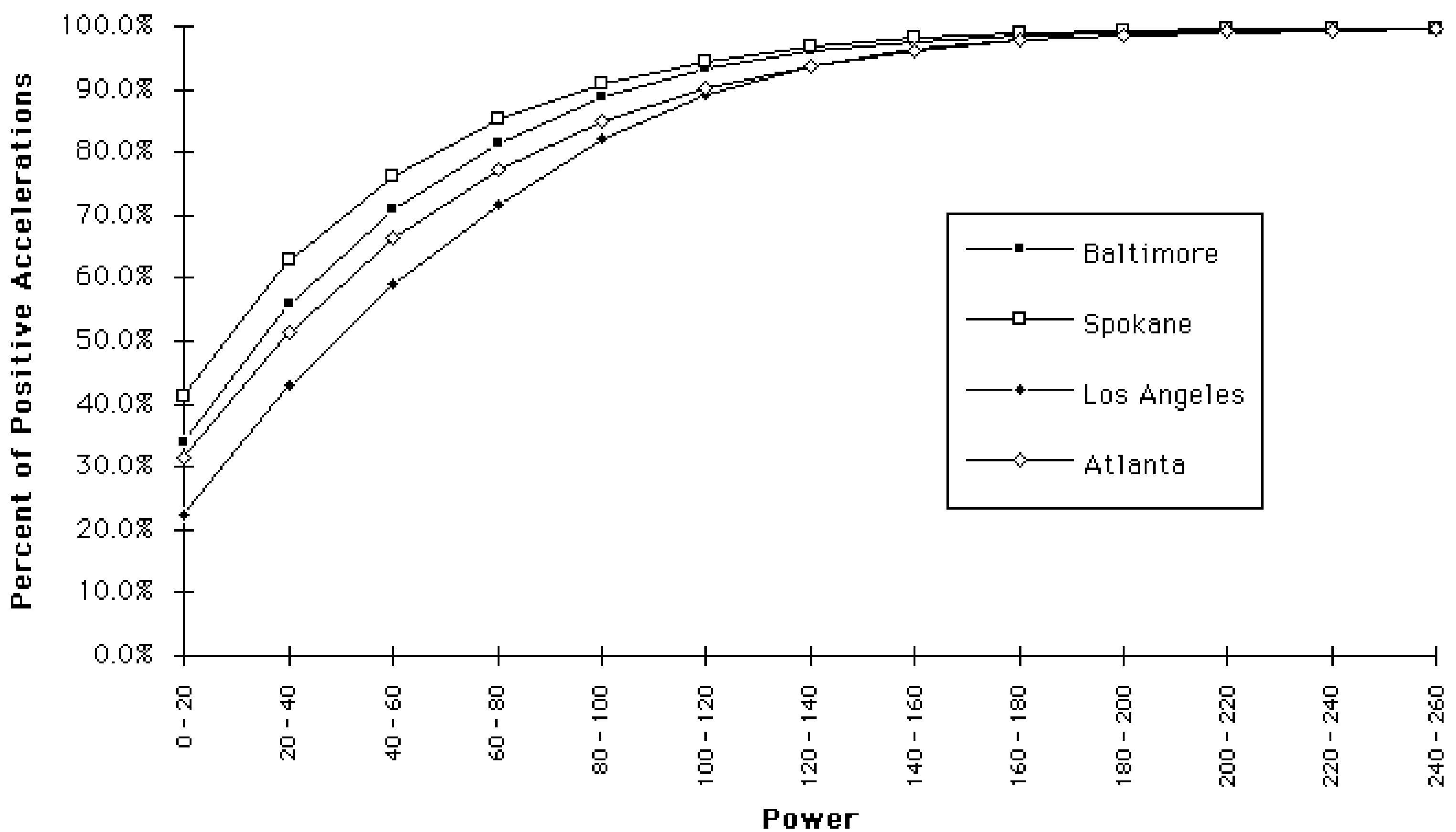


Figure 6-2
Distribution of Power
Baltimore, Spokane, Los Angeles, Atlanta



Atlanta (51.72 mph^2/sec), and lowest in Spokane (40.14 mph^2/sec). Baltimore's average power, 46.02 mph^2/sec, placed it in the middle.

Figure 6-2 presents the frequency distribution for specific power for the four cities. Since power is calculated only for positive values of acceleration (see Section 5.1.1), the power distributions are based on total number of seconds of positive acceleration (1,407,908 seconds out of 3,365,504 seconds of total vehicle operating time, or 42 percent). Differences in the frequency distribution of the power value across cities gives an indication of the varying "intensity" of driving in the four cities. For example, 63 percent of driving time in Spokane occurred with power values less than or equal to 40--such power values correspond to low speed and near-cruise driving. In contrast, only 44 percent of power values in Los Angeles were 40 or less. The corresponding percentages for Atlanta and Baltimore were 52 and 57 percent, respectively.

The upper tail of the power distribution is of particular interest, as it may be the best single measure of aggressive driving. The percentage of specific power values greater than 200 is highest for Los Angeles (1.5 %); Atlanta, with 1.25 percent, was next, followed by Baltimore (0.77%) and Spokane (0.57%).

6.1.2. Driving Behavior - Trip Analysis

Speed, acceleration, and power measure driving behavior on a second-by-second basis. Alternatively, driving behavior can be examined over a more extended period of time. Trip-based measures summarize driving behavior from the time the vehicle is started until it is turned off-again.

Overall, trip measures for the four cities show an ordering of the cities similar to that found for the speed and acceleration measures (these are also in Table 6-1). The average trip length in Spokane was 3.56 miles while Baltimore's average trip distance was 4.89 miles and Atlanta's was 6.04 miles. Not surprisingly, trip durations reiterate this pattern with trips averaging about 9 minutes, 12 minutes and 13 minutes in Spokane, Baltimore, and Atlanta, respectively. The Los Angeles trip measures were considerably longer than the other cities. The average L.A. trip covered 7.78 miles in about 16 minutes. It is likely that these long trips can be attributed in large measure to methodological differences between the chase car and instrumented vehicles approaches (see Section 4.5.1).

6.1.3. Choosing Representative Survey Data

The analysis of in-use driving behavior requires a more detailed examination than provided by the summary statistics described previously. For this preliminary report, the 3-parameter instrumented vehicle data from Baltimore and Spokane are the only practical candidates for such analysis, as discussed in Section 4.5.2. However, the summary statistics presented in the previous section suggest a certain uniqueness to Spokane driving patterns relative to the other three cities. This calls into question Spokane's appropriateness for representing other ozone nonattainment areas. The discussion following outlines features of Baltimore's instrumented vehicle data which make it the best candidate for representing ozone nonattainment areas in this preliminary technical report on in-use driving behavior.

As discussed in Section 4.2.1, the Baltimore data can be categorized according to the I/M stations from which the vehicles were recruited. The Exeter station is located in the central part of Baltimore. In contrast, the Rossville station is in a suburban location. A comparison of the driving behavior from the two sites gives a view of urban/suburban driving differences. The assumption is made that vehicles recruited in a suburban site will have a tendency to be driven primarily in an suburban environment, likewise for the urban-station vehicles.

The average speed for Exeter (urban) was much lower than Rossville (suburban), 20.90 mph and 28.11 mph, respectively. The average trip length was 3.99 miles for Exeter compared to 5.89 for Rossville. These differences are consistent with expectations of suburban and urban driving patterns; higher speeds and longer trips are presumed for a suburban road network with a large percentage of freeways and extensive land-use patterns.

After taking this disaggregated view of Baltimore, driving patterns for the Exeter station turn out to be similar to those found in Spokane, and the Rossville station's driving behavior is very consistent with that found in Atlanta. Figure 6-3 compares the speed distribution of vehicles from the Baltimore-Exeter station to Spokane and Figure 6-4 compares Baltimore-Rossville with Atlanta. Furthermore, the average trip length for Baltimore-Exeter is similar to that in Spokane, 3.99 miles vs. 3.56 miles. Baltimore-Rossville and Atlanta also have very close mean trip lengths of 5.89 miles and 6.04 miles, respectively. Thus, it appears that Spokane driving most closely represents driving patterns found in a urban, central city location, while failing to capture the suburban driving patterns common in many of the major metropolitan areas.

Figure 6-3
Distribution of Speed
Baltimore-Exeter and Spokane

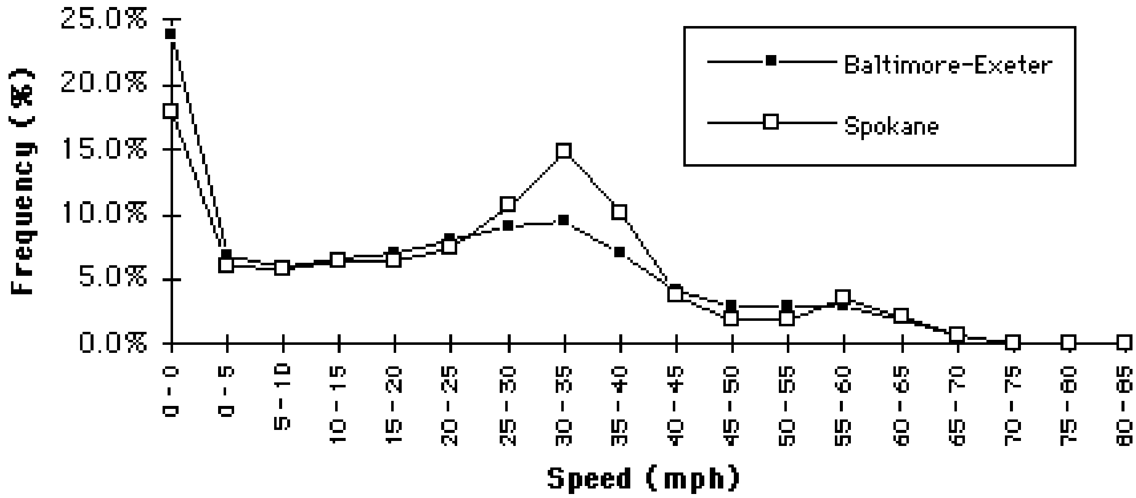
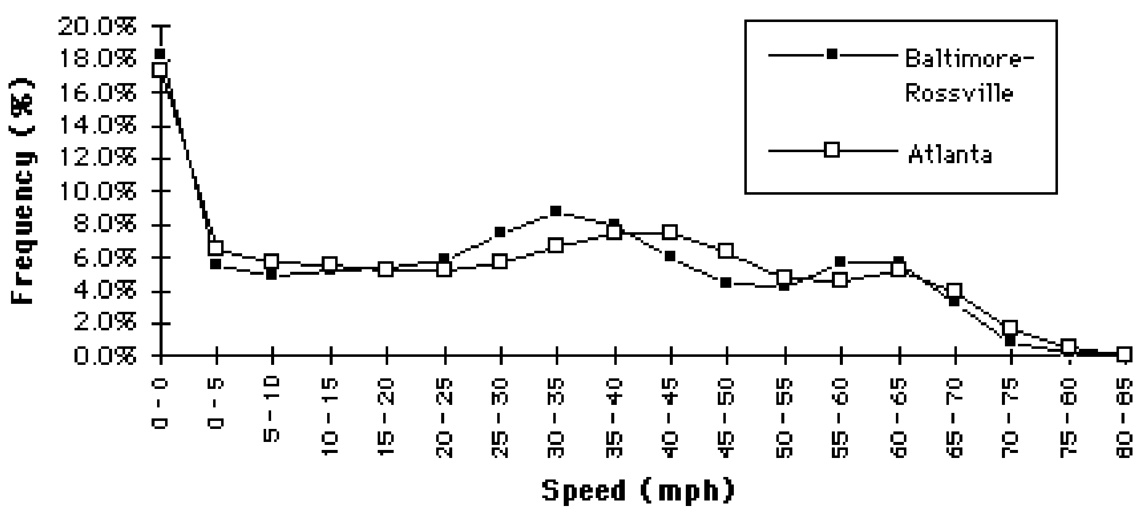


Figure 6-4
Distribution of Speed
Baltimore-Rossville and Atlanta



The driving behavior differences described for Spokane and the other cities have many potential explanations. One compelling explanation is the differences in the configuration and utilization of the road network. For example, the Spokane road network is much smaller than Baltimore's. Spokane has only one east-west freeway and a handful of principal arterials. In contrast, Baltimore has an extensive and diverse road-network system. Data from the chase car study can be used to gather some insight into the differences in the road-network systems of Spokane and Baltimore. Table 6-2 shows the fraction of chase car operation time by road type. The Baltimore chase car data contain a much larger fraction of freeway operation than the Spokane data, 18.9 percent vs. 11.2 percent. Almost 80 percent of Spokane driving took place on arterials and collectors compared to 64 percent of total driving time in Baltimore.

Table 6-2

Comparison of Road Type Distribution for Baltimore and Spokane

Road Type	Baltimore		Spokane	
	Number of seconds	Percent of total driving	Number of seconds	Percent of total driving
Private	2,407	1.26	1,571	0.90
Local	22,932	12.00	12,678	7.24
Arterial/ Collector	122,156	63.92	138,249	78.94
Freeway	36,113	18.90	19,592	11.19
Ramp	7,382	3.86	3,047	1.74
Carpool lane	3	0.00	0	0
Other	126	0.07	0	0
Total	191,119	100.00	175,137	100.00

Based on the these factors, EPA feels that it is inappropriate to use a combined Spokane and Baltimore data set to represent urban in-use driving behavior. A more accurate representation can be made analyzing Baltimore separately. (Adding Atlanta to the Spokane and Baltimore data set might be even better, but as the Atlanta data are not yet available for detailed analyses, this is currently not a viable option.) The similarity between Spokane and the Baltimore-Exeter station ensure that Spokane-type driving is included, and the Baltimore-Rossville data helps to capture the type of driving which is more consistent with that seen in Atlanta and Los Angeles. Thus, the remainder of the driving behavior analysis will focus on just Baltimore driving patterns. (One exception is the trip start activity section; all instrumented vehicle data are used.) We expect future analyses of the instrumented vehicle data will include Spokane and Atlanta.

6.2. Analysis of Baltimore Driving Conditions

The comparison of driving across four cities gave several descriptive measures of Baltimore driving behavior. This section provides additional detail on overall patterns found in the 3-parameter instrumented vehicles sampled in that city, along with comparisons of driving over the levels of several factors likely to influence behavior. The 93 vehicles and some of their characteristics are listed in Appendix B.

6.2.1. Speed-based Measures of Driving Behavior

The speed, acceleration, and specific power variables form the basis for analyzing second-to-second driving behavior. Methods of analyzing data for these variables were discussed in Chapter Five. It is useful to consider these variables in absolute terms and in comparisons across the levels of driving determinants that influence driving behavior.

Overall Driving Behavior

In discussing overall speed-based descriptive measures for Baltimore, two data sets are useful: the complete three-parameter second-by-second sample, and the subset of these data for non-zero speeds corresponding to that portion of operation when the vehicle is moving. In Appendix C, Tables C-1 to C-4 and Figures C-1 to C-3 provide summary statistics, distributions, and graphs for speed, acceleration and specific power of the Baltimore data for the full and vehicle-moving sets. After removing idle-mode data, average speed rises from 24.50 mph to 31.06 mph. The median speed is less affected by extreme values, and thus is smaller in the positively skewed speed distribution. For Baltimore, the approximate median is 23.70 mph for all driving, and 30.25 mph for non-idle driving.

Speeds ranged to nearly 95 miles per hour; 2.61% of total driving time, and 3.30% of time while moving, were spent over 65 mph. Accelerations varied from about -20 to +15 mph per second; 4.25% of driving time is spent in decelerations below -3 mph/sec (5.18% of non-idle); 3.17% of the time is positive accelerations above +3 mph/sec (4.03% of non-idle); the remaining 92.58% (90.79% non-idle) of driving time lies between -3 and +3 mph/sec.

The distribution graphs reflect driving time-in-mode patterns quite typical of vehicle second-by-second data. The tri-modal speed distribution was commented on earlier. Accelerations exhibit a standard unimodal pattern around zero. Cumulative graphs of acceleration are used in this report because they tend to draw a clearer distinction between two or more distributions.

The less intuitive specific power is a multiplicative composite of speed and acceleration. Mean and median specific power are 46.02 mph^2/sec and 34.69 mph^2/sec. Appendix Figure C-3 shows the cumulative distribution of specific power for Baltimore. (Because it is defined only for positive acceleration, there is no comparable distribution that includes the idle mode.) The distribution of specific power is highly skewed, reflecting the joint tailing off of speed and acceleration. As with acceleration, the cumulative graph presents a more useful picture of the specific power distribution; this form is used throughout this section. Of all driving time, 0.22% is spent at specific power above 200 (0.77% of driving in the positive acceleration mode).

The joint distribution of speed and acceleration describes the percentage of driving time spent in different modes. It's importance to emissions is discussed in Chapter 5. Appendix Table C-5 gives this distribution for the entire Baltimore 3-parameter data set. Figure 6-5 presents a three dimensional view of this distribution. This surface graph is characteristic of such data, with a large spike at zero speed and acceleration (idle mode) and a ridge of varying height corresponding to the speed pattern observed earlier. In Figure 6-6, the same data are portrayed with the idle portion of driving removed. This better contrasts the speed-acceleration pattern of distribution during non-idle operation.

A second way of visualizing the interaction between speed and acceleration is to compare the "conditional" distributions of acceleration at different speed levels. Figure 6-7 presents this comparison for several speed categories. Each distribution corresponds to a specific row in the speed-acceleration matrix of

Appendix Table C-5. These are essentially cross-sectional views of acceleration-frequency plane from the speed-acceleration surface distribution. They reveal the pattern of relatively low

Figure 6-5

Distribution of Speed and Acceleration - Baltimore

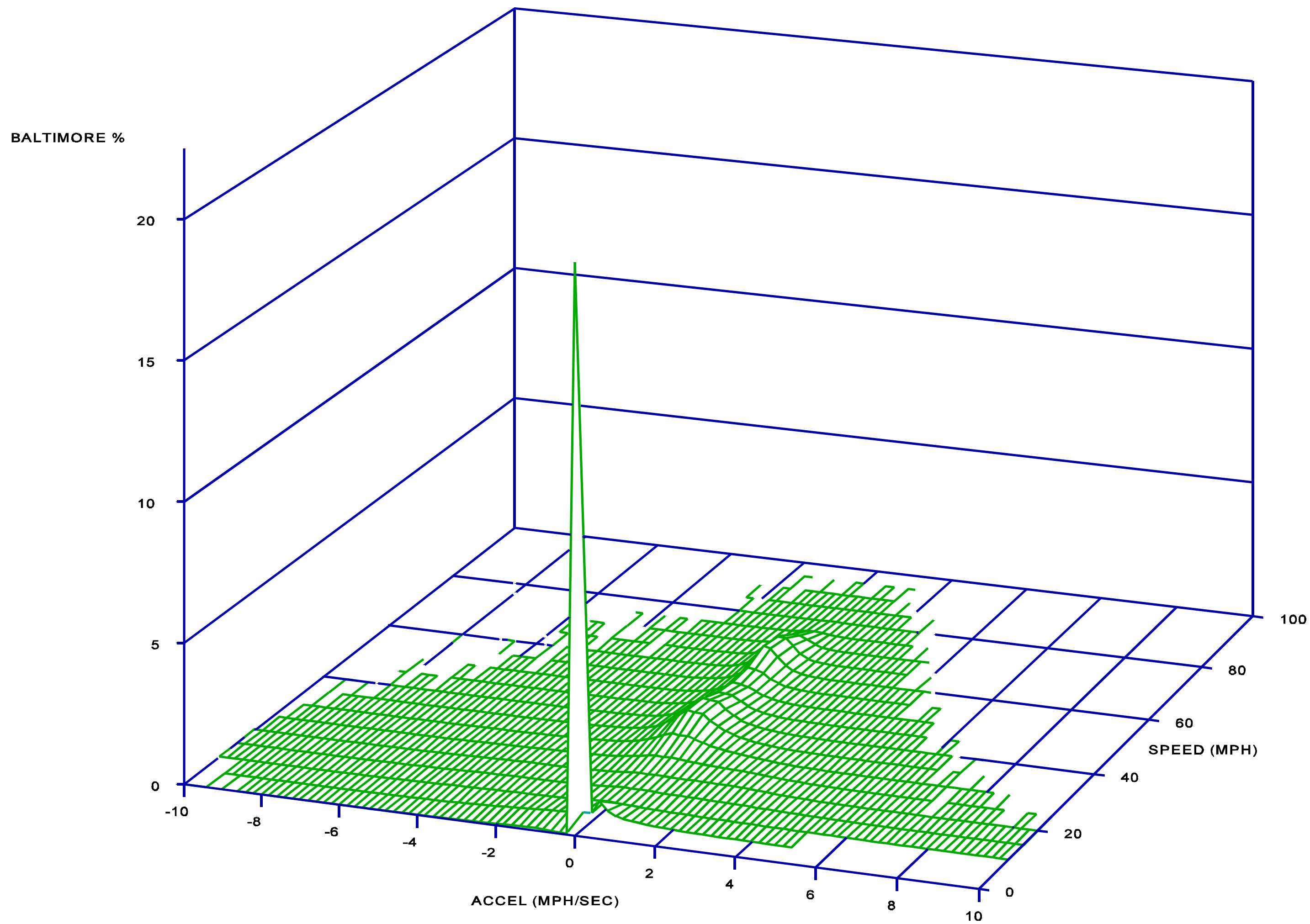


Figure 6-6

Distribution of Speed and Acceleration - Baltimore
Idle Excluded

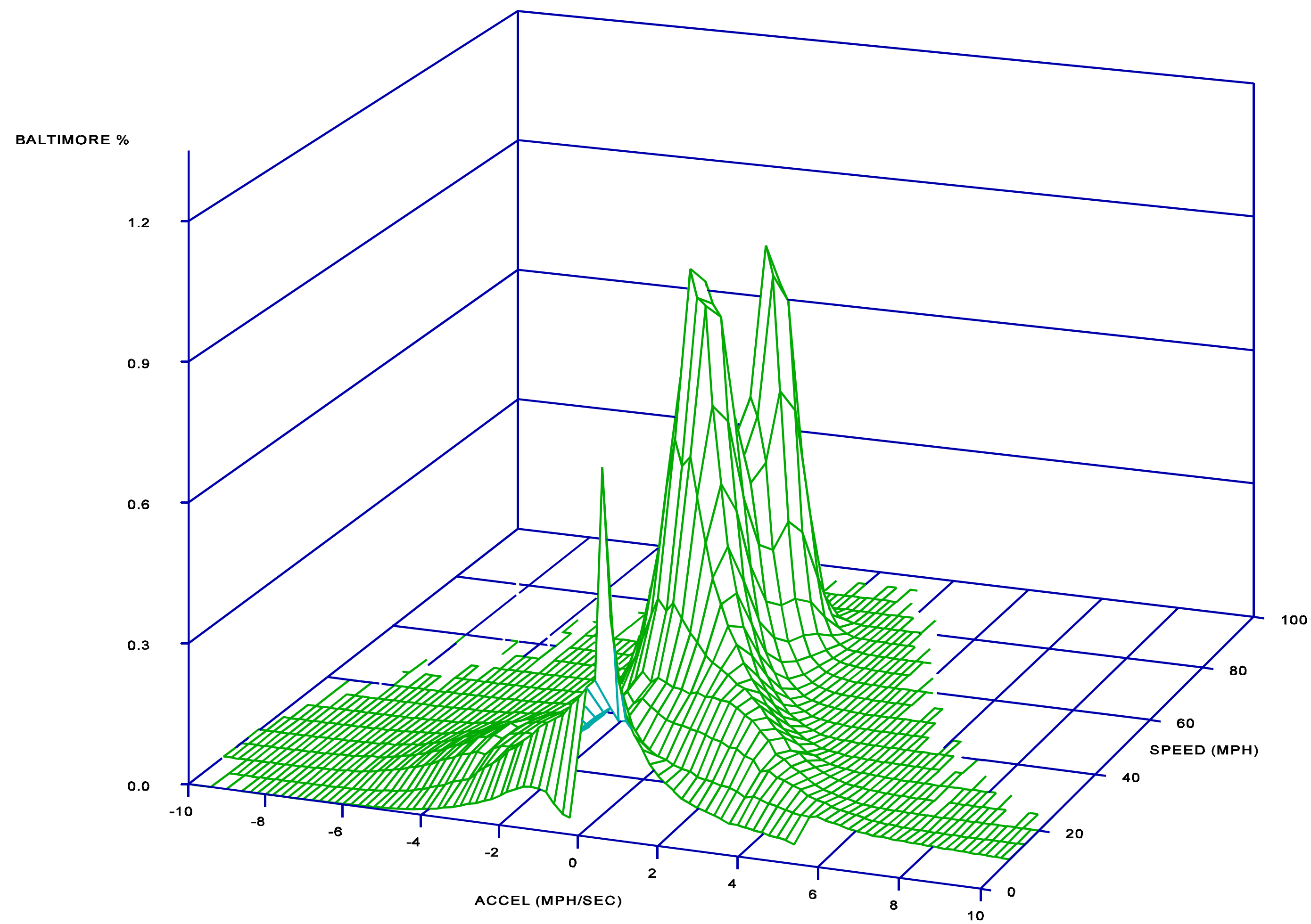
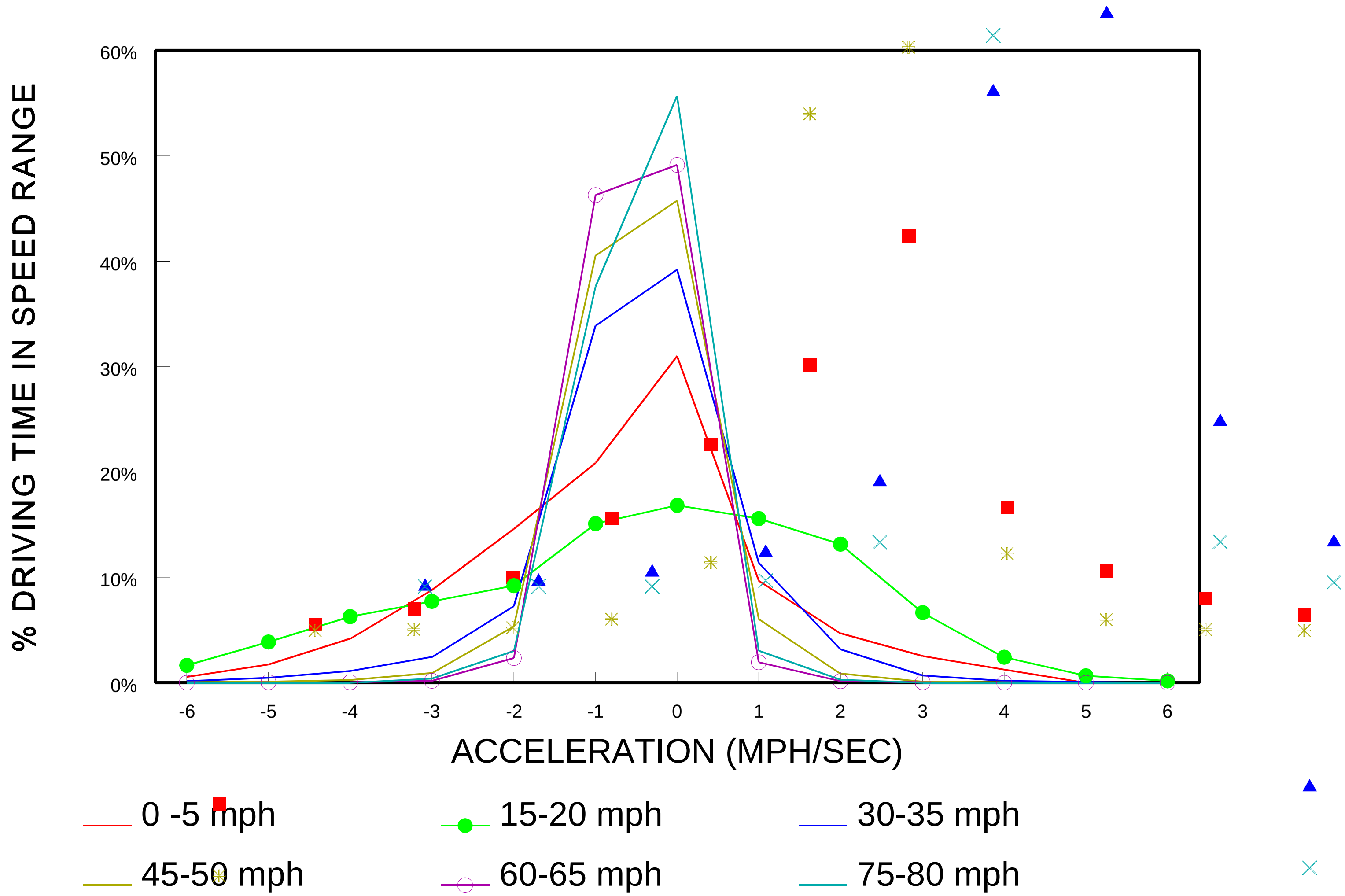


Figure 6-7

Conditional Distributions of Acceleration
Baltimore 3-Parameter Vehicles



variation in acceleration at both low and high speeds, where speed changes are physically or legally constrained.

Driving Behavior Determinants/Factors

While a number of factors are known to influence individual driver behavior, the survey conducted for the current study obtained only limited information on such factors. In particular, no data were collected on driver demographics. Some vehicle characteristic information was identified, and other variables relating to time of observation were generated from the datalogger output. This section examines the speed, acceleration, and specific power results across several available factors in terms of speed-based and vehicle-based measures.

Stratification of speed-based measures includes vehicle type and age, time of day and time of week.

Vehicle Type. One possible factor in explaining how vehicles are driven is the vehicle itself. This is a complex issue, since vehicles can be characterized in many different ways. One possible set of variables might be described as engineering-based: engine size, power-to-weight ratio, transmission type, or body style. A second set relates to the vehicle's primary functions: work commuting, long-distance travel, family errands, freight transport. Another set of vehicle variables might in some way reflect the owner's self-image: conservative, outdoors-oriented, sporty.

These and other potential factors are correlated and choosing factor levels is rather subjective. In this study, virtually no information is available on the second and third factor types discussed above. Limited data have been obtained concerning the survey vehicle engineering characteristics. In the analysis that follows, a "Vehicle Type" factor is defined on the basis of power/weight, body type, and assumptions concerning owner/driver "perception" of the vehicle's performance capabilities.

Using this approach, three vehicle categories were identified:

- Luxury/Sedan/Station Wagon
- Pickup/Van/Utility
- Sports Car/High Performance

The Baltimore 3-parameter sample consisted of 68 Luxury/Sedan/ Station Wagon vehicles, 21 Pickup/Van/Utility, and 4 Sports Car/High Performance. (See Appendix B for a list of survey vehicles.)

In Appendix C, Tables C-6 to C-9 and Figures C-4 to C-6 present summary statistics, distributions, and graphs describing each of the vehicle categories. Average speed is lowest for the Sedan class (24.07 mph) and highest for the Pick-up class (25.59 mph). Mean specific power is somewhat higher for the High Performance category.

Comparing the upper percentiles for the speed distributions gives essentially the same picture as the mean values. If aggressive driving is judged by high speed levels, then no clear picture emerges. The percentage of driving over 55 mph is greater for the Sport category (12.48%) than for the other vehicles (Sedan, 10.65%, and Pickup, 10.60%). This order changes for speeds over 65 mph: the Sport vehicles exceeded that level only 1.15% of the time; the Sedan class, 2.98%; Pick-up, 1.82%.

Similarly, high acceleration levels do not clearly identify one vehicle type as being more or less aggressively driven. Accelerations over 3 mph/sec occurred with highest frequency within the Sedan group (3.32%) and lowest for the Pick-up class (2.85%)

The specific power variable presents a somewhat more definitive result. Using high specific power as a measure of aggressive driving, the Sport group displays by far the greatest proportion of high values. For example, Sport vehicles exceeded a specific power level of 200 mph^2/sec during 0.76% of driving (1.89% while in positive acceleration mode) of driving. This compares with 0.26% and 0.39% (0.63% and 0.90% in positive accelerations) for the Sedan and Pick-up groups, respectively.

It might also be instructive to look at how low performance vehicles are driven. However, these data are not currently available due to the lack of a systematic definition of "low performance." Developing this definition and analysis of driving behavior for these vehicles is planned for the future.

Vehicle Age. The age of the sample vehicle was used to define three categories corresponding approximately to the evolution of engine and emission control technologies. These categories include:

Age Category	Model Years
Old	Pre-1975
Medium	1975-1982
New	1983-1992

The Baltimore 3-parameter vehicles included only members of the Medium and New age groups. Of the 93 vehicles, 15 fall in the Medium class, and 78 are New.

It might be assumed that vehicle age is a proxy for various factors influencing driving behavior. For example, older vehicles tend to be used for purposes resulting in lower mileage accumulation and less highway driving. Comparing driving behavior across age categories should illuminate these factor effects.

Appendix C Tables C-10 to C-13 and Figures C-7 to C-9 show summary statistics, distributions, and graphs for the speed-related variables in these categories. On average, newer vehicles were driven some 4 mph faster than those in the medium age category (25.10 mph vs. 21.15 mph). Accelerations among the medium age vehicles actually vary somewhat more than for the new category (standard deviation 1.53 mph/sec vs. 1.49 mph/sec).

Average specific power is slightly higher in the new vehicle category (46.15 vs. 45.22 mph/sec). Median specific powers compare similarly: New, 34.77 mph^2/sec and Medium, 34.18.

High speed driving is more common in newer vehicles, with 11.33% of driving time spent over 55 mph compared to 7.32% for the Medium category. As with the summary statistics, the acceleration and specific power distributions differ less dramatically.

Time of Day. Because the dataloggers recorded the exact time of day for each speed observation, it is a simple matter to categorize speed-related measures by that factor. As a first cut in relating driving behavior to time of day, the twenty-four hour period was subdivided into the following classes:

1:00 am to 6:00 am	
6:00 am to 9:00 am	Morning Rush
9:00 am to 4:00 pm	
4:00 pm to 7:00 pm	Evening Rush
7:00 pm to 1:00 am	

An observation was included in a given time interval if the trip containing the value began during that interval. Thus, summary statistics of actual driving for a given class may include data values for driving that occurred in a later interval. Presumably, vehicle operation depends on trip purpose and traffic conditions, both of which in turn are related to trip start time.

In Appendix C, Tables C-14 to C-17 and Figures C-10 to C-12 summarize the speed, acceleration and specific power levels for the five time categories. Average speed was lowest during the evening rush hour of 4:00 to 7:00 pm (22.98 mph) and highest during the morning rush period (25.42 mph) and night driving period of 9:00 pm to 1:00 am (25.43 mph).

Daytime driving, between 6:00 am and 7:00 pm exhibits the largest percentage of high speed driving (over 55 mph). Extremes of acceleration and specific power do not appear to be highly influenced by time of day.

Time of Week. A second time classification of interest is weekday versus weekend. As with time of day, there is reason to suspect that different trip and traffic congestion patterns for the two periods may influence driving behavior.

Summary statistics, distributions, and graphs comparing these categories appear in Appendix C Tables C-18 to C-21 and Figures C-13 to C-15. The hypothesis that differences exist for the two parts of the weeks appears to be supported in terms of the Baltimore 3-parameter speed variable. Average weekday speed is substantially lower than on weekends: 23.92 mph and 26.35 mph, respectively. Differences between acceleration and specific power statistics are less pronounced.

The distributions of speed-related variables give further insight into their relation to time of week. For example, 9.81% of weekday driving exceeded the speed 55 mph; this increased to

13.56% on weekends. This reinforces the impression of higher speed weekend driving. However, using acceleration and specific power to indicate driving aggressiveness, no evidence indicates that weekend driving is more extreme than on weekdays.

6.2.2. Trip Measures

The nature and patterns of vehicle trips are another important area in the study of driving behavior. This section examines such trip characteristics as trip duration, trip distance, time between trips, and vehicle operating modes summarized over the trip. In addition, extremes of speed-based measures are analyzed from a trip perspective.

For this study, a trip basically begins when the engine is turned on and ends when the engine is shut off. (See Section 5.1.1 for a more detailed discussion of trip definition.) This definition allows for very short trips, such as moving a vehicle in the driveway. Even zero distance trips are possible with this definition--a car is started, probably with the intent of driving it somewhere, but never moved. In fact, 64 zero mile trips were recorded in Baltimore.

The 3-parameter instrumented vehicles in Baltimore generated a total of 4,681 trips. The average trip covered 4.89 miles and lasted an average of 12 minutes. The median values for trip distance and duration indicate a much shorter "typical" trip of 8.8 minutes in duration and 2.53 miles in distance.

Figures 6-8 and 6-9 present the frequency distribution for trip time and distance. A little more than a quarter of the

Figure 6-8
Distribution of Trip Time
Baltimore 3-Parameter Vehicles

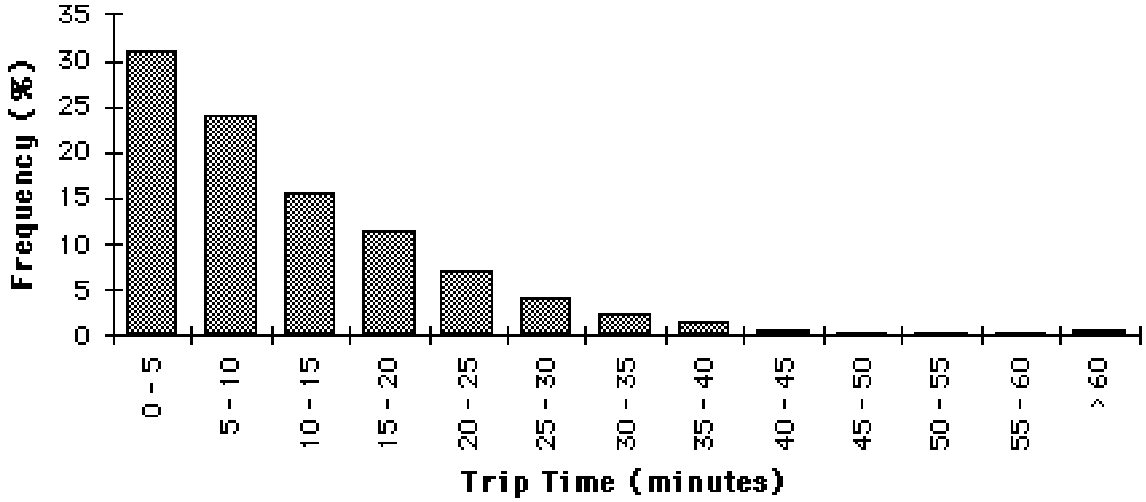
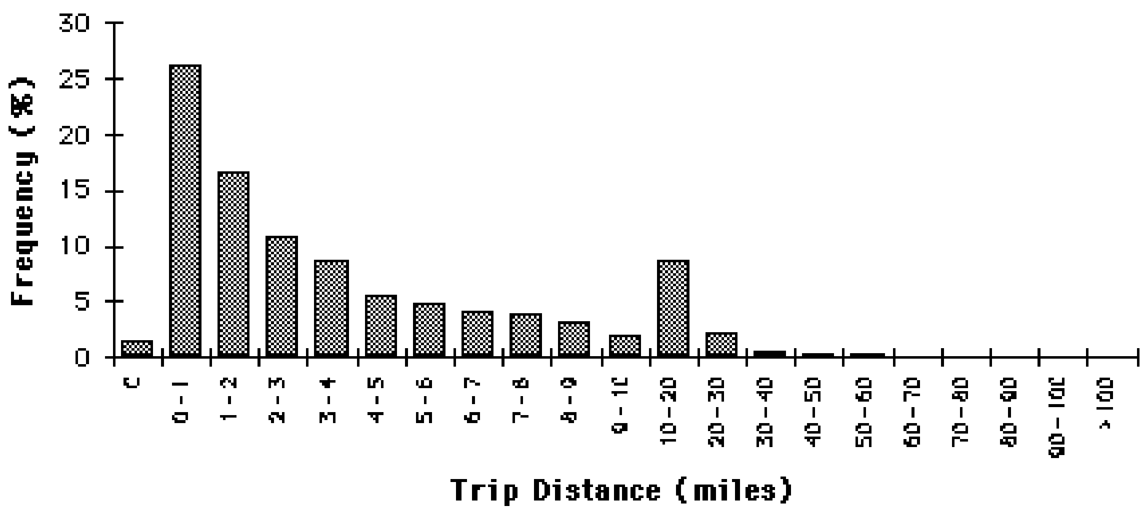


Figure 6-9
Distribution of Trip Distance
Baltimore 3-Parameter Vehicles



trips are a mile or less. Only about 12 percent of the trips were longer than 10 miles. In terms of trip duration, about 5 percent of the trips were very short, lasting a minute or less.

Over the course of a trip, a vehicle will spend a certain fraction of time in each of four operating modes: idle, cruise, acceleration, and deceleration. In Baltimore, the average trip involved 23 percent idle operation, 34 percent cruise, 22 percent acceleration and 20 percent deceleration. (See Section 5.1.2 for mode definitions.)

Trip Factors/Determinants

The characteristic features of a trip are dependent upon numerous factors including trip purpose, driver attitude, trip location, and the driving environment encountered during the course of the trip. None of these factors can be determined from the survey data. However, certain known variables can be used as a proxy for one or more of these unknown factors. Knowing the time of day when a trip took place, it may be possible to make some crude aggregation of such factors as trip purpose, driving environment, and possibly driver attitude. For example, a trip occurring between 6am and 9am could be considered a morning commute trip driven under congested conditions by a driver who may react to a very familiar driving environment in an aggressive manner.

This section considers several factors for which trip data were collected. Time of day and time of week (weekday vs.

weekend) are examined along with vehicle type and vehicle age. These preliminary analyses serve as a starting point for further work in understanding the complex nature of trip patterns.

Time of Day. As in Section 6.2.1, time of day is separated into 5 categories, selected to roughly represent 2 periods of peak vehicle operation (6am-9am, 4pm-7pm) and 3 periods of off-peak operation (1am-6am, 9am-4pm, 7pm-1am). Table 6-3 presents summary statistics for trip time, distance, and idle time stratified by time of day. A large fraction of the trips occurred during the off-peak times, with nearly half of all trips taken during the mid-day period. Almost twice as may trips were taken in the afternoon peak period than in the morning peak. The morning peak period had the longest average trip distance (6.65 miles) while mid-day trips averaged only 4.45 miles. Average trip time was greatest during the early morning off-peak period. From these summary measures it appears that the afternoon peak-period looks more like the mid-day off peak than the morning peak.

Time of Week. Trips were also stratified by weekend and weekday to examine the need for isolating weekday operation for future analyses. Trip time and distance are typically longer on weekends than weekdays. These differences are not particularly large; the median trip length of 2.56 miles for weekends compares to a median of 2.35 miles for weekdays. The variation in distance and duration weekend trips is considerably greater than found for trips taken during the week. The standard deviations shown in Table 6-3 illustrate these differences.

Vehicle Type. It is reasonable to expect that the type of vehicle could have an impact on trip behavior. For example, a commuting car may only be used to make long trips to and from the workplace and a sports utility vehicle may be used for long trips on weekends. The vehicle type classification for this report is very broad, categorizing vehicles as either: luxury, sedan, station wagon; pick-up, van, utility; and sport/high performance (see Section 6.2.1).

The average trip time of sport/high performance vehicles (12.71 minutes) was longer than for either pick-ups (12.56 minutes) or sedans (11.8 minutes). Trip length differences among the vehicle types were less distinct. The average trip length for pick-ups was 5.32 miles, slightly higher than mean trip length of 5.22 for sports/high performance (see Table 6-3). The sedans average trip length was just 4.72 miles. Interestingly, the median trip length was longer for sport/high performance vehicles than pick-ups. The contrasting results for the mean and median suggest that the pick-up class had some extremely long trips which only impacted the mean. In fact the longest trip for pick-ups was 113 miles compared to only 37 miles for the sport/high performance vehicles.

Vehicle Age. The age of a vehicle can affect the way the vehicle is driven in terms of the type and frequency of trips. Concerns regarding a vehicle's reliability may lead people to limit their driving of older vehicles to short trips. To take a very cursory look at the influence of vehicle age on trip patterns, EPA categorized vehicles into three broad age groups:

pre-1975, 1975-82, 1983-1992. For Baltimore, the I/M program restricted recruitment to 1977 and newer model year vehicles; thus, only the two newer categories are considered here.

The newer vehicles' (1983-92) average trip time was 12.36 minutes and covered an average of 5.14 miles. Both measures were considerably shorter for older vehicles(1975-82), with a mean trip time of 10.48 minutes and a trip length average 3.7 miles (see Table 6-3).

Table 6-3.

Baltimore Stratified Trip Measures

Characteristic	Trips		Trip time (minutes)			Trip Distance (miles)			Distance between stops (miles)
	Number	Percent of total	Mean	Median	Std.	Mean	Median	Std.	
Time of Day									
1am to 6am	100	2.14	14.37	15.06	9.23	5.85	3.77	5.87	1.33
6am to 9am	572	12.22	15.78	13.28	12.46	6.65	3.91	8.95	1.08
9am to 4pm	2,284	48.79	10.89	7.74	11.39	4.45	2.18	8.29	0.80
4pm to 7pm	1,047	22.37	11.97	8.80	10.85	4.55	2.45	6.07	0.78
7pm to 1am	678	14.48	12.44	9.05	12.80	5.27	2.80	8.74	1.01
Time of Week									
Weekday	3,578	76.44	11.94	8.87	10.85	4.75	2.56	7.04	0.84
Weekend	1,103	23.56	12.32	8.53	14.06	5.35	2.35	10.49	0.97
Vehicle Type									
Luxury, sedan, station wagon	3,294	70.37	11.80	8.43	11.77	4.72	2.37	8.15	0.81
Pick-up trucks, van, utility	1,207	25.79	12.56	9.28	11.70	5.32	2.80	7.80	1.04
Sports, high performance	180	3.85	12.71	10.88	9.72	5.22	3.89	5.82	0.96
Vehicle Age									
1975 to 1982	816	17.43	10.48	7.43	10.82	3.70	1.81	6.62	0.64

1983 to 1992	3,865	82.57	12.36	9.05	11.83	5.14	2.66	8.23	0.92

Trip-based Analysis of Speed, Acceleration, and Power

The driving behavior exhibited over the course of a given trip varies greatly and is affected by a host of factors. Thus, even on a trip basis, one would expect to see considerable variation in driving behavior variables such as speed, acceleration, and power. A trip-based analysis of the extremes of these driving behavior variables provides an alternative perspective of the incidence of aggressive driving.

High speed operation(> 60 mph) accounts for 7 percent of total driving time. On a trip basis, it is clear that the majority of trips in Baltimore do not involve driving at high speeds. Only about 14 percent of all trips had a maximum speed greater than 60 mph. Figure 6-10 shows the cumulative distribution of maximum speed per trip.

In marked contrast to high speeds, extreme values of power are found on disproportionately large fraction of trips relative to their overall frequency. About 30 percent of all trips had a maximum power value greater than 200, while as a percentage of total instances of positive power values, a power value of 200 or greater accounts for only 0.77 percent (0.22 percent of total vehicle operation). (See Figure 6-11)

High acceleration rates illustrate this point as well. Nine out of ten trips contain accelerations greater than 3 mph/second, yet these accelerations only account for about 3 percent of total driving time. (See Figure 6-12)

These differences illustrate how certain driving parameters are closely related to the type or purpose of a trip (high speed operation), while others (speed and acceleration) are a more

Figure 6-10
Cumulative Distribution: Maximum Speed per Trip
Baltimore 3-Parameter Vehicles

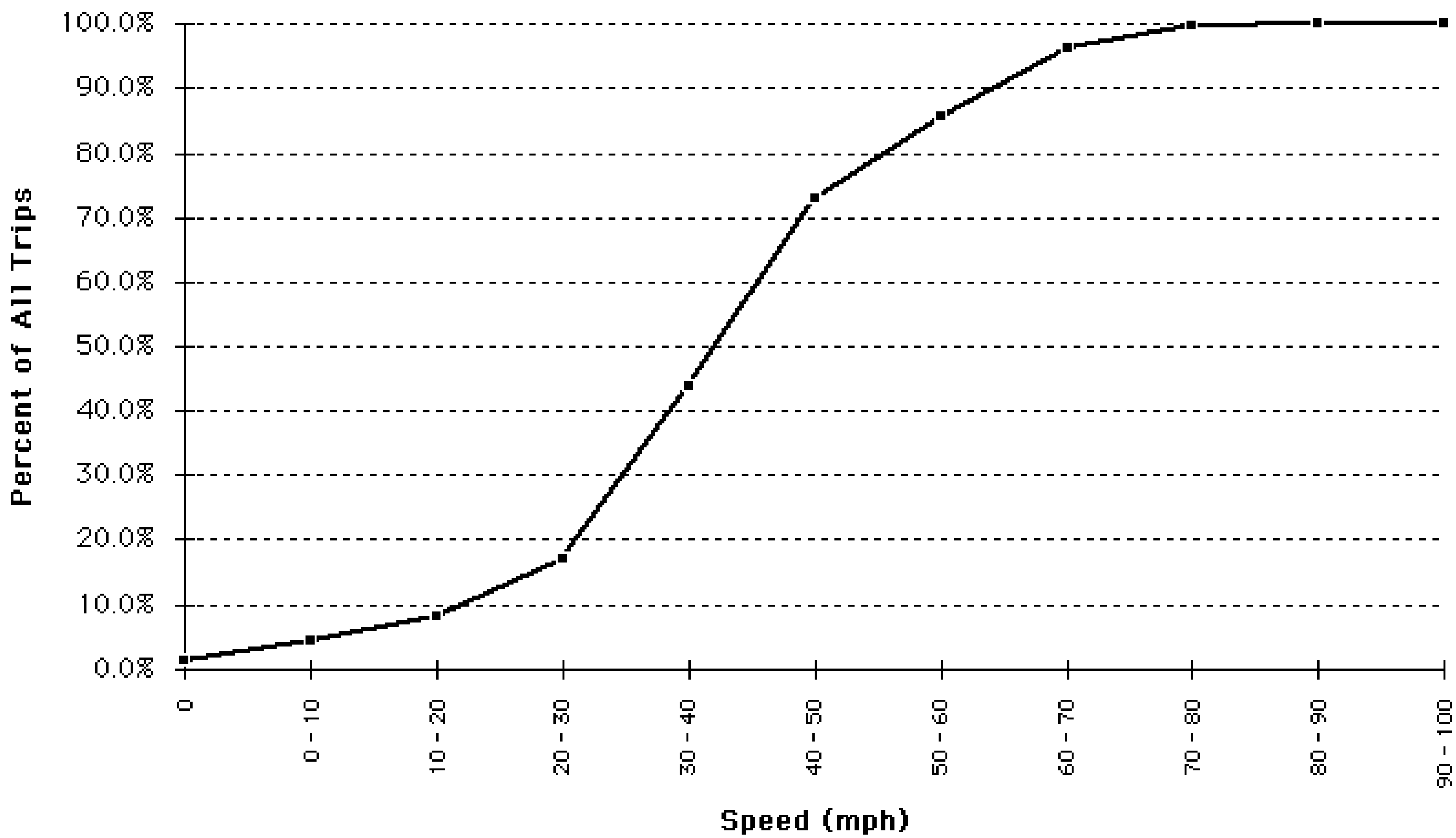


Figure 6-11
Cumulative Distribution: Maximum Power per Trip
Baltimore 3-Parameter Vehicles

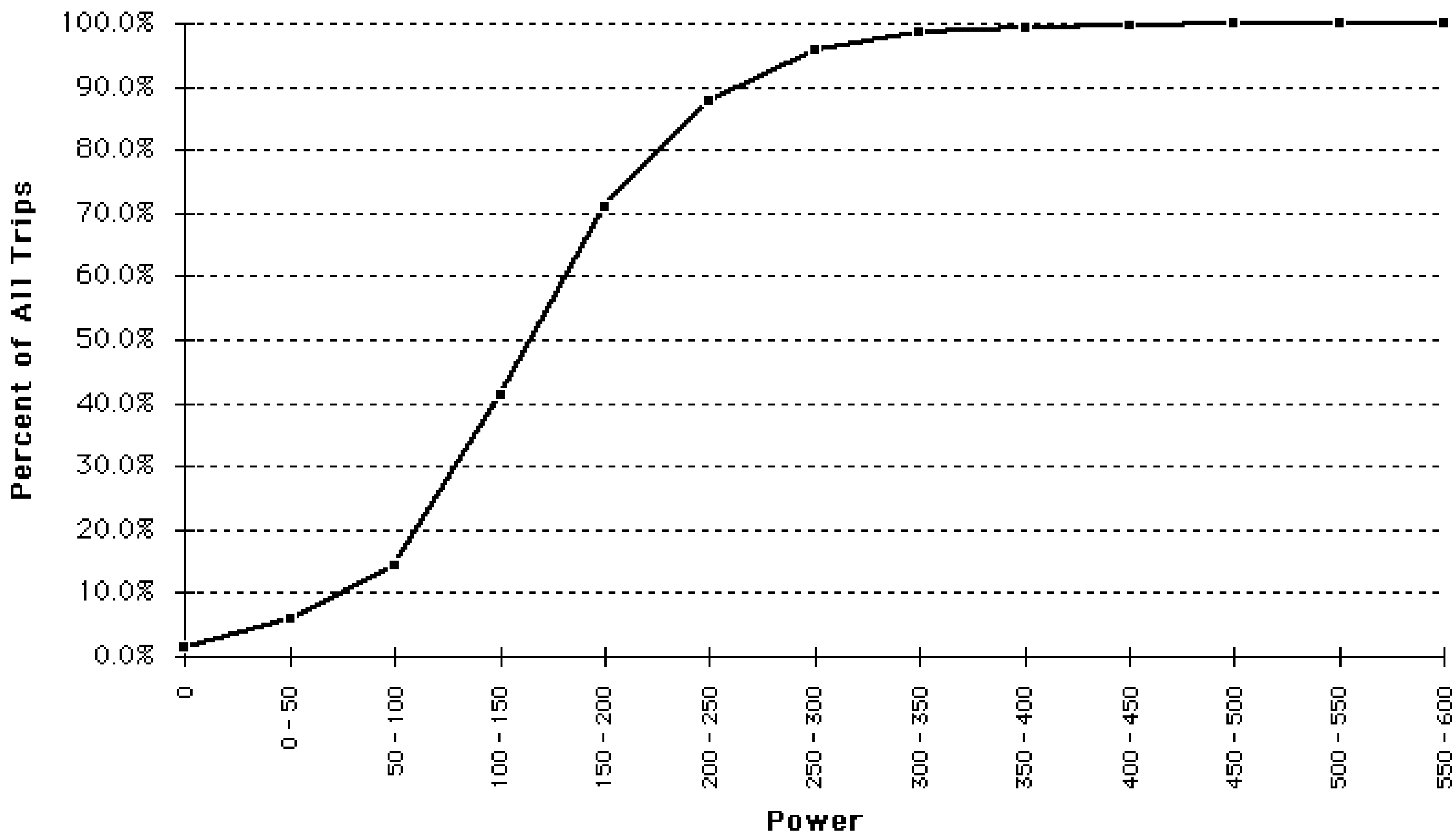
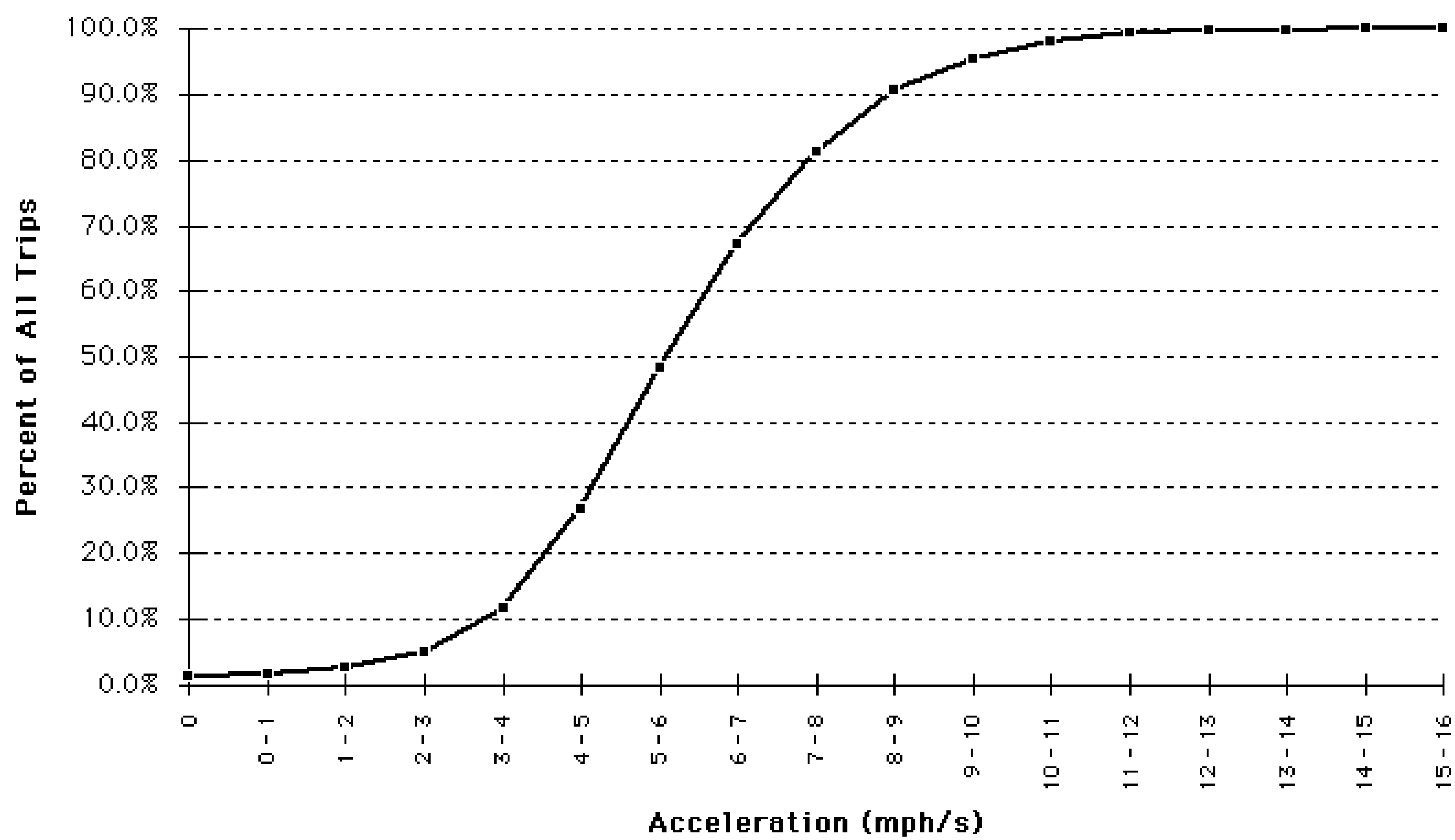


Figure 6-12
Cumulative Distribution: Maximum Acceleration per Trip
Baltimore 3-Parameter Vehicles



universal trip characteristic. From this perspective, the "tails" of the acceleration and power distribution take on greater significance.

6.2.3. Vehicle-based Measures

Several summary statistics were compiled from the survey to describe driving behavior variation among vehicles. These are reviewed briefly here, for all Baltimore 3-parameter driving, and for several factor comparisons. Refer to the Radian Corporation report for additional detail on these and related variables.[43]

The Baltimore 3-parameter sample contained 93 vehicles. Variables described in this section were listed earlier: miles driven per day, number of trips per day, number of minutes of operation per day, and number of stops per hour of operation.

In summarizing the data for these variables, it was appropriate to weight their values to account for differing amounts of instrumentation time and operation time. Therefore, in the outcomes reported below, means and standard deviations for the first three variables are weighted by the number of days the vehicle was instrumented; for the last variable, those statistics are weighted by the number of hours the vehicle was operated.

In Appendix C, Table C-22 gives summary results for the 93 Baltimore vehicles. Mean daily mileage is 30.56, while one

[43] Radian Corporation, "Light Duty Vehicle Driving Behavior: Private Vehicle Instrumentation, Volume 1," Draft Report to U.S. EPA, August 24, 1992.

vehicle averaged over 105 miles per day. Daily time of operation averaged over 75 minutes; number of trips, 6.25 per day; and number of stops, over 35 per hour of operation.

The vehicle-based measures used in the discussion of overall Baltimore driving behavior were summarized by the levels of several factors, including vehicle type and age, and time of week. As before, means and standard deviations are weighted appropriately.

Comparisons of these statistics for several stratification factors are found in Appendix C Tables C-23 to C-25. The factor levels are defined in Section 6.2. Some general observations follow. Newer vehicles were driven somewhat longer and farther per day, and averaged fewer trips and fewer stops per hour. Weekday driving produced substantially higher average time, higher distance and number of trips than weekdays. For the vehicle type factor, average daily usage is considerably higher for the Pickup/Van/Utility class than for the Sedan and Sport classes; the per hour stop rate of Sedans was somewhat higher. Presumably, these outcomes relate to differences in trip purpose associated with these vehicle types.

6.2.4. Vehicle Soak

The soak period[44] is a critical factor in the level of emissions generated after a vehicle start. For illustration,

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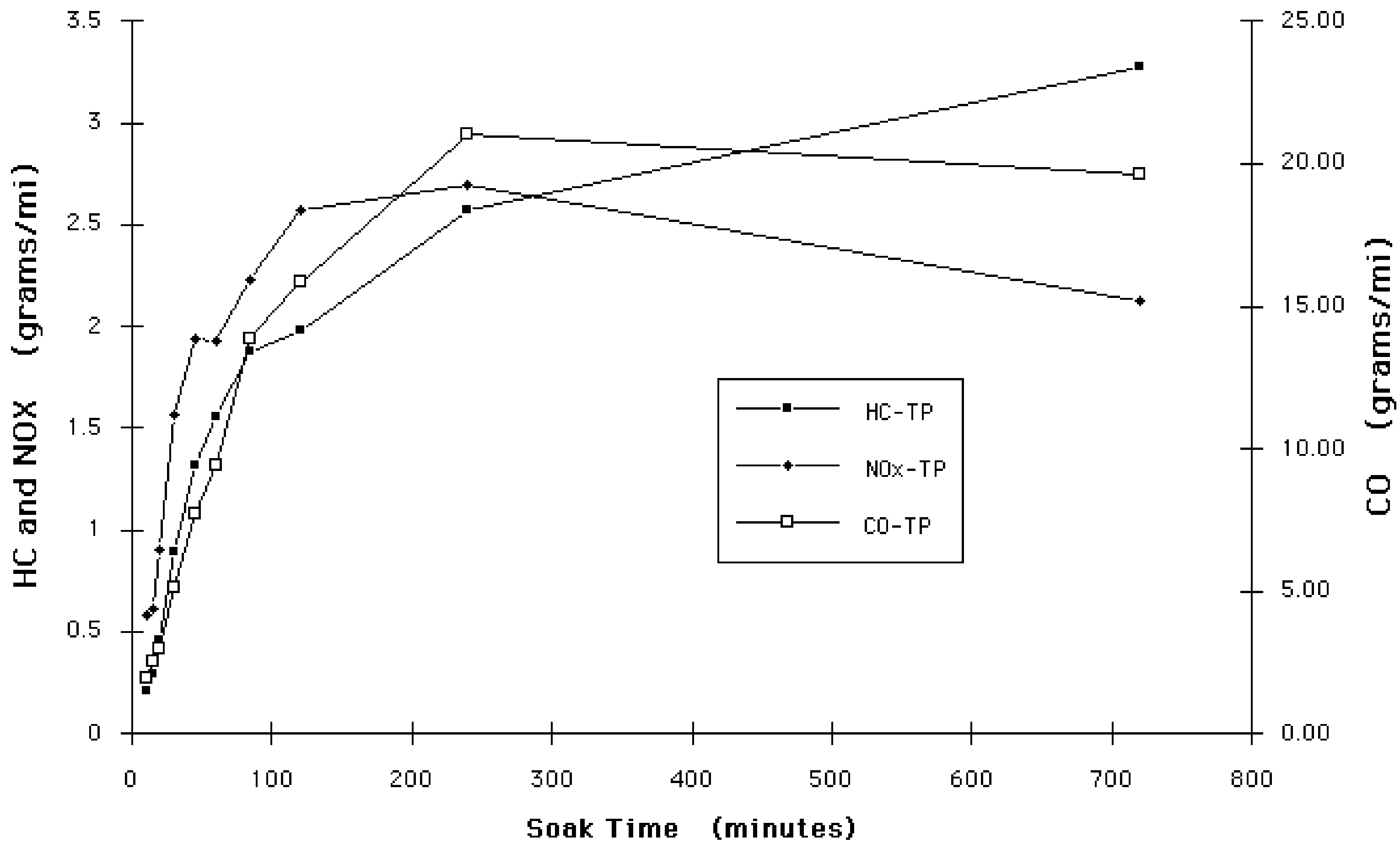
[44]"Soak period" is the time after the vehicle has been turned off until it is restarted.

Figure 6-13 shows the average emissions after soak periods ranging from 10 minutes to overnight for 5 vehicles run over the first micro-trip of the FTP (that is, the first 125 seconds of the cycle).[45] The data indicate that HC and CO emissions during

[45]The data is from a test program run at EPA's National Vehicle and Fuel Emissions Laboratory in Ann Arbor, MI. All the soaks were conducted with an ambient temperature of 75○F and second-by-second emission data were gathered on a modal test bench. The vehicles tested were a 1992 Ford Crown Victoria with a 4.6L engine, a 1992 Dodge Dakota pickup with a 5.2L engine, a 1991 Honda Accord with a 2.2L engine, a 1991 Dodge Caravan with a 3.0L engine, and a 1990 Pontiac 6000 with a 3.1L engine.

Figure 6-13.
Hill 1 - Average Tailpipe Emissions



the first 2 minutes of operation can increase by a factor of 10 after long soak periods, relative to 10 minute soak periods, and NOx by a factor of 5. Even relatively short soaks of 45 minutes increased all emissions by a factor of 4-5.

This emission increase occurs due to engine and catalyst cooldown. Typical engine and catalyst cooldown curves can be generated using the equations developed from the Albany Emission Laboratory work, as discussed in Section 5.5.1. Figure 6-14 shows the predicted cooldown curves for a 6-cylinder vehicle at 75^{o}F with a 4 MPH wind and dry pavement. The curves demonstrate that the catalyst cools off much faster than the engine. Thus, most of the emission increase found when increasing soak time from 10 minutes to about an hour is probably due to catalyst cooldown. After an hour, engine cooldown becomes increasingly important as the soak time continues to increase and the catalyst cooldown becomes less important (as the catalyst light-off temperature is around 650^{o}F, the catalyst is close to being completely cold after 45-60 minutes).

Because of the potential emission impacts, one of the primary objectives of the driving surveys was to examine the distribution of actual soak times. Figure 6-15 summarizes the distribution of soak times found for the Baltimore 3-parameter data set. A more detailed distribution is presented in tabular form in Appendix D.

The soak distributions include a large number of relatively short soak periods. This indicates that drivers frequently string trips together. In fact, only about 18% of the trips occurred after a soak period greater than 8 hours, indicating that single trips directly to work (or some other destination) and then home again for the night are more the exception than the rule.

Figure 6-14.
Typical Catalyst and Engine Cooldown Curves

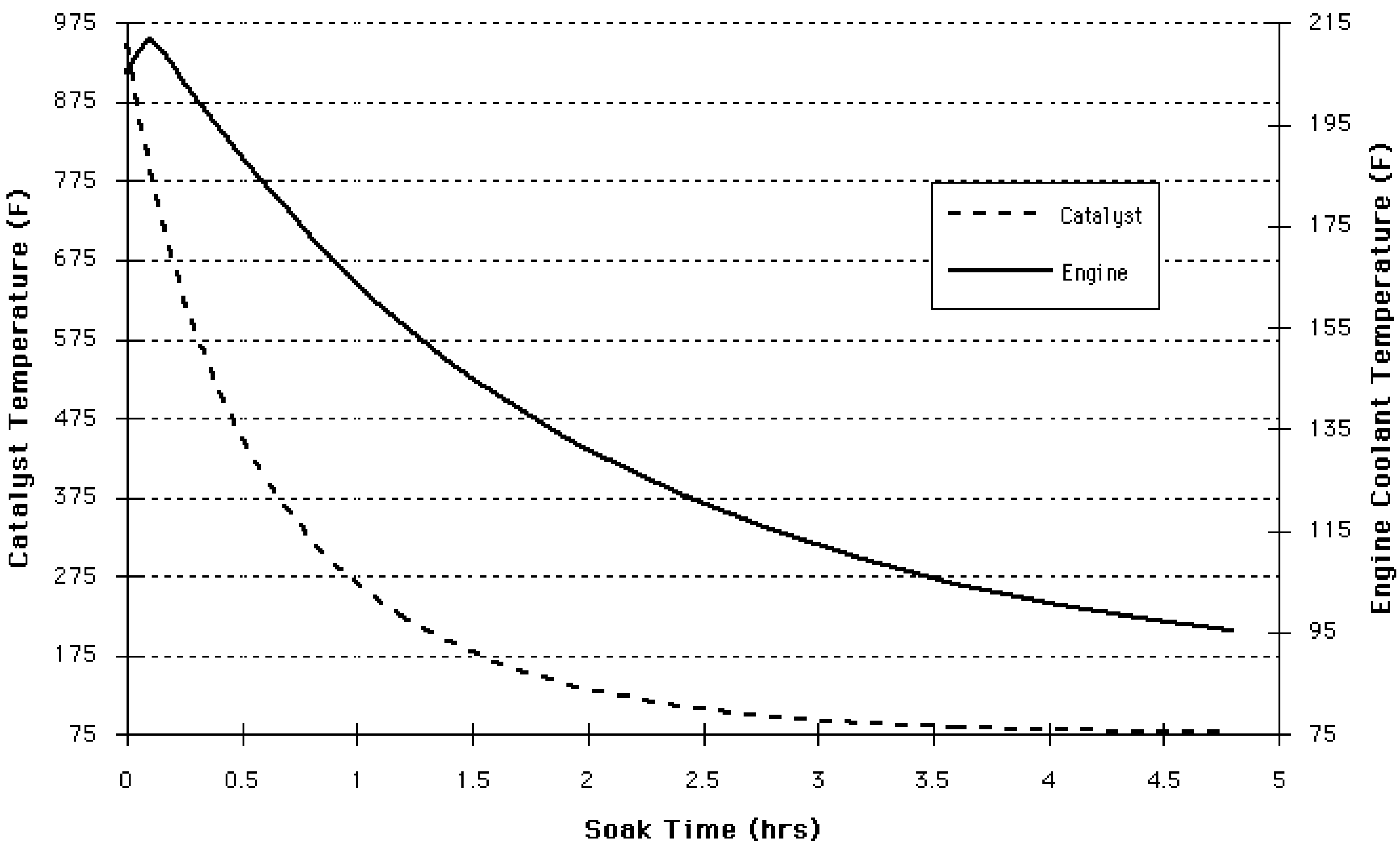
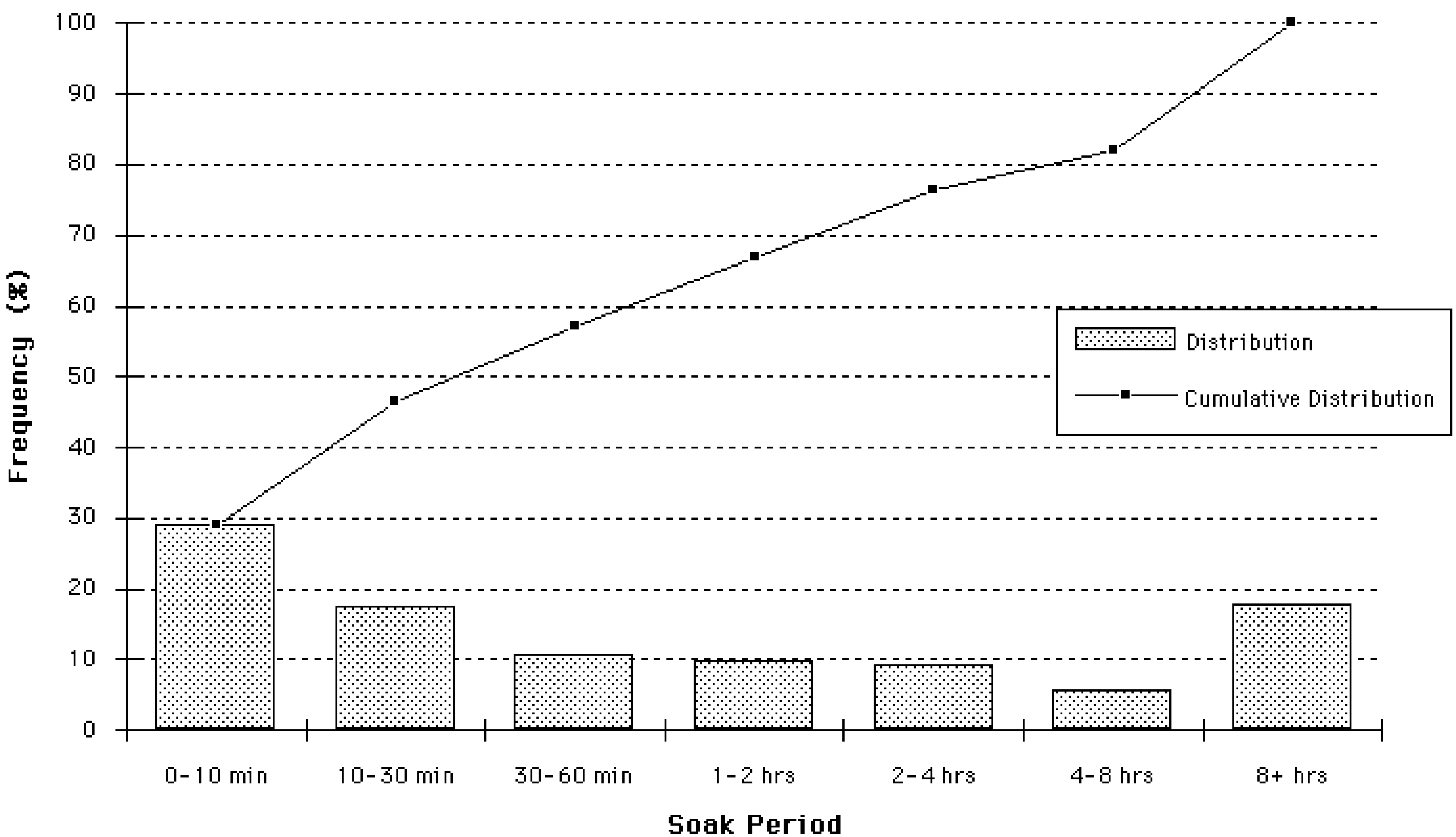


Figure 6-15.
Baltimore Soak Period Distributions



To help put the soak time information into context, the cooldown formulas developed in Section 5.5.1. were applied to the Baltimore soak distributions to develop a profile of engine and catalyst temperatures at vehicle start (assuming an ambient temperature of 75°F, wind of 4 MPH, and dry pavement). These temperature distributions are presented in Table 6-4. It should be noted that these temperature distributions overstate the initial temperatures to some degree, as it was assumed that the engine and catalyst had reached normal operating temperatures prior to the soak period, which is not true for every soak.

Table 6-4

Temperature Distribution at Trip Start

Catalyst		Engine	
Temperature (^oF)	Frequency (Percent)	Temperature (^oF)	Frequency (Percent)
800+	22	180+	51
700-800	9	160-180	7
		140-160	6
600-700*	7	120-140	6
		100-120	7
500-600	6	<100	23
400-500	5		
300-400	5		
200-300	6		
<200	40		

*Catalyst light-off range

The data indicate substantial differences between catalyst and engine conditions upon vehicle start-up. A high proportion of vehicle starts (at least 62%) occur with catalyst temperatures below the light-off range. However, the engine is quite warm for most vehicle starts. Only about 23% of starts occur with engine temperatures below 100^oF and about 64% of all starts had engine temperatures above 140^oF.

6.2.5. Trip Start Driving Activity

Vehicle soak periods impact emissions by affecting engine and catalyst temperatures at the start of the next trip; the longer the soak period, the more the engine and catalyst cool off. How the vehicle is operated after start-up may also impact emissions, as it affects the rate at which the engine and catalyst warm up and the level of emissions from the vehicle during the warmup period.

Most of the exhaust emissions from modern, properly operating vehicles occur during the first 1-3 minutes of operation after the vehicle has been started. However, this was not the case when the current FTP driving cycle was developed. Vehicles in the late '60's always ran with rich air/fuel ratios and did not have catalysts. Start emissions from these vehicles were not very different from hot stabilized emissions and how the vehicles were driven during the engine warmup period had little impact on overall emission levels. Thus, there was little need to evaluate whether vehicles are driven differently after they are started.

The introduction of the catalyst and more sophisticated fuel control systems dramatically altered the relationship between emissions during the warmup period and hot stabilized emissions. Hot stabilized emissions have been reduced to relatively low levels with modern catalysts, plus improvements in fuel systems ensure efficient catalyst operation even during moderate transient operation. However, emissions shortly after cold (and warm) starts have not been reduced proportionally due to the need to warm up the catalyst and the inability to immediately enter closed-loop operation. Thus, how vehicles are driven shortly after they have been started is a much more important consideration today than when the FTP was developed.

One concern that EPA investigated was whether or not the length of the soak period influenced driving behavior after start-up (for example, are vehicles driven differently after overnight soaks at home than they are after short soaks at stores). Therefore, the first step of the analysis was to divide the start data into cold, warm and hot starts. A cold start is where both the engine and catalyst are cold, a warm start is where the engine is warm and the catalyst is cold, and a hot start is where both engine and catalyst are warm (as catalysts cool off much faster than engines, starts with warm catalysts and cold engines are not a concern). Based on previous test programs, it is known that catalysts warm up after about two minutes of driving. The work by New York's Albany Emission Laboratory indicated that catalysts cool off to fairly cold levels in about 45 minutes. Thus, a start was classified as having a warm catalyst if two conditions were met: (1) the previous trip prior to the soak was less than two minutes in duration, and (2) the soak period was less than 45 minutes. If either the previous trip was less than 2 minutes or the soak period was longer than 45 minutes, the start was classified as having a cold catalyst.

For engine classification, Radian developed engine warmup and cooldown algorithms from the 6-parameter data vehicles (which monitored coolant temperature). The warm-up algorithm related engine temperature rise to idle time and vehicle speed while moving. The cooldown algorithm related engine temperature fall to ambient air temperature, engine displacement, and soak time. These algorithms were then used by Radian to predict engine temperature at the beginning of every trip in the 3-parameter data set (both Spokane and Baltimore). If the predicted engine temperature at the beginning of the trip was within 10°C of the ambient temperature, the start was classified as having a cold engine. If the difference was greater than 10°C, the start was classified as a warm engine.

The next step in assessing start driving behavior was to define the length of time[46] after a vehicle start that driving should be classified as "start", as opposed to hot stabilized. To facilitate this analyses, EPA decided to strip off the initial idle period and analyze it separately from the data after the vehicle began to move. This was done because of the substantial impacts of ambient temperature on the initial idle time and to equitably compare driving after cold, warm, and hot starts.

The criteria established for the start period was to encompass the portion of the warm-up period that relates to elevated emission levels. Based upon an analysis of trip start emission activity by Sierra Research,[47] a coolant temperature

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[46]Time was used instead of distance because the data was gathered in second-by-second increments. A distance criteria would also create problems when generating new testing cycles, which are time based.

[47]Reference: Technical Note Under Contract No. 68-C1-0079 In Response to Work Assignment 1-05, "Evaluation of Trip Start Activity, Subtask 1b, Definition of Trip Start Condition", by Sierra Research, dated April 12, 1993.

threshold of 140°F was selected as the point at which elevated emission levels largely disappear during vehicle warmup.

Using the 140°F coolant temperature threshold, Radian analyzed the 6-parameter coolant temperature data for the amount of time it took to reach 140°F on each trip, excluding the initial idle. The distribution of these times are listed in Appendix E, both for all trips (Table E-1) and broken down by cold, warm, and hot starts (Tables E-2 to E-4, respectively). The data indicate that over 50% of all cold starts reach 140°F coolant temperature after 240 seconds of operation. Also, almost 95% of all warm starts reach 140°F coolant after 240 seconds and over 90% of all starts, combined, reach 140°F after 240 seconds. Thus, 240 seconds, excluding the initial idle period, was selected as the "start" portion of overall driving. To further distinguish the sequence of driving behavior after starts, this 240 second period was broken up into three equal 80 second "phases" for analysis purposes.

Radian analyzed speed, acceleration, and power distributions for each combination of the 80 second phases and the different trip start definitions. The averages and standard deviations for each group, as well as for overall driving, are presented in Table 6-5.

The averages and standard deviations indicate that driving behavior is not significantly affected by the length of the soak time. For any given time phase, the averages of speed, acceleration, and power are very similar for each start category (i.e. cold, warm, and hot). Graphs comparing the actual distribution of speed and power are presented in Appendix E (Figures E-1 to E-3 show the speed distribution by start category for phases 1-3, respectively; Figures E-4 to E-6 show the cumulative power distributions). The distributions for each individual phase show remarkable similarity across all three start categories. Thus, the only driving behavior that needs to be considered as a function of soak time is the initial idle period.

The data in Table 6-5 also indicate that driving behavior immediately after a start (be it cold, warm, or hot) is different

Table 6-5

Trip Start Driving Behavior by 80-Second Phases

Start Phase	Type of Start	Number of Seconds	Speed (mph)		Acceleration (mph/sec)		Power (mph^2/sec)	
			Mean	Std.	Mean	Std.	Mean	Std.
1	Cold	154,397	14.4	11.9	.25	1.87	41.4	42.4
	Warm	171,764	14.2	12.0	.23	1.84	40.5	43.4
	Hot	313,433	14.5	12.6	.23	1.79	40.5	43.3
	Wgt. avg.		14.4	12.3	.24	1.82	40.7	43.1
2	Cold	145,684	22.5	15.1	.02	1.67	48.6	44.6
	Warm	156,818	21.1	15.0	.01	1.66	47.1	44.5
	Hot	273,546	21.4	15.5	-.01	1.63	45.9	42.4
	Wgt. avg.		21.6	15.3	.00	1.65	46.9	43.5
3	Cold	134,348	25.4	16.8	.01	1.53	47.0	44.1
	Warm	141,539	24.0	16.2	.00	1.57	45.6	43.2
	Hot	233,245	23.5	16.6	-.02	1.54	44.9	42.1
	Wgt. avg.		24.1	16.6	-.01	1.55	45.7	43.0
Hot*		3,365,299	28.1	20.3	-.04	1.42	43.5	41.6

*Hot stabilized operation (that is, driving after the first 240 seconds of each trip).

than after stabilized operation has been reached. The average speeds for all the start phases are lower than for hot stabilized driving (that is, driving after the 240-second start period), especially phase 1. Phase 1 also has lower average power values than all the other phases, although phase 2 and phase 3 actually have higher average power values than hot stabilized driving.

Figure 6-16 displays the speed distribution for Baltimore and Spokane by phase (i.e. each of the first three 80 second phases of driving, plus driving after the first 240 seconds, with the different start types combined). This figure shows that the speed distribution during the initial 80 second phase is completely different than for subsequent driving, with the most frequent driving speed range being 0-5 mph and the frequency dropping steadily with increasing speed. The speed distributions for all subsequent driving phases have more similar shapes, with the most frequent speed range being 30-35 mph. Phase 2 and Phase 3 of start driving behavior are especially similar, although Phase 3 has a little less driving in the 5-25 mph range and a little more in the 45-65 mph range. The speed distribution for hot stabilized driving (that is, the "rest of trip") differs in having substantially more driving in the 50-75 mph range.

Cumulative power distributions for each phase of driving are presented in Figure 6-17. These distributions demonstrate that the aggressiveness of the driving for each phase is more similar than the speed distributions. Phase 1 spends substantially more time at very low power levels, but the distribution of power levels above 80 is very similar to hot stabilized driving. Phase 2 and Phase 3 are virtually identical to each other, although both are a little more aggressive than either Phase 1 or hot stabilized driving.

Figure 6-16.
Speed Distribution by Phase

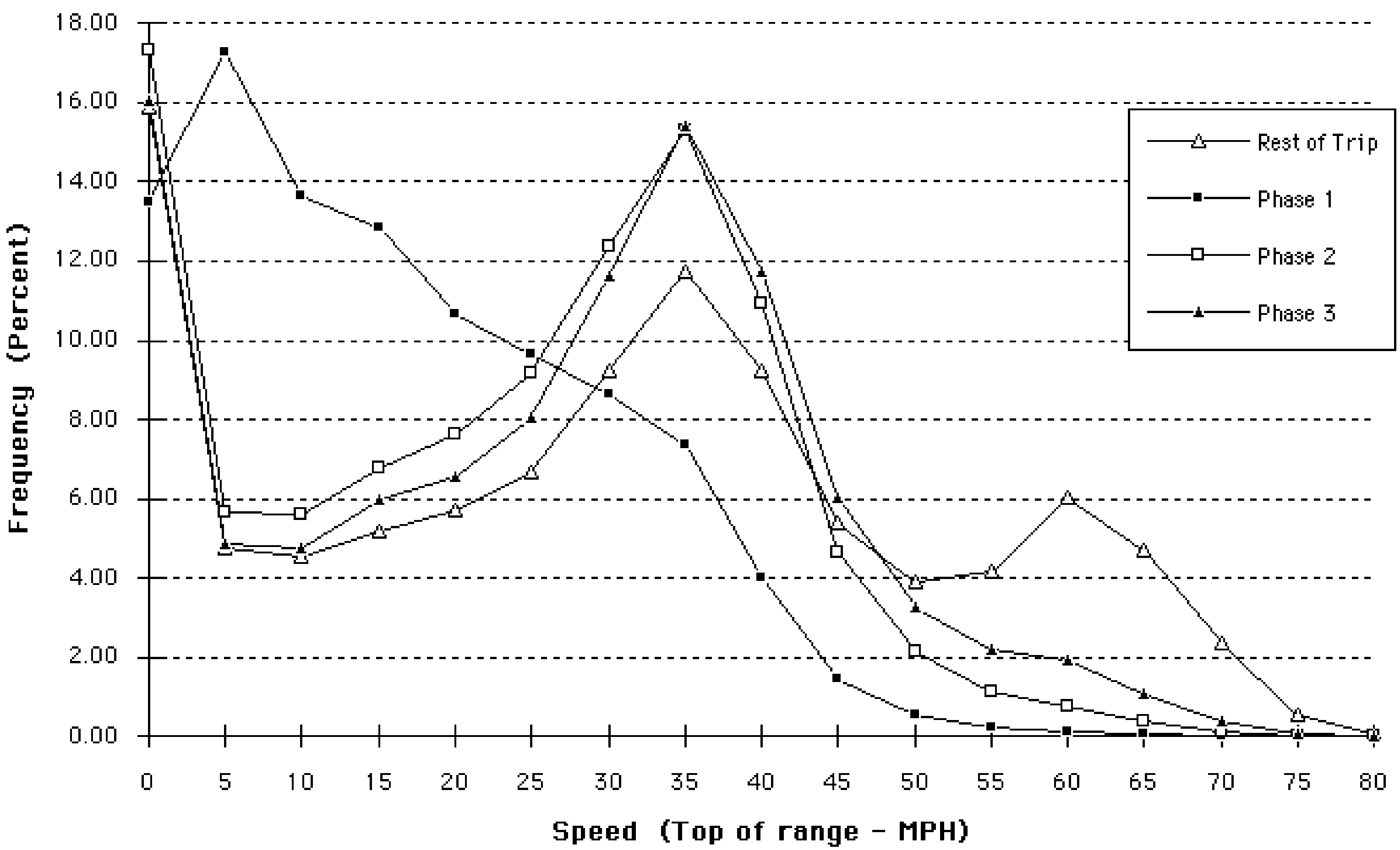
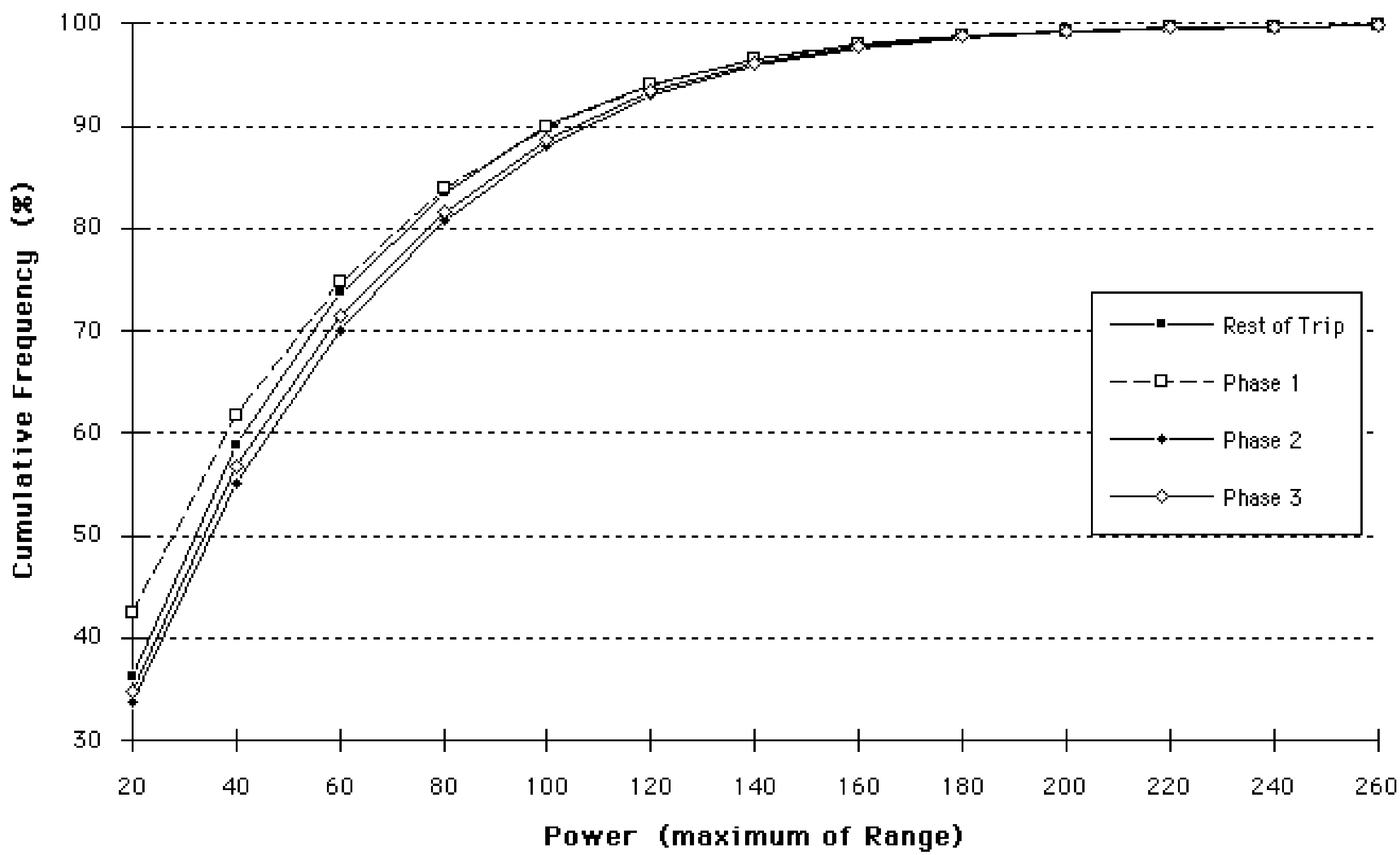


Figure 6-17.
Cumulative Power Distribution by Phase



Initial Idle

The distribution of the initial idle time for all trips (3-parameter, Spokane and Baltimore) has been analyzed and is presented in Appendix E for each start category (Tables E-5 to E-7 for cold, warm, and hot starts, respectively). Table 6-6 summarizes the average and median initial idle times for Spokane and Baltimore.

Table 6-6

Initial Idle Time, Baltimore and Spokane

Start Type	Mean (seconds)	Median (seconds)
Cold start	59	13
Warm start	28	8
Hot start	15	5
Overall	29	

The large discrepancy between the mean and the median initial idle time is due to a significant number of extended idles. The data indicate that 10% of all cold starts had initial idles greater than 2 minutes, and 5% exceeded 5 minutes. This discrepancy needs to be addressed in the course of generating representative test cycles.

The data also indicates that cold starts have much longer initial idle times than hot starts. This also needs to be addressed during cycle development.

One potential problem with the Baltimore and, especially, Spokane data is that the studies were conducted during colder weather when people frequently let their cars warm up before driving off. The average daily temperature during the survey period was roughly 40°F and 50°F for Spokane and Baltimore, respectively. The initial idle periods would probably be shorter during the summer months more representative of ozone nonattainment, especially after a cold start.

One way to mitigate this concern would be to use the Atlanta data to calculate initial idle time, as the Atlanta survey was conducted during August and early September. The average daily temperature during the survey period in Atlanta was between 70 and 75○F. A comparison of the Atlanta to the combined Spokane and Baltimore initial idle times is presented in Table 6-7 (the distribution of initial idle times for Atlanta are presented in Appendix E, Tables E-8 to E-10 for cold starts, warm starts, and hot starts, respectively).

Table 6-7

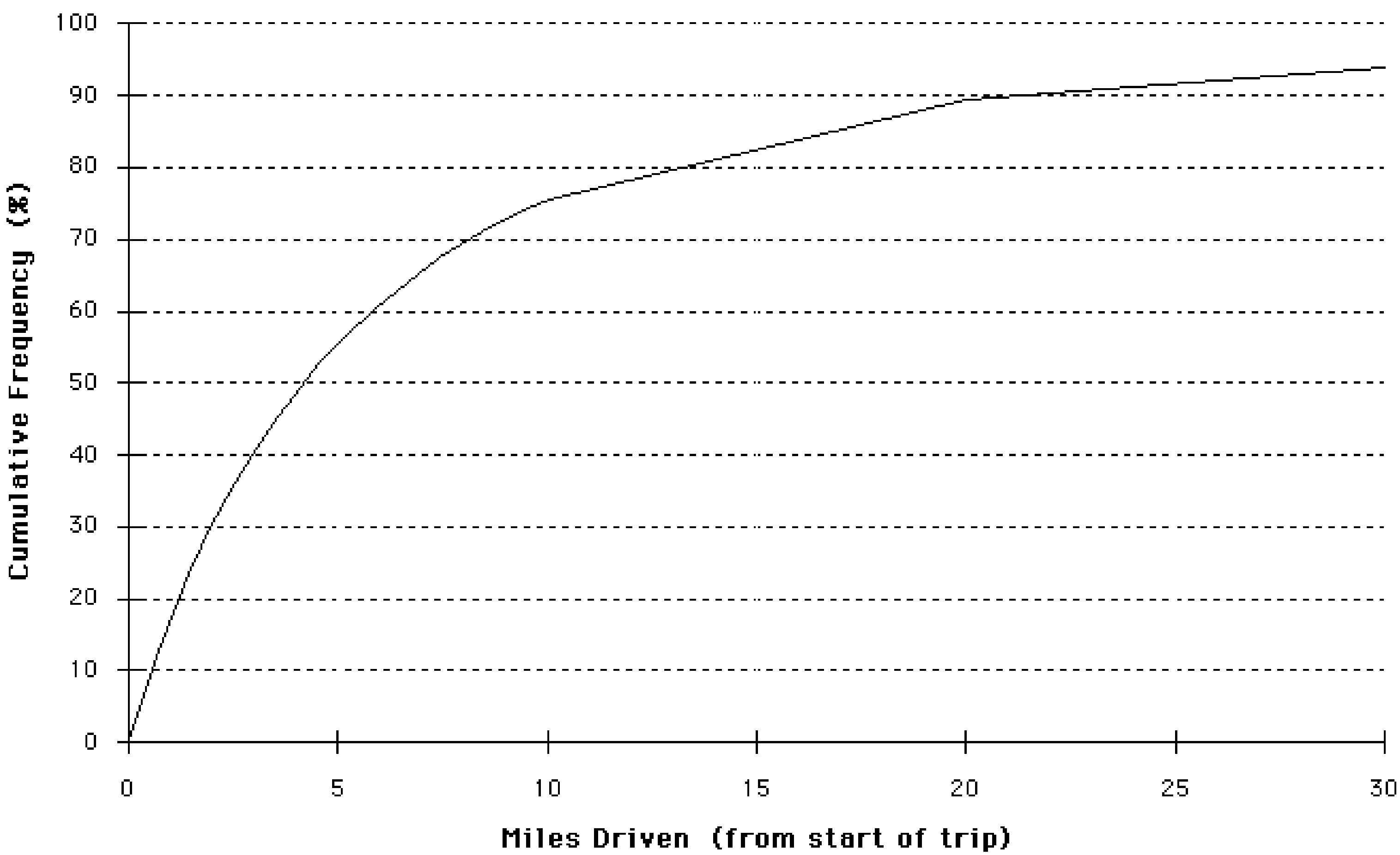
Initial Idle Time for Baltimore/Spokane vs. Atlanta

Start Type	Baltimore and Spokane		Atlanta	
	Mean (seconds)	Median (seconds)	Mean (seconds)	Median (seconds)
Cold start	59	13	28	9
Warm start	28	8	18	7
Hot start	15	5	12	5

Proportion of Driving Occurring After Starts

The final factor that will be needed to assess the emission impact of start driving behavior is the proportion of overall driving represented by the start driving behavior. A breakdown of the survey data into miles driven from the start of each trip is presented in Figure 6-18 (the cumulative distribution can be read as "the proportion of all driving that was driven less than or equal to the number of miles on the X-axis after the start of a trip"). The reduction in the miles spent in each speed range as the miles since the start of the trip increases reflects the high percentage of short trips in the data base.

Figure 6-18.
Distribution of Miles Driven from Start of Trip



6.3. Comparisons to the Federal Test Procedure

The Federal Test Procedure is intended to represent in-use driving behavior. The Baltimore 3-parameter data offer an empirical source for judging the success of the FTP in capturing real driving characteristics. This section compares the FTP and Baltimore data using the various descriptive tools employed earlier.

6.3.1. Speed-based Measures

Using the speed-related data, driving on the FTP is more conservative than that observed in Baltimore. Table 6-8 compares summary statistics on speed, acceleration and specific power for the two sources. Typical FTP speeds are lower than for the Baltimore data: the mean FTP speed is 19.59 mph (24.14 mph when the vehicle is moving), compared to 24.50 mph (31.06 mph when moving) for Baltimore. Accelerations in Baltimore range from -15 to +20 mph/sec, with standard deviation 1.50; the FTP range is much narrower, -3.3 mph/sec to +3.3 mph/sec, with standard deviation 1.40. Specific power (during positive acceleration) for the Baltimore sample averaged 46.02 mph^2/sec; the median is 34.7. For the FTP, the mean and median are much lower, 38.60 and 21.6, respectively.

Tables 6-9 to 6-11 and Figures 6-19 to 6-21 contrast the distributions of speed-related variables for Baltimore with those of the FTP. As is well documented, the FTP contains no speeds above 56.7 mph, and no positive or negative accelerations in excess of 3.3 mph/sec. In Baltimore, roughly 8.5% of speeds (between 6.35% and 10.73%) fell above 56.7 mph. For accelerations, about 2.5% of driving exceeded 3.3 mph/sec, while around 3.5% of decelerations were under -3.3 mph/sec.

The largest FTP specific power is 192 mph^2/sec. In the Baltimore survey, about 0.3% of all driving time exceeded that level (about 1% of time in positive acceleration mode).

Table 6-8
Summary Statistics
Baltimore and FTP
Baltimore 3-Parameter Vehicles

Speed (mph)		
	FTP	Baltimore
Mean	19.59	24.50
St Dev	14.69	20.52
Max	56.70	94.46
Min	0.00	0.00
Count	1,369	3,365,504
Acceleration (mph/sec)		
	FTP	Baltimore
Mean	0.00	0.00
St Dev	1.40	1.50
Max	3.31	15.19
Min	-3.31	-19.49
Count	1,368	3,360,550
Power (mph^2/sec)		
	FTP	Baltimore
Mean	38.60	46.02
St Dev	31.74	42.96
Max	191.85	557.69
Min	0.01	0.00
Count	544	1,407,908

Table 6-9
DISTRIBUTION OF SPEED
Baltimore and FTP
Baltimore 3-Parameter Vehicles

	Baltimore			FTP		
Speed (mph)	Count	Percent	Cum. %	Count	Percent	Cum. %
0-0	710,890	21.1	21.1	258	18.8	18.8
0-5	207,698	6.2	27.3	76	5.6	24.4
5-10	181,442	5.4	32.7	74	5.4	29.8
10-15	201,708	6.0	38.7	80	5.8	35.6
15-20	209,420	6.2	44.9	129	9.4	45.1
20-25	231,917	6.9	51.8	265	19.4	64.4
25-30	280,040	8.3	60.1	248	18.1	82.5
30-35	308,521	9.2	69.3	86	6.3	88.8
35-40	253,681	7.5	76.8	42	3.1	91.9
40-45	173,105	5.1	82.0	8	0.6	92.5
45-50	125,294	3.7	85.7	27	2.0	94.4
50-55	121,004	3.6	89.3	52	3.8	98.2
55-60	147,398	4.4	93.7	24	1.8	100.0
60-65	125,917	3.7	97.4	0	0.0	100.0
65-70	66,826	2.0	99.4	0	0.0	100.0
70-75	17,485	0.5	99.9	0	0.0	100.0
75-80	2,803	0.1	100.0	0	0.0	100.0
80-85	253	0.0	100.0	0	0.0	100.0
85-90	91	0.0	100.0	0	0.0	100.0
90-95	11	0.0	100.0	0	0.0	100.0
Total	3,365,504	100.0		1,369	100.0	

Table 6-10
DISTRIBUTION OF ACCELERATIONS
Baltimore and FTP
Baltimore 3-Parameter Vehicles

	Baltimore			**FTP**		
Accel						
-20 to -19	1	0.0	0.0	0	0.0	0.0
-19 to -18	0	0.0	0.0	0	0.0	0.0
-18 to -17	0	0.0	0.0	0	0.0	0.0
-17 to -16	0	0.0	0.0	0	0.0	0.0
-16 to -15	0	0.0	0.0	0	0.0	0.0
-15 to -14	3	0.0	0.0	0	0.0	0.0
-14 to -13	2	0.0	0.0	0	0.0	0.0
-13 to -12	11	0.0	0.0	0	0.0	0.0
-12 to -11	34	0.0	0.0	0	0.0	0.0
-11 to -10	44	0.0	0.0	0	0.0	0.0
-10 to -9	149	0.0	0.0	0	0.0	0.0
-9 to -8	545	0.0	0.0	0	0.0	0.0
-8 to -7	1,801	0.1	0.1	0	0.0	0.0
-7 to -6	5,756	0.2	0.2	0	0.0	0.0
-6 to -5	17,199	0.5	0.8	0	0.0	0.0
-5 to -4	41,575	1.2	2.0	0	0.0	0.0
-4 to -3	76,005	2.3	4.3	76	5.6	5.6
-3 to -2	120,151	3.6	7.8	56	4.1	9.6
-2 to -1	219,036	6.5	14.4	85	6.2	15.9
-1 to 0	767,792	22.8	37.2	258	18.9	34.7
0	702,538	20.9	58.1	349	25.5	60.2
0 to 1	899,795	26.8	84.9	314	23.0	83.2
1 to 2	267,355	8.0	92.8	125	9.1	92.3
2 to 3	133,587	4.0	96.8	49	3.6	95.9
3 to 4	62,415	1.9	98.7	56	4.1	100.0
4 to 5	27,375	0.8	99.5	0	0.0	100.0
5 to 6	10,639	0.3	99.8	0	0.0	100.0
6 to 7	3,712	0.1	99.9	0	0.0	100.0
7 to 8	1,649	0.0	100.0	0	0.0	100.0
8 to 9	776	0.0	100.0	0	0.0	100.0
9 to 10	325	0.0	100.0	0	0.0	100.0
10 to 11	187	0.0	100.0	0	0.0	100.0
11 to 12	62	0.0	100.0	0	0.0	100.0
12 to 13	20	0.0	100.0	0	0.0	100.0
13 to 14	8	0.0	100.0	0	0.0	100.0
14 to 15	2	0.0	100.0	0	0.0	100.0
15 to 16	1	0.0	100.0	0	0.0	100.0

	Baltimore		FTP	
Accel				
Total	3,360,550	100.0	1,368	100.0

Table 6-11
DISTRIBUTION OF POWER
Baltimore and FTP
Baltimore 3-Parameter Vehicles

	Baltimore			**FTP**		
Power (mph^2/sec)	Count	Percent	Cum. %	Count	Percent	Cum. %
0 - 20	477,725	33.9	33.9	182	33.5	33.5
20 - 40	308,000	21.9	55.8	154	28.3	61.8
40 - 60	215,625	15.3	71.1	104	19.1	80.9
60 - 80	149,080	10.6	81.7	49	9.0	89.9
80 - 100	100,442	7.1	88.8	30	5.5	95.4
100 - 120	64,170	4.6	93.4	11	2.0	97.4
120 - 140	38,864	2.8	96.2	5	0.9	98.3
140 - 160	22,726	1.6	97.8	5	0.9	99.3
160 - 180	13,099	0.9	98.7	1	0.2	99.4
180 - 200	7,386	0.5	99.2	3	0.6	100.0
200 - 220	4,306	0.3	99.5	0	0.0	100.0
220 - 240	2,566	0.2	99.7	0	0.0	100.0
240 - 260	1,565	0.1	99.8	0	0.0	100.0
260 - 280	1,023	0.1	99.9	0	0.0	100.0
280 - 300	582	0.0	99.9	0	0.0	100.0
300 - 320	302	0.0	100.0	0	0.0	100.0
320 - 340	187	0.0	100.0	0	0.0	100.0
340 - 360	103	0.0	100.0	0	0.0	100.0
360 - 380	72	0.0	100.0	0	0.0	100.0
380 - 400	42	0.0	100.0	0	0.0	100.0
400 - 420	20	0.0	100.0	0	0.0	100.0
420 - 440	8	0.0	100.0	0	0.0	100.0
440 - 460	7	0.0	100.0	0	0.0	100.0
460 - 480	7	0.0	100.0	0	0.0	100.0
480 - 500	0	0.0	100.0	0	0.0	100.0
500 - 520	0	0.0	100.0	0	0.0	100.0
520 - 540	0	0.0	100.0	0	0.0	100.0
540 - 560	1	0.0	100.0	0	0.0	100.0

Total	1,407,908	100.0	544	100.0

Figure 6-19
Distribution of Speed: Baltimore and FTP
Baltimore 3-Parameter Vehicles

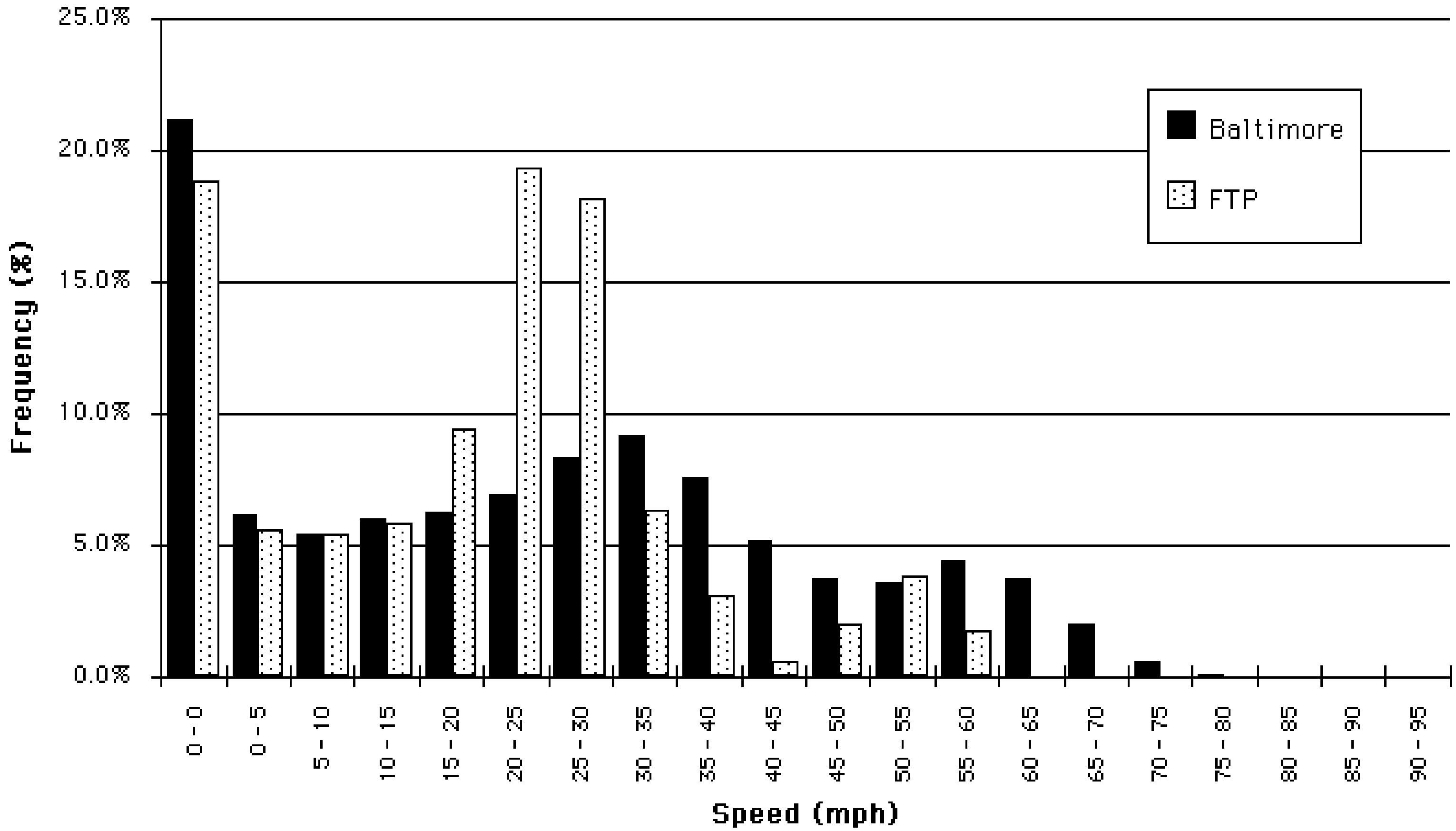


Figure 6-20
Cumulative Distribution of Acceleration: Baltimore and FTP
Baltimore 3-Parameter Vehicles

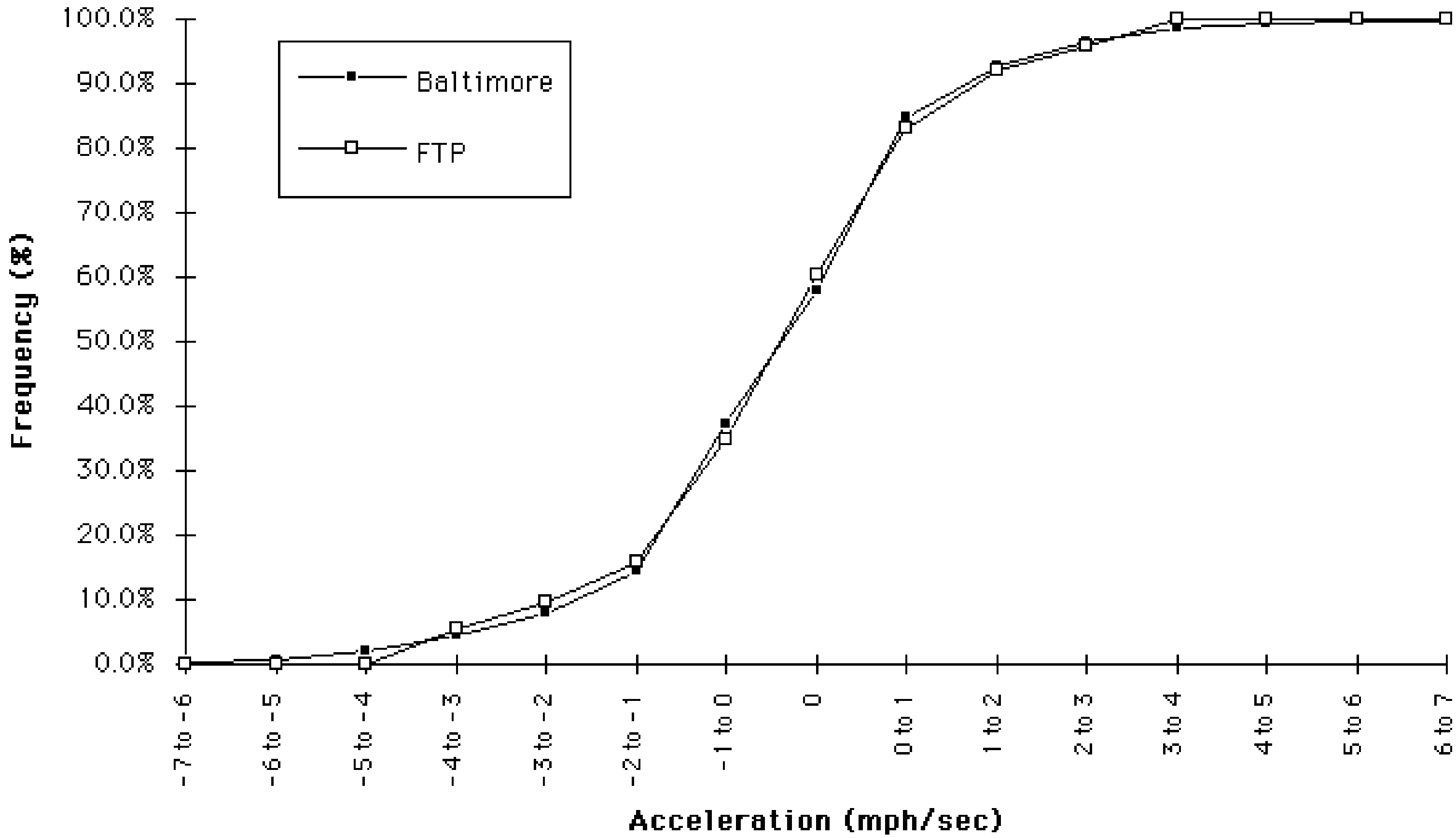
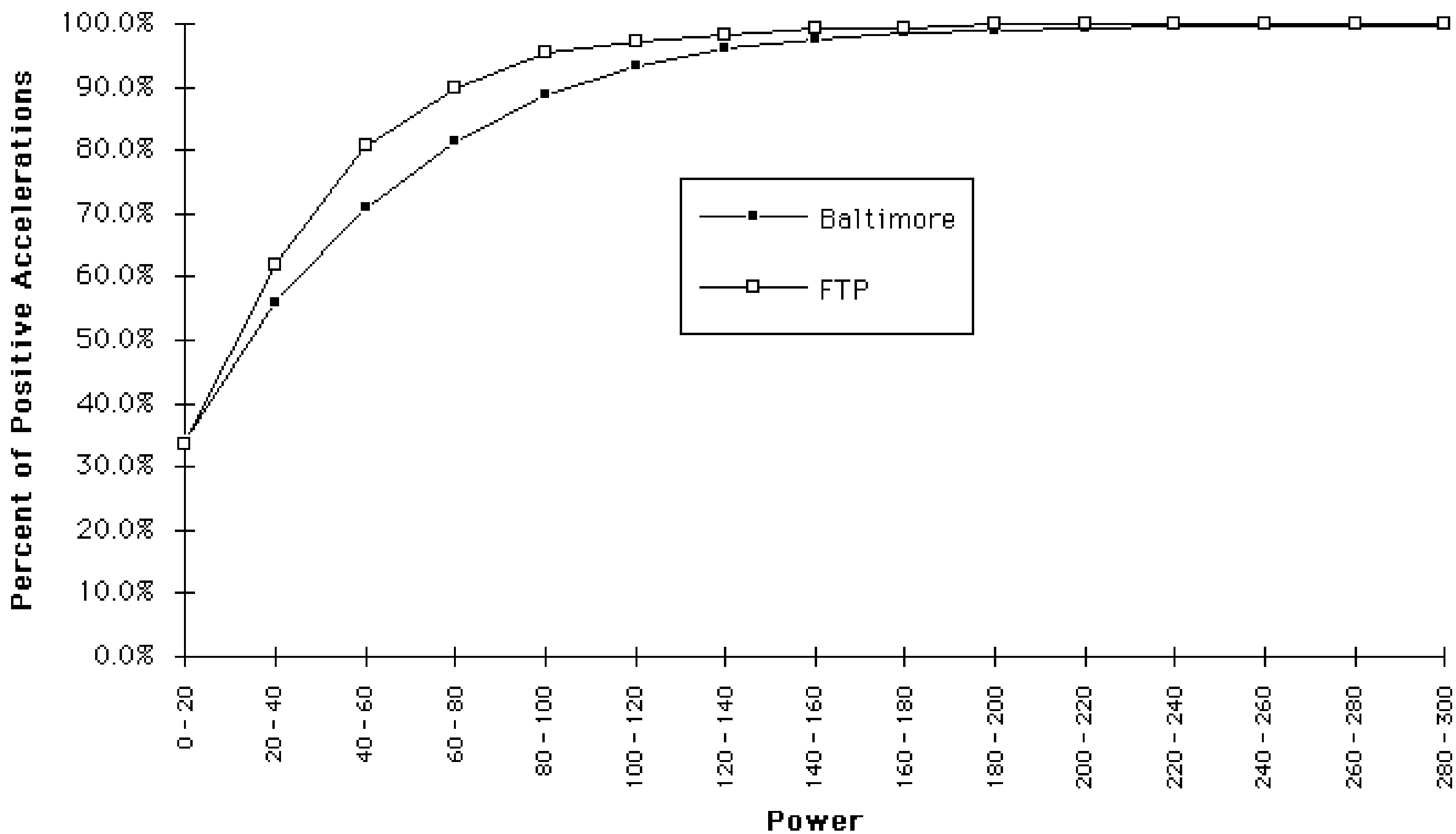


Figure 6-21
Cumulative Distribution of Power: Baltimore and FTP
Baltimore 3-Parameter Vehicles



Combinations of speed and acceleration also can be compared in order to judge how well the FTP "covers" the range of in-use driving. To make this comparison, it is necessary to define in the two-dimensional sense what is meant by FTP and non-FTP driving. Figure 6-22 displays the speed-acceleration plane with points corresponding to all realized combinations of these two variables. Both variables are given to an accuracy of 0.1. These points can be said to define an "envelope" of driving, but there currently is no generally accepted method of defining the boundary of this region.

Typical two-dimensional displays of speed and acceleration imply that the maximum absolute value of acceleration tends to decrease as speed increases. This suggests one possible definition for the FTP envelope: maximum acceleration (or deceleration) at a given speed equals the largest acceleration (deceleration) occurring at or above that speed. The outline in Figure 6-22 is drawn using this definition. All points on or inside this line represent FTP conditions; all points outside are considered non-FTP driving.

Figure 6-23 displays the scatter of speed-acceleration points occurring in the Baltimore sample outside the FTP envelope as defined above. These points represent about 18% of total Baltimore driving time.

Two other views of the FTP/non-FTP contrast are useful. Figure 6-24 depicts the <u>difference</u> in the distribution of driving time found in the FTP and the Baltimore in-use data. This draws attention to those combinations of speed and acceleration that are under- or over- represented by the FTP. The distribution of Baltimore non-FTP driving is shown in the surface graph of Figure 6-25, which helps emphasize regions of relative importance.

Figure 6-22

FTP Speed-Acceleration Envelope

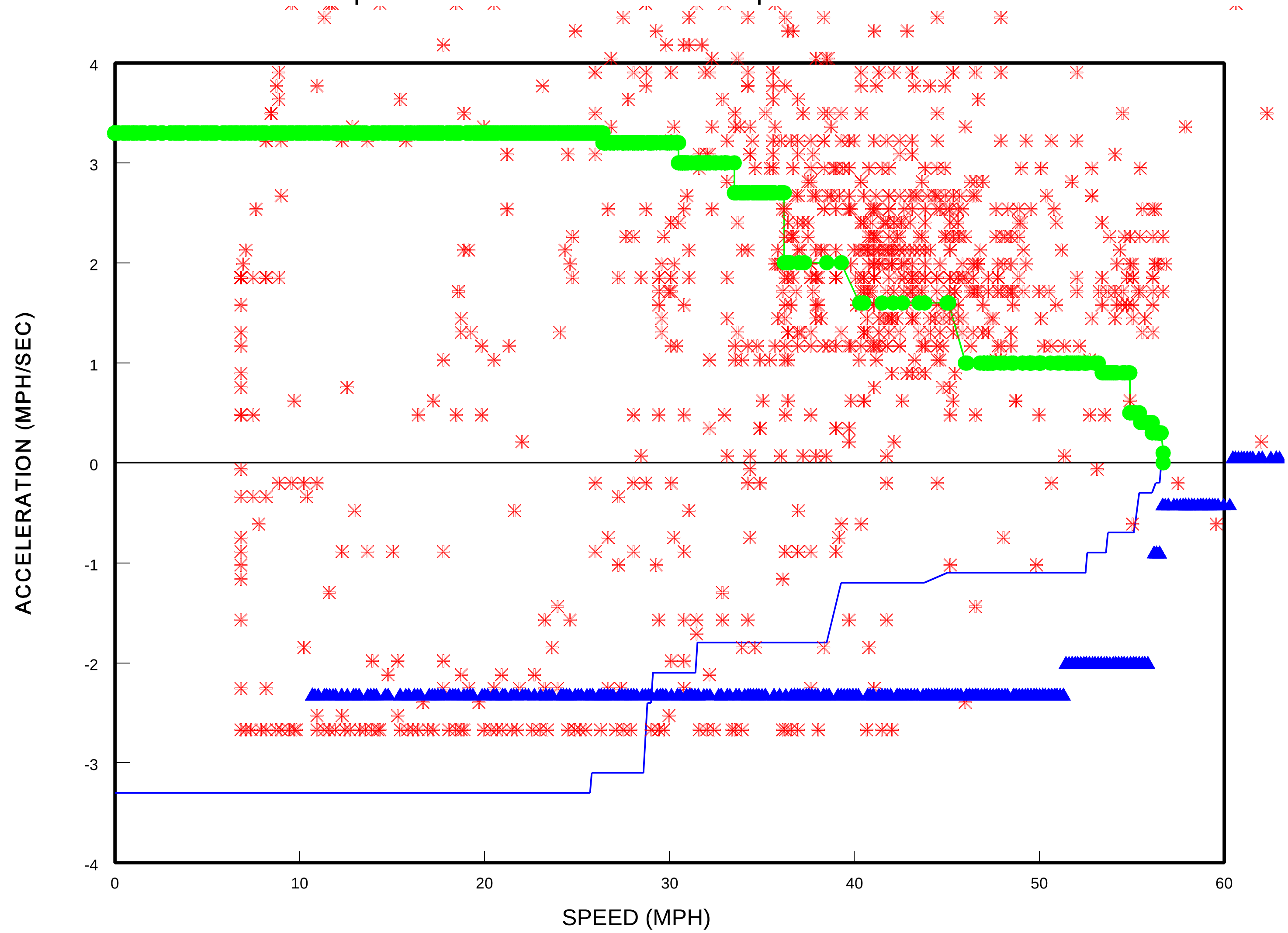


Figure 6-23

Baltimore 3-Parameter Speed-Acceleration Range with FTP Envelope

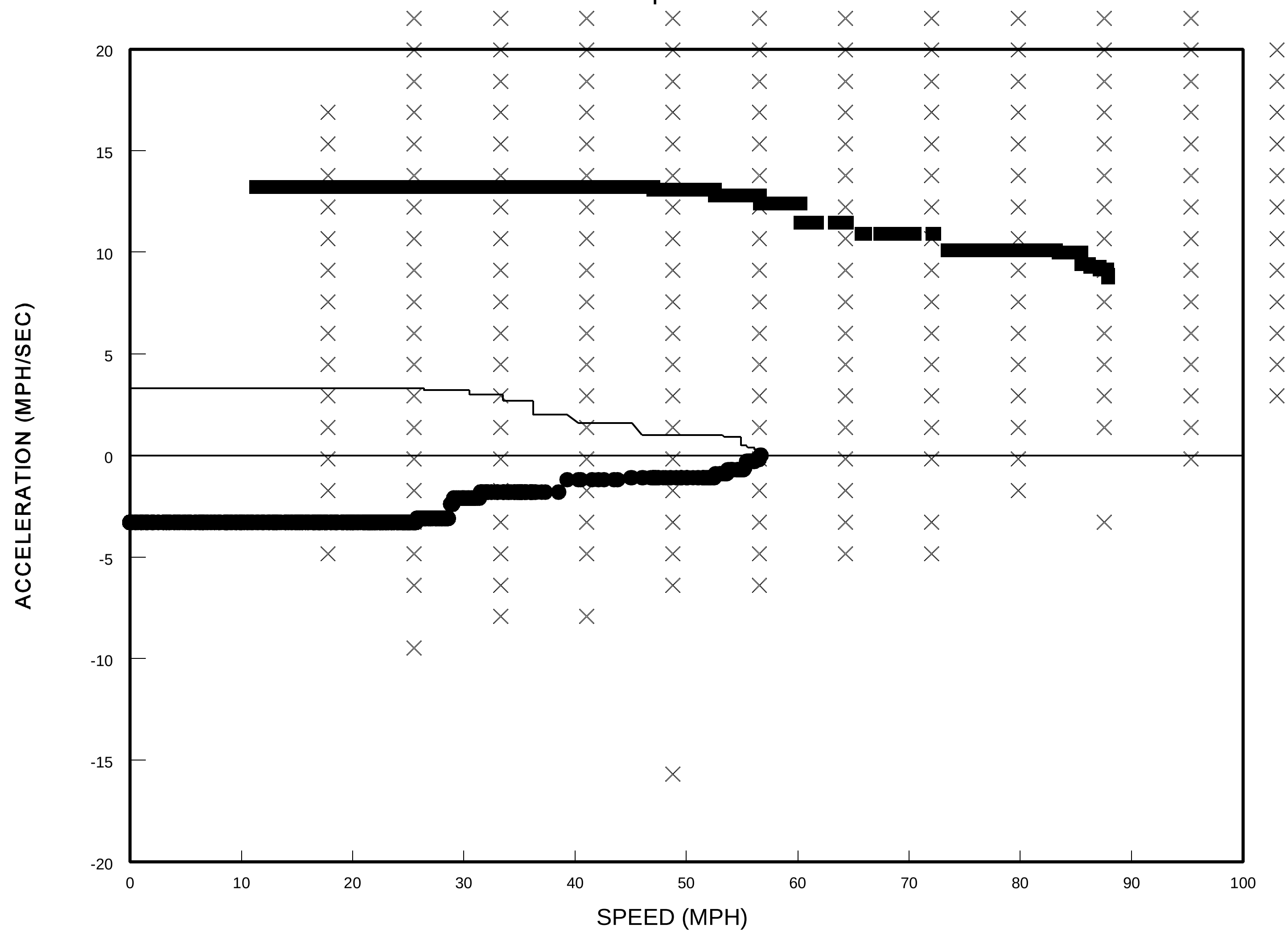


Figure 6-24

FTP Envelope: Difference between Baltimore and FTP
Balt % is percent of all Baltimore Driving Time

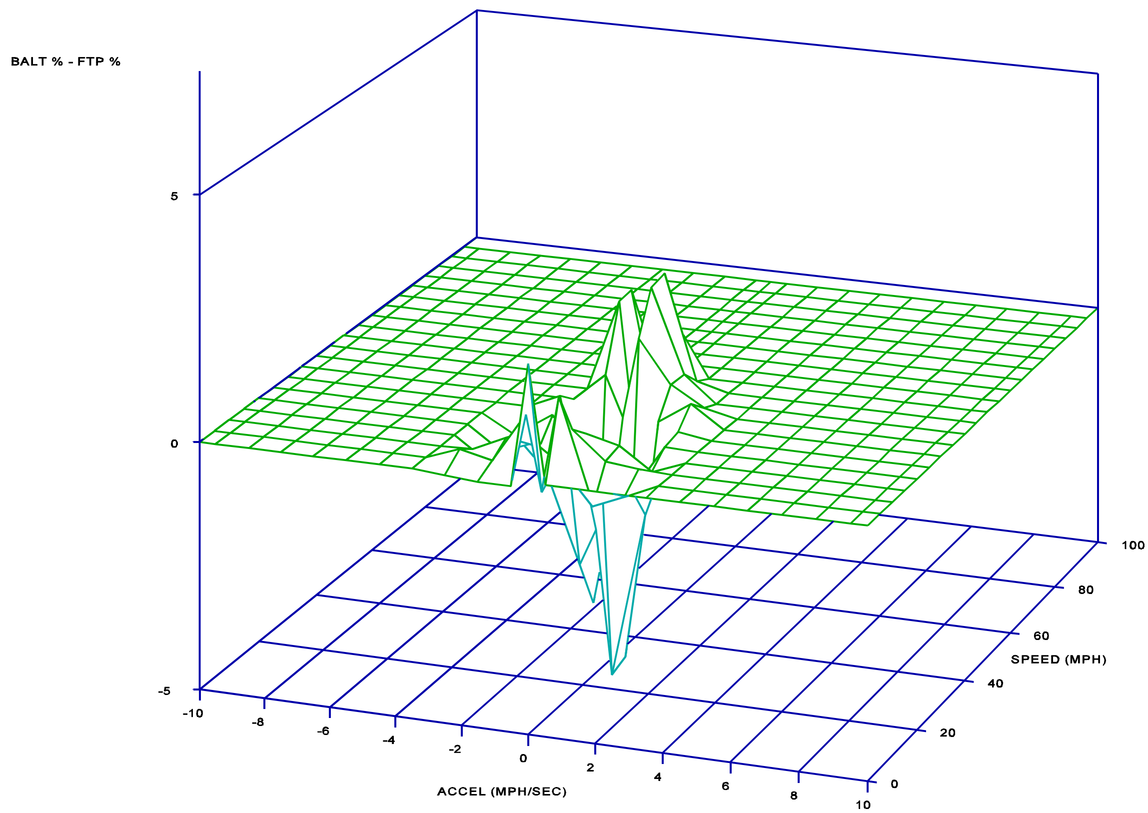
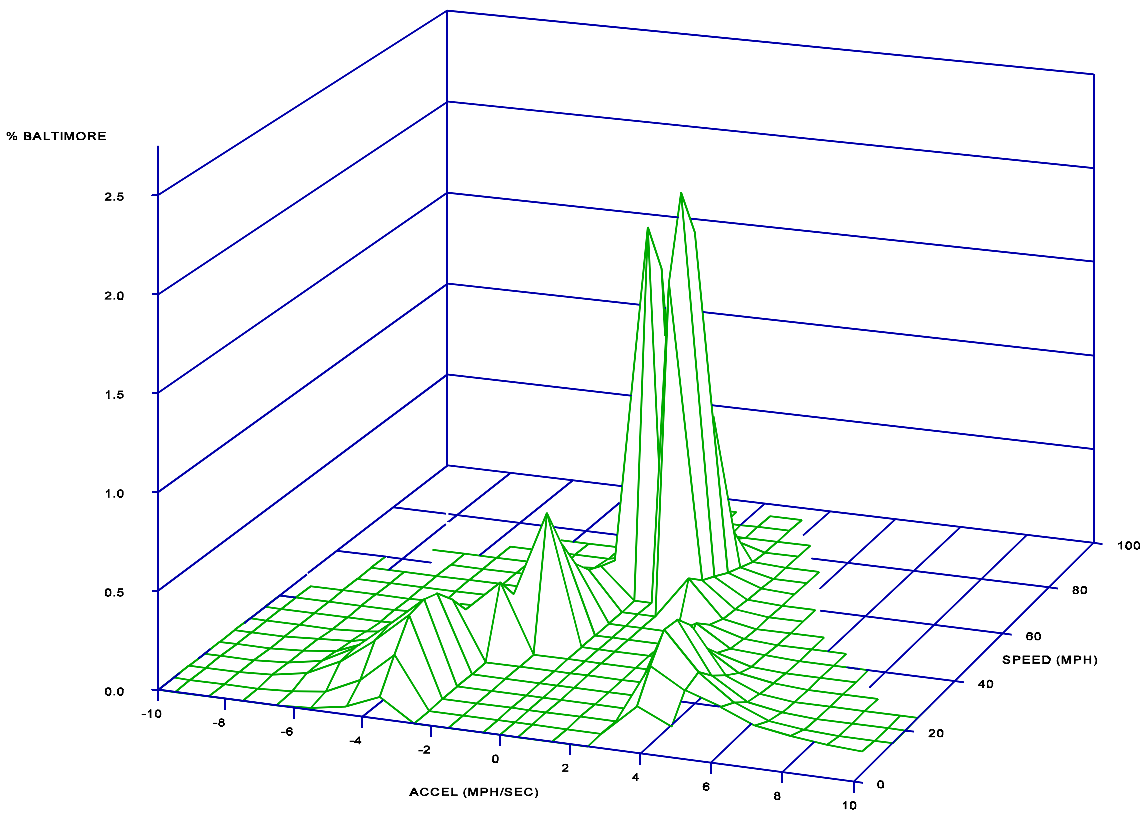


Figure 6-25

Distribution of Speed and Acceleration
Baltimore Driving Outside FTP Envelope



6.3.2. Trip Comparison

The FTP driving cycle was based on a driving route developed to represent driving patterns found on a morning commute trip in Los Angeles, circa 1966. The original route was over 12 miles long, considerably longer than the average trip length of 7.45 miles. In generating the FTP driving cycle, EPA shortened the actual driving trace to 7.45 miles while maintaining the characteristics of the longer cycle.[48]

Table 6-12 compares the FTP "trip" to overall trip data for Baltimore, as well as to Baltimore's typical morning commute trips. The FTP is longer in duration and distance than either of the Baltimore trip measures, although the FTP most closely resembles the Baltimore morning trips.

Comparisons can also be in terms of the proportion of time spent in the four operating modes: idle, cruise, acceleration, and deceleration. The percentage of idle time is slightly higher for Baltimore compared to the FTP. Cruise operation accounts for a little more than a third of operating time for the FTP and on the Baltimore trips. The differences between the in-use data and the FTP for the other operating modes are also minor.

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[48] Kruse, Ronald E., and Thomas A. Huls, "Development of the Federal Urban Driving Schedule," SAE Paper #730553.

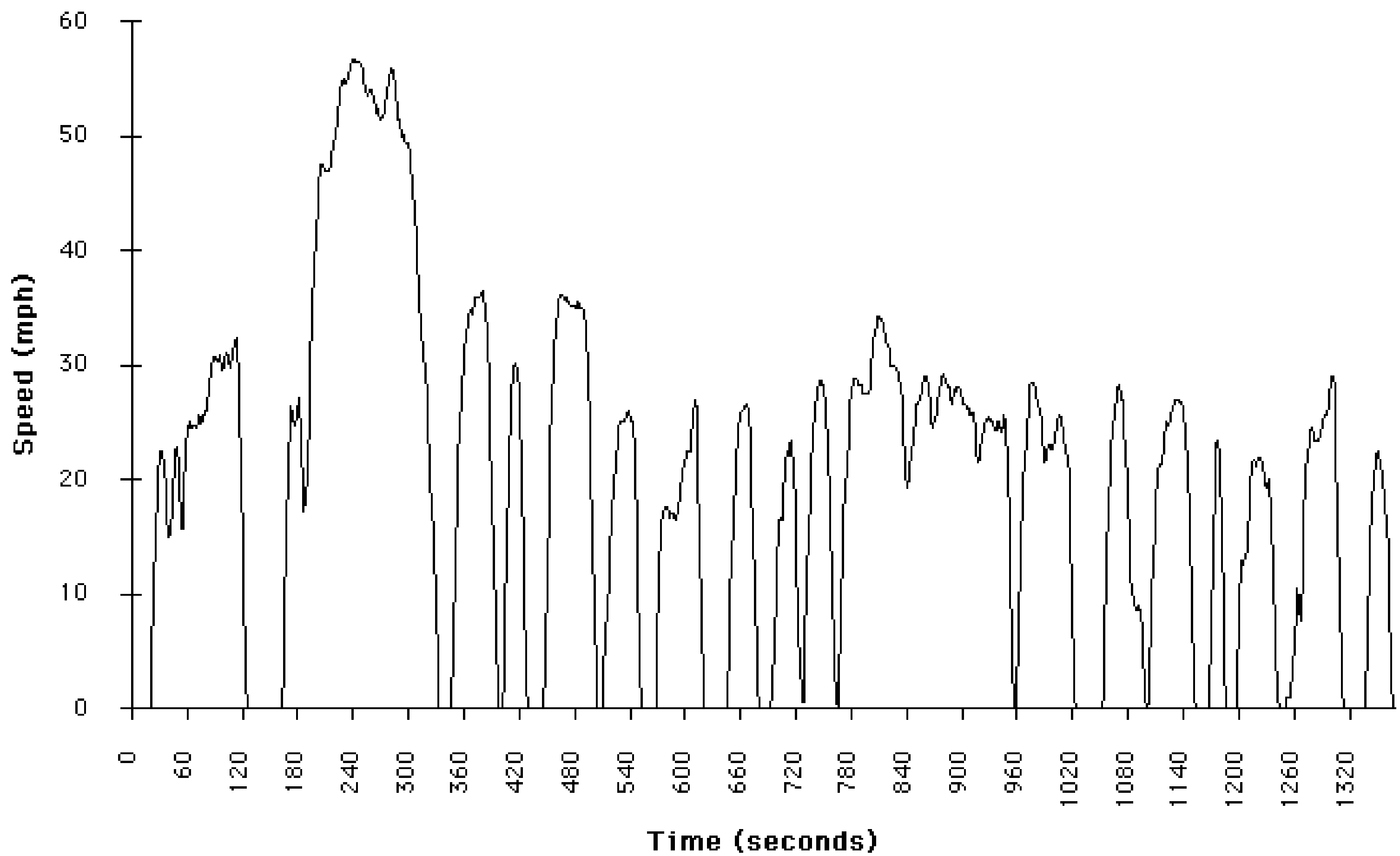
Table 6-12
Comparison of Trip Measures for FTP and Baltimore

Trip Measure	FTP	Baltimore	
		All Trips	Morning commute trips
Duration (minutes)			
Average	22.82	12.03	15.78
Median	22.82	8.80	13.28
Distance (miles)			
Average	7.45	4.89	6.65
Median	7.45	2.53	3.91
Percent time in mode*			
Idle	19.58	22.81	24.34
Cruise	36.23	34.38	34.18
Acceleration	24.18	22.46	21.89
Deceleration	20.01	20.36	19.59
Average distance between stops	0.41	0.87	1.08

*See Section 5.1.2. for definition of modes.

As shown in Figure 6-26, the FTP consists of a series of 18 hills, or microtrips, separated by a short periods of idle. If one thinks of the idle between the trips as a stop, the average distance between stops on the FTP is 0.41 mile. For all Baltimore trips, 0.87 mile is the average distance between stops, more than double the FTP distance. During the morning commute period, the corresponding distance grows to 1.08 miles.

Figure 6-26
Federal Test Procedure (FTP) Driving Trace



At 7.5 miles, the FTP is longer than the average Baltimore trip (4.9 miles); the median Baltimore trip length indicates that "typical" trips are even shorter, only 2.5 miles. The frequency of stops on the FTP is also uncharacteristic of in-use trips, with more frequent stops on the FTP. Despite these differences, the FTP and Baltimore trips disagree only slightly in the proportion of time in various operational modes.

6.3.3. Vehicle Soak

The FTP includes two soaks; a 10 minute soak and an overnight soak. Clearly, when compared to Figure 6-15 of Section 6.2.4, the 10 minute soak in the FTP is appropriate, as 0-10 minute soaks were the largest mode in Baltimore. However, almost 40% of the soaks in Baltimore occurred with soak periods between 10 minutes and 2 hours, the most critical period for catalyst cooldown. To illustrate this point, Table 6-13 compares the temperatures at trip start calculated for the Baltimore data (from Table 6-4) with engine and catalyst temperatures calculated from the cooldown formulas for the FTP.

The data demonstrate that the FTP substantially overstates both the proportion of starts with hot catalysts (that is, catalyst temperatures above the light-off range) and the proportion of starts with cold engines. The FTP implicitly assumes that 57% of all starts occur with hot catalysts, while the actual data indicate that only about 30% of all starts occur with hot catalysts (as discussed in Section 6.2.4., the Baltimore figures in Table 6-13 are likely to overstate the actual catalyst and engine temperatures upon start-up). The FTP also assumes that

Table 6-13
FTP vs. Baltimore Temperature Distribution at Trip Start

Catalyst			Engine		
Temperature Range (°F)	Frequency (%)		Temperature Range (°F)	Frequency (%)	
	Balt.	FTP		Balt.	FTP
800+	22	--	180+	51	57
700-800	9	57	160-180	7	--
			140-160	6	--
600-700*	7	--	120-140	6	--
			100-120	7	--
500-600	6	--	<100	23	43
400-500	5	--			
300-400	5	--			
200-300	6	--			
<200	40	43			

*Catalyst light-off range

43% of all starts occur with cold engines, while the data suggest that less than a quarter of all starts occur with engine temperatures within 25°F the ambient temperature.

From an overall emission inventory point of view, the overstatement of hot catalysts and cold engines in the FTP are offsetting factors which may largely cancel each other out. However, while the 10 minute and overnight soaks in the FTP represent the most frequent modes of soak periods, they offer no incentive for manufacturers to delay catalyst cooldown. Catalysts remain above light-off temperatures after a 10 minute soak and it is not practical to delay cooldown enough to obtain a benefit after an overnight soak. Thus, there may be a "lost opportunity" for inclusion of an intermediate soak time in the FTP. Such an intermediate soak time, if it proved to be feasible, would offer an incentive to improve catalyst light-off times or delay catalyst cooldown (which could be done with catalyst insulation). Thus, the feasibility and potential emission benefits of an intermediate soak period should be included in future emission assessments.

6.3.4. Trip Start Driving Activity

As indicated earlier, the FTP, overall, has lower speeds and is less aggressive than actual driving behavior. However, the reverse occurs during the first few minutes of driving after vehicle starts. Both the FTP and actual driving begin with an initial idle period (20 seconds for the FTP and variable for actual driving, depending on the type of start and ambient air temperature). The FTP then goes into a 105 second micro-trip with an average speed of 23.1 MPH. The average speed during the first 80 seconds of actual driving after the initial idle is only 14.4 mph (as reported in Section 6.2.5). The FTP follows the first micro-trip with a 39 second idle, then launches into the most aggressive section of the entire cycle, reaching speeds over 50 mph 200 seconds after the initial idle. The actual driving activity during the second and third 80-second phases averages about 23 mph, including 27 seconds of idle, and only has about 6% of total operation above 45 mph.

A comparison between the FTP and the actual driving activity from the Spokane and Baltimore data (combining cold, warm, and hot starts), both broken down into 80-second phases, is presented in Table 6-14.

Table 6-14
Comparison of FTP and Actual Start Driving Behavior
(by 80-second phases after initial idle)

	Speed		Acceleration		Power		% Time at Idle*
	Avg	St Dev	Avg	St Dev	Avg	St Dev	
Phase 1							
Actual	14.4	12.3	.24	1.82	40.7	43.1	13.5
FTP	22.7	5.9	.38	1.15	34.1		0.0
Phase 2							
Actual	21.6	15.3	.00	1.65	46.9	43.5	17.3
FTP	11.9	13.2	-.06	1.51	39.9		49.0
Phase 3							
Actual	24.1	16.6	-.01	1.55	45.7	43.0	16.1
FTP	46.0	12.1	.35	1.03	68.2		0.0

*Not including the initial idle time.

These 80-second phase comparisons are skewed by the fact that all of the idle time during the first 240 seconds of the FTP (after the initial idle) occurs in one long 39-second segment that falls in phase 2, while idle time is distributed across all 3 phases of actual driving. Thus, a more meaningful comparison would be to compare the first micro-trip on the FTP (Hill 1) with phase 1 of the in-use driving and to compare the next section of the FTP (106 to 240 seconds after the initial idle) with phase 2 and 3 combined. As the first micro-trip on the FTP is already longer than the first phase of actual driving (105 seconds v. 80), the 39-second idle should be assigned to the second section of the FTP to keep the initial driving comparisons as compatible as possible. These comparisons are presented in Table 6-15.

Table 6-15
Revised FTP and Actual Start Comparison

	Speed		Acceleration		Power		% Time at Idle*
	Avg	St Dev	Avg	St Dev	Avg	St Dev	
Phase 1 - Actual	14.4	12.3	.24	1.82	40.7	43.1	13.5
Hill 1 of FTP	23.1	7.2	.00	1.45	31.8		1.0
Phase 2+3 Actual	22.8	15.9	.00	1.60	46.3	43.3	16.7
2nd Phase of FTP**	29.8	22.6	.40	1.06	64.8		28.1

*Not including the initial idle period.
**Starts 106 seconds after the initial idle and ends 240 seconds after the initial idle. Includes the 39-second idle between the 1st 2 micro-trips.

The data clearly show that the speeds on the FTP are much higher than encountered in-use after a vehicle start. Figure 6-27 presents the speed distributions. The solid lines compare Hill 1 of the FTP to phase 1 of in-use driving; the FTP has far less driving in the 0-15 mph range and much more in the 15-35 mph range. The dashed lines compare the 2nd section of the FTP to phase 2 and 3 of actual driving combined; the FTP has less driving in both 0-15 mph and 30-40 mph ranges, plus far more in the 45-60 mph range.

The aggressiveness of the driving is also skewed, with the first micro-trip on the FTP less aggressive than Phase 1 and the second micro-trip on the FTP clearly overaggressive. Figure 6-28 compares the cumulative power distributions (that is, the amount of driving occurring at or below a given power level). Hill 1 of the FTP spends less time at the higher power levels (i.e. the line rises faster) than Phase 1 of actual driving, while the 2nd section of the FTP spends far more time at the higher power levels. The speed and power data clearly show that the FTP

Figure 6-27.
FTP v. In-use: Start Speed Distribution

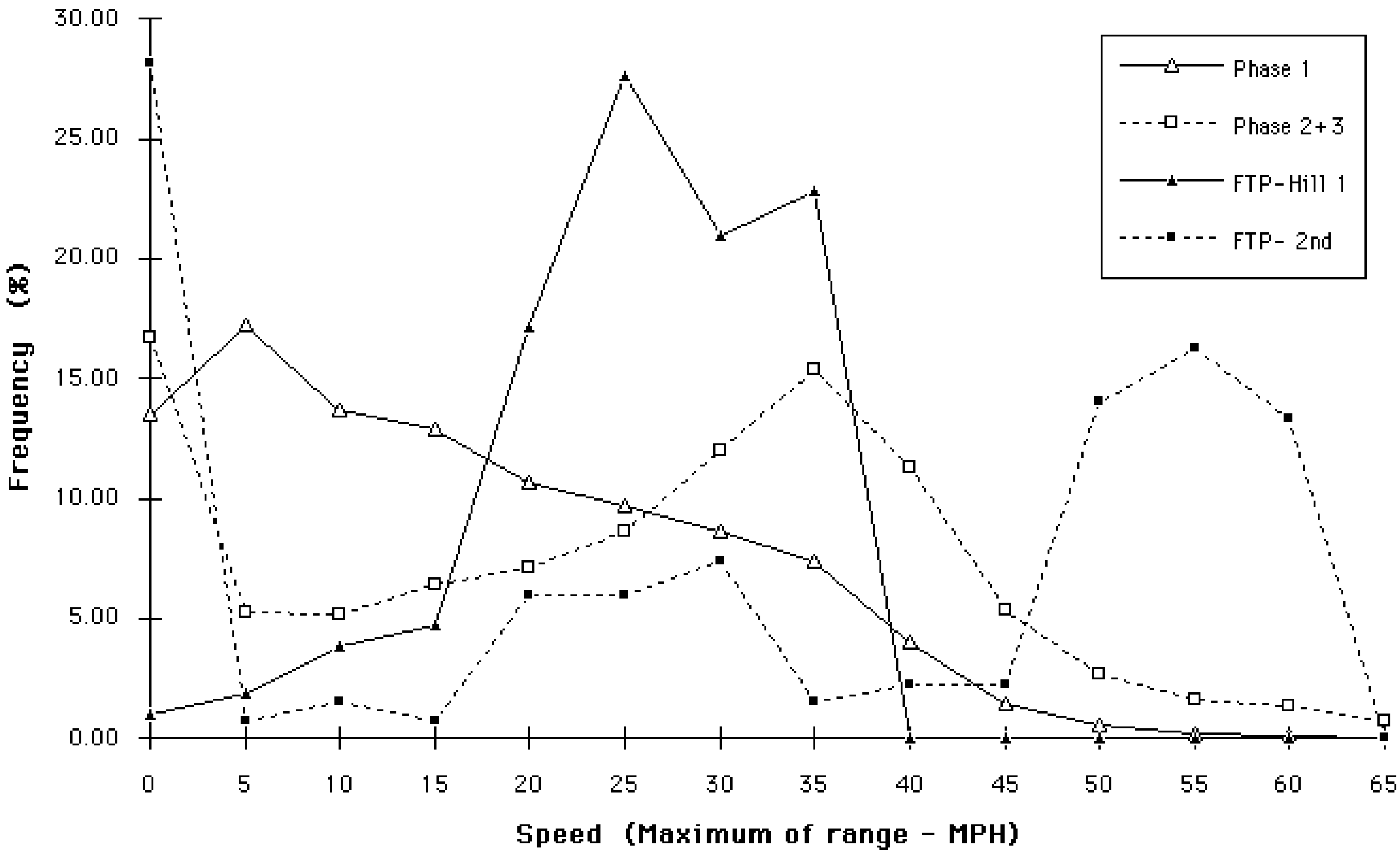
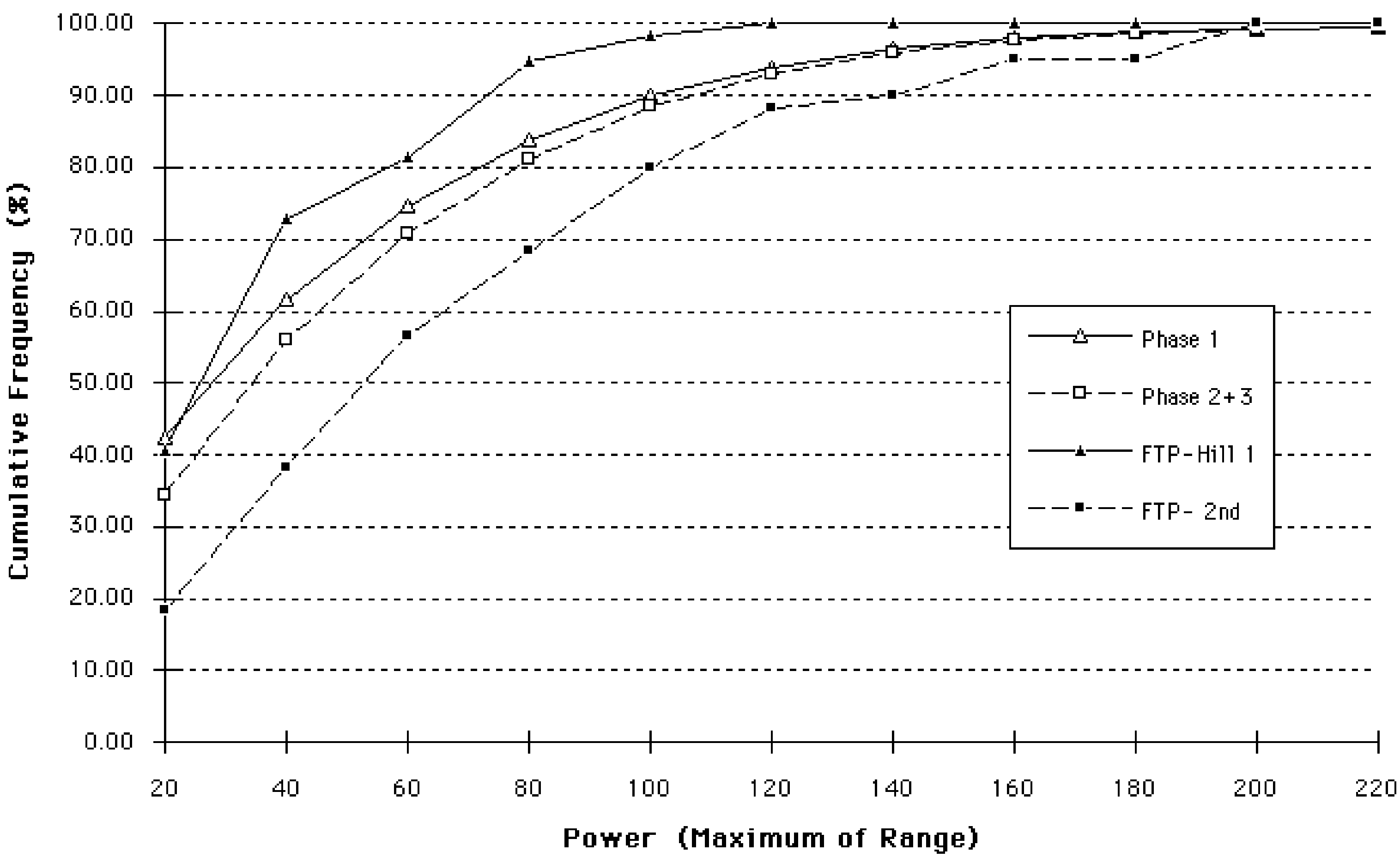


Figure 6-28.
FTP v. In-use: Start Cumulative Power Distributions



contains speed/acceleration events that are seldom encountered in-use during the first 240 seconds of operation.

The impact of driving behavior immediately after a vehicle start on exhaust emissions is subject to interpretation. Higher speeds and loads increase the mass flow through the engine, which would cause more engine out emissions to pass through the catalyst unconverted during warm or cold starts. On the other hand, the engine and catalyst heat up faster during higher mass flows, decreasing the length of time needed for fuel enrichment and catalyst light-off. Compounding the assessment is the fact that the first micro-trip of the FTP has much higher speeds than are encountered in-use during a similar period after a start, but is also less aggressive. The overall impact of these offsetting factors should be investigated in future emission assessment and testing programs. Of course, for compatibility with cycles developed for hot stabilized operation, any start cycle developed for use in emission assessments should be based only on the Baltimore 3-parameter data.

Initial idle time

Table 6-16 presents the initial idle times for Spokane/Baltimore (combined), Atlanta, and the FTP.

Table 6-16.

Initial Idle Times

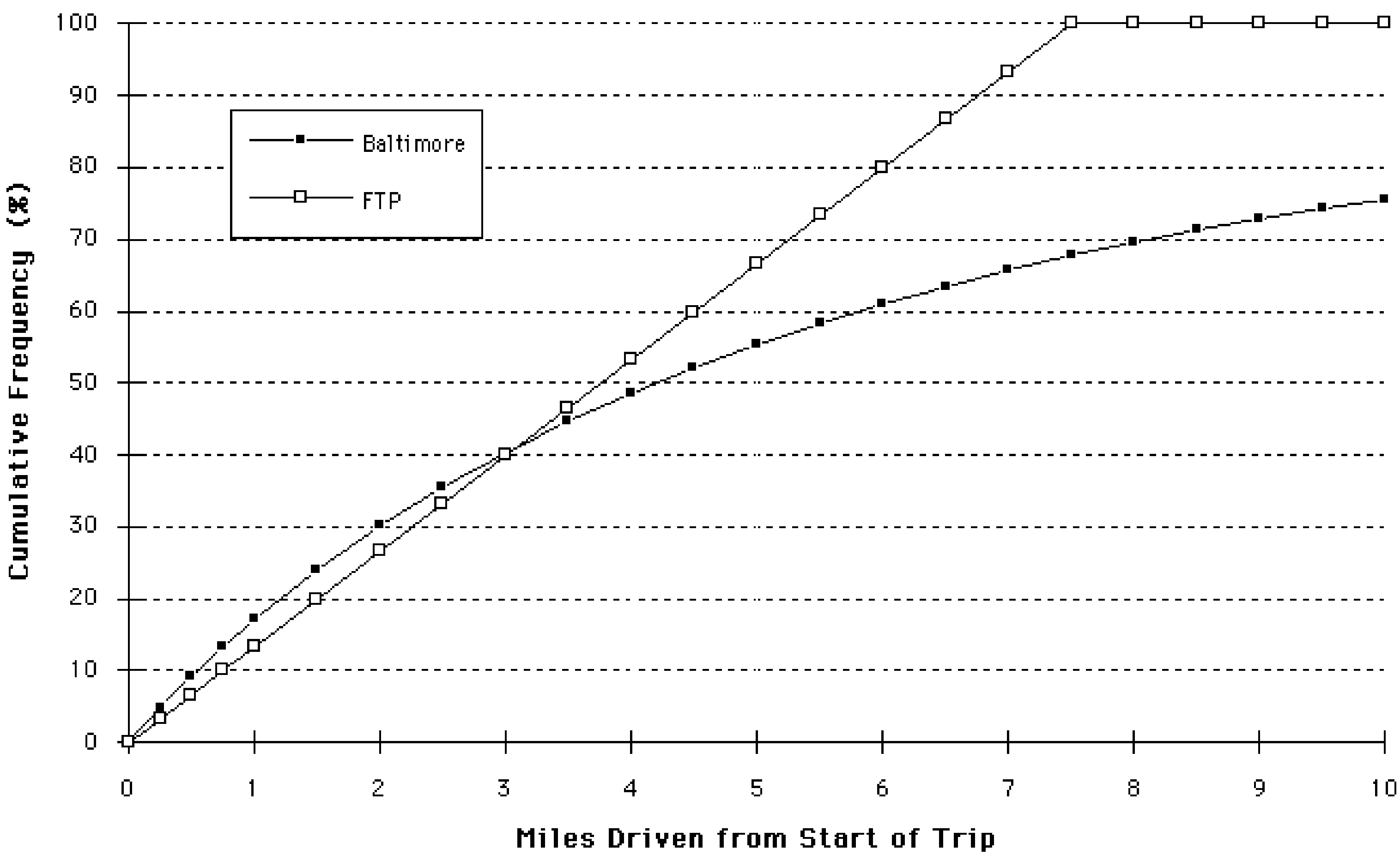
Start Type	City	Mean (seconds)	Median (seconds)
Cold Start	Spokane/Baltimore	59	13
	Atlanta	28	9
	FTP	20	20
Warm Start	Spokane/Baltimore	28	8
	Atlanta	18	7
	FTP	N/A	N/A
Hot Start	Spokane/Baltimore	15	5
	Atlanta	12	5
	FTP	20	20

The data show that the initial idle time after a cold start on the FTP falls between the mean and median initial idle times for Atlanta. Thus, the cold start initial idle time appears to be reasonable. However, the initial idle time after a hot start on the FTP is substantially longer than the mean initial idle time in Atlanta, and four times as long as the median time in all the cities.

Proportion of Driving Occurring After Starts

Figure 6-29 compares the distribution of miles driven since the start of the trip on the FTP to the actual distribution. As the FTP is one trip of 7.5 miles, its distribution appears as a straight line up to 7.5 miles. Due to substantial numbers of trips

Figure 6-29.
FTP v. In-Use: Distribution of Miles Driven



longer than 7.5 miles in-use, the actual distribution shows a large discrepancy in the range of 5-10 miles from the start of the trip. However, this is not likely to be of concern from an emission point of view, as the engine and catalyst are fully warmed up and stabilized after 1-3 miles of operation. Whether the driving after this point occurs 3-7.5 miles from the start of the trip or extends out to higher mileages should not impact the level of hot stabilized emissions.

The differences between the FTP and actual driving less than one mile from the start of the trip are of much more interest, as this relates to the amount of driving that occurs before catalysts or engines have warmed up. While these differences are much smaller in terms of absolute frequency than the differences at higher miles, the relative differences are substantial. Table 6-18 compares the FTP distribution of the first mile driven from the start of the trip to the distribution recorded in Baltimore.

Table 6-17

FTP v. Baltimore Comparison of Miles Driven from Start of Trip

Mileage Range from Start of Trip	FTP Proportion	Baltimore Proportion	In-Use Increase (%)
0-0.25	3.33 %	4.78 %	43 %
0.25-0.50	3.33 %	4.42 %	33 %
0.50-0.75	3.33 %	4.09 %	23 %
0.75-1.00	3.33 %	3.81 %	14 %
0-0.67 (Equivalent to Hill 1 of FTP)	8.93 %	12.01 %	34 %

It is clear that the FTP substantially underestimates the amount of time vehicles actually spend in the initial portions of a trip.

6.3.5. Road Grade

The current FTP speed-time trace was developed without attention to the effects of road gradient. The original road cycle in Los Angeles contained at least one freeway on-ramp (Harbor Freeway, southbound), which was no doubt approached at some rate of acceleration, yet the transcription of the road cycle to a dynamometer trace assumed a flat surface. Thus, the additional engine loads caused by operation on freeway on-ramps and other gradients are not adequately represented.

Regardless of the current limitations of road gradient data, a comparison of in-use driving with the FTP is relatively easy: the FTP is flat, the world is not. The DOT data presented in Table 5-1 illustrates, in nationwide terms, that fully 30% of VMT are traveled on gradients greater than 2 percent, and almost half occur on gradients greater than 1 percent. It is quite clear that emission effects due to road gradient are not represented on the current FTP and that this should be an area of concern for the Agency, but it is also clear that more work is needed to better identify these effects and develop a better understanding of the amount of driving that occurs in urban areas on various road gradients.

Chapter 7. Test Cycle Development Methods and Approach

7.1. Test Cycle Methods

A driving cycle is a time series of vehicle speeds occurring at successive (equally spaced) time points. For emission testing, a test driving cycle attempts to synthesize real driving conditions with respect to a number of measures, including speed, acceleration, specific power, trip patterns, road grade, and temperature. As a practical matter, the cycle must be of reasonable length and it must be "driveable," that is, consist of speeds and accelerations that can be physically realized by vehicles running on a dynamometer.

Following review of the adequacy of the current Federal Test Procedure, EPA will determine whether the driving cycle represented by the FTP should be modified to ensure that future testing better represents actual in-use driving. The comparison of the FTP with results of the driving behavior research presented in Chapter 6 of this report will be a central consideration in developing and judging new test cycles. A full assessment will require combining these pure driving measure comparisons with emission test data.

Generation of a specific cycle requires the choice of a method for selecting the speed sequence. Researchers and practitioners have proposed and used a number of different methods. These are briefly reviewed in the current section. In the following sections, development of a sample cycle is discussed, together with EPA's plans for new cycle generation.

Drive cycle development aims to satisfy two general goals of vehicle emission testing: emission control and emission inventory. Emission control strategies are designed to limit emissions occurring across the range of actual driving behavior and conditions. Emission inventory estimates are obtained by combining vehicle test results with fleet and mileage information. This distinction has an important implication for test cycle development. A cycle used to achieve emission control does not necessarily have to be representative of overall in-use driving. It may artificially emphasize aspects of driving behavior most critical to emission control.

7.2. Method Types

The report bibliography cites previous work on drive cycle method and development. Most of this research is of an applied, empirical nature, with little substantial theoretical basis. Method that have been studied fall into two general categories: segment-splicing and Monte Carlo simulation. A third method might be called the "engineering" approach, whereby a cycle is developed using criteria that do not necessarily include the frequency of occurrence of in-use driving patterns.

7.2.1. Segment-splicing Methods

Probably the most widely accepted approach to cycle generation is to select and splice together segments of observed speed-time trace data that satisfy some set of driving behavior criteria. The current FTP was created by applying this method to speed-time data collected during morning rush-hour driving in Los Angeles, California.[49]

Perhaps the greatest appeal of the segment-splicing approach lies in its use of real driving sequences that are known to be driveable (although it is not necessarily true that all on-road driving can be replicated on laboratory dynamometers). This method does, however, raise a number of questions and problems. The most obvious issue is the selection of segments in order to adequately meet cycle requirements. In practice, this has been performed by sampling in a variety of ways, at random or otherwise, from an in-use database.

Once a set of segments is chosen, they must be connected to produce a single cycle. If the segments are full "microtrips" (extending from one idle to another), this splicing operation is straightforward and is not likely to jeopardize the driveability of the full cycle. However, it sometimes is desirable to use only parts of microtrips (called kinematic sequences or modal segments) which begin and/or end at non-zero speed. Connecting such segments must be done more carefully in order to achieve realistic driving behavior.

7.2.2. Monte Carlo Simulation

Simulation provides an alternative method for generating a drive cycle. In a Monte Carlo simulation, a model is established

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[49] Kruse, R.E. and T.A. Huls, "Development of the Federal Urban Driving Schedule," SAE Technical Paper Series, 730553, 1973.

for describing how actual driving occurs. The model includes both deterministic and probability, or "stochastic," elements to account for known physical properties of driving as well as unexplained random phenomena. Using random number generation to simulate the probability component, a time sequence of speeds is produced with characteristics resembling those of the underlying model.

The principal challenge in applying this technique is to create a suitable model. The typical model will be estimated by fitting a set of assumptions to in-use data. For example, in developing EPA's heavy duty test cycle,[50] second-to-second speed transitions were assumed to obey a "Markov" process, in which the probability of a given speed at the end of the second depends only on the vehicle's speed at the end of the previous second. These conditional probabilities were estimated from in-use driving data frequency distributions. However, evidence exists that the model used in that work is not sufficiently complex to capture all important emission-related elements of real driving, such as the duration of acceleration events. Even the current large sample of second-by-second data may not permit accurate estimation of parameters needed to describe such behavior.

The Monte Carlo simulation approach offers considerable flexibility in modeling driving behavior and generating cycles. It is less popular than the segment-splicing method for the reasons given and because resulting cycles are "artificial" - the second-to-second sequences have not actually been driven in-use. This

[50]Smith, M. Heavy-Duty Vehicle Cycle Development, U.S. Environmental Protection Agency (EPA-460/3-78-008), 1978.

raises the fear that a simulated cycle may not be driveable or, in emission testing, may yield emissions that do not or cannot occur in real driving.

7.2.3. Engineering Cycles

An engineering cycle is a speed-time trace that satisfies certain criteria not generally based on the frequency distribution of in-use driving behavior. For example, it may be the designer's judgment that a cycle should include certain extreme levels of speed, acceleration, or specific power. These objectives can be achieved without reference to in-use data, possibly using simple "straight-line" construction methods. This approach to cycle development is useful as a way of forcing certain conditions that may occur infrequently, or to implement feasibility testing.

7.3. Cycle Criteria

Most applications of cycle methodology have attempted to represent the full range of second-to-second driving behavior; that is, all combinations of speed and acceleration likely to occur in-use. In some circumstances, it may be desirable to construct a cycle that overrepresents various types of driving. In particular, in considering modifications to the FTP, a cycle with a disproportionately high amount of non-FTP driving has potential advantages. This poses special problems, especially for the microtrip-splicing method, because it may be difficult to find largely non-FTP microtrips that are sufficiently short in length to obtain a cycle of realistic duration. In splicing of modal segments or Monte Carlo methods, this is less of a concern.

7.4. Cycle Validation

Once a cycle is generated by either the segment-splicing or Monte Carlo method, it is necessary to test how well it satisfies the objectives of the problem. Usually, this involves matching various characteristics of the cycle to comparable features of in-use driving. The features may include the summary statistics and distributions used in Chapter 6 to describe the Baltimore 3-parameter instrumented vehicle sample. A cycle is considered valid if its statistical properties are reasonably close to those of the data supporting its generation. In practice, this involves selecting a set of arbitrary statistical tests (or "filters"). A cycle that passes these tests at a desired level of significance becomes a candidate for testing. This process is normally followed by a more qualitative evaluation to assure selection of a realistic cycle.

7.5. Current EPA Test Cycle Development

As part of the current study of non-FTP driving, EPA has undertaken the development of new test cycles using the survey data described in this report. This effort includes reviewing cycle development methods and cycle validation techniques and programming of cycle generation algorithms. Through two of its contractors, the Agency currently is engaged in creating cycles for use in emission testing and as candidates for new regulation, pending final conclusions from this study.

List of Appendixes

The following appendixes are presented in their order of first occurrence in the text of the report.